SPARC

Stratosphere-troposphere Processes And their Role in Climate

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Lenticular clouds form over the Crown Range in New Zealand as strong winds are forced over the mountain range. A team meeting of the SPARC Gravity Wave Activity discussed parametrisation of drag created in such conditions in models, and how to improve observations and modelling of orographic wave drag (see report on page 31).

Photo credit: Katja Riedel Photography

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WCRP World Climate Research Programme
WORLD METEOROLOGICAL ORGANIZATION
UNESCO United Nations Educational, Scientific and Cultural Organization
Intergovernmental Oceanographic Commission
International Science Council

JSC-40 meeting report

Mareike Kenntner[1] , Judith Perlwitz[2], Neil R.P. Harris[3], Boram Lee[4], and Hans Volkert[1]

[1]SPARC Office, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany, (**office@sparc-climate.org**), [2]Physical Sciences Division, NOAA Earth System Research Laboratory, Boulder, CO, USA., [3]Centre for Environmental and Agricultural Informatics, Cranfield University, UK, [4]WCRP Joint Planning Staff, WMO, Geneva, Switzerland.

The 40th Session of WCRP's Joint Scientific Committee (JSC) was held in Geneva from 6-10 May, 2019. Detlef Stammer (Univ. Hamburg) was elected as new chair, with Helen Cleugh (CSIRO) as new vice-chair of the JSC. The majority of the JSC members are new (**www.wcrp-climate.org/jsc-contacts**). Over the last year, the WCRP through its Joint Scientific Committee (JSC) and working with the broader climate science community, has produced a new Strategic Plan (SP) for the period 2019-2028 (**www.wcrp-climate.org/wcrp-sp**).

WCRP implementation plan

The next stage is for the JSC to work with the community to formulate an Implementation Plan (IP) and to ensure that the priorities outlined in the SP are implemented effectively. Along with the IP, a transition plan will be developed that ensures a smooth and uninterrupted transition from the current mode of working to the new WCRP structure.

During the weekend prior to the main meeting, a small group of core project co-chairs, working group leaders, JSC members and JPS staff met to develop a conceptual framework for the new implementation plan and the transition process. This draft was further developed during the first two days of the JSC-40 session. The plan focusses on connecting the expertise of the WCRP scientists with the necessary infrastructure (modelling resources, observation platforms, administrative support, *etc*) in order to develop the bedrock science to address societally relevant questions and help provide valuable information for decision makers. An important emphasis lies on being able to reach out to partners in all sectors and to use resources and partnerships in collaborations which facilitate WCRP's work. There is broad agreement of the need to better coordinate expertise within WCRP.

The discussions showed the large interest in constructive collaborations across the whole program, and led to a unified proposal from the co-chairs of the core projects and CORDEX. The proposal is to put certain regions of interest into the focus, where science from all core projects will provide input and be combined to understand the processes special to those regions. The co-chairs proposed to investigate the feasibility of projects on the Himalayas, the Arctic (and the Greenland ice sheet in particular), or the Andes, although other joint projects with more global focus were also discussed. The scope of the initially identified projects will be developed, with a progress report to be presented to the JSC in 2020. These project plans will take into account the gaps and priorities identified in the major scientific assessments such as IPCC AR6. The regional activities and projects therein will be coordinated and supported by the Coordination Office for Regional Activities (CORA; see below).

Visit **www.wcrp-climate.org/wcrp-ip-docs** for:
The Implementation and Transition Meeting Report. Please note that the report reflects discussions during the 2-day meeting, but also lists the key outcomes following the JSC-40, in particular, the timeline and conceptual framework, to avoid confusion.
A presentation containing information on the WCRP Strategic and Implementation Plans for dissemination their the key details the implementation process.
Planned schedule: **www.wcrp-climate.org/wcrp-ip-schedule**

Responses from Sponsors and Partners

A number of WCRP sponsors and partners attended the meeting offering their perspective on the strategic plan and the emerging implementation plan. **Elena Manaenkova** (WMO) noted the growing interest in more frequent assessments of the state of climate science (e.g. to complement the IPCC Assessment in a 5-7 year cycle) to inform climate policy, and that the WCRP community may play an important role therein. **Vladimir Ryabinin** (Intergovernmental Oceanographic Commission of UNESCO, IOC) stressed IOC's continued interest in sponsoring WCRP, noting especially the need for ocean science input to the upcoming UN Decade of Ocean Science for Sustainable Development (2021-2030). The IOC called for an active role of WCRP in developing a decadal science plan within this framework.

Concerning the WCRP implementation plan, **Salvatore Arico** later noted that the IP should present the relevance of science to society more clearly and specifically; meanwhile, consider potential risk that more scientific assessments might raise the tiredness in the policy arena.

Mathieu Denis (International Science Council, ISC) emphasised that it is important to work across the board. ISC's goal is that fundamental science is carried out in all disciplines, but it also strongly encourages engagement with stakeholders, and offers help connecting with communities. The ISC, too, appreciates that basic research is WCRP's core mandate and advises that it remains WCRP's focus.

On behalf of the WMO World Weather Research Program (WWRP), **Sarah Jones** reported that for the 20-year anniversary of the program an online museum on the history of weather research was developed (**www.tiki-toki.com/timeline/entry/1096683/Online-Museum-on-the-History-of-Weather-Research/**).

The strongest connection of the Global Atmospheric Watch (GAW) to WCRP is through the SPARC community. **Greg Carmichael** (Chair of the Scientific Steering Committee for Environmental Pollution and Atmospheric Chemistry) expressed his strong desire to maintain this good collaboration, and possibly to extend the collaborative arrangements to higher levels. The Global Climate Observing System (GCOS, **Stephen Briggs**) also strongly values WCRP as source of scientific requirements and feedback. The Global Framework for Climate Services (GFCS, **Filipe Lucio)**, is currently in a restructuring process, aiming at simplifying its governance structure. It is anticipated that WMO would maintain its priority for climate services in its strategic planning for 2020-2023.

Future Earth (**Amy Luers**) introduced the launch of the Earth Commission that aims to underpin the setting of science-based targets for a resilient planet, and an emerging effort to identify and facilitate the research on Global Systemic Challenges. She proposed that WCRP and Future Earth deepen collaborations through joint efforts particularly in the areas of sustainability research, as well as through science responses to policy requests. **Erica Key** (Belmont Forum) reported that Belmont Forum calls for proposals on climate topics are open and coming up, and expressed Belmont Forum's interest in developing closer ties with the WCRP research community in the future. She noted that the wording of the WCRP Strategy is well-chosen to resonate with possible future sponsors and partners, and reaffirmed the support of Belmont Forum for the open data concept. The Belmont Forum encouraged the WCRP community to consider reaching out to the private sector, which is already engaged in sustainability development and building resilience, and proposed to share Belmont Forum's 'lessons learned' in interacting with the private sector.

Updates from projects and panels

Pavel Kabat reported on the ongoing deliberation on the WMO governance reform that includes the changes in research coordination – a new Research Board (RB) and Scientific Advisory Panel (SAP) will be established. The continuous and increasing emphases for the organization are on the seamless and Earth system approach. WMO calls for closer collaborations of WCRP with WWRP, GAW and other external partners. Pavel Kabat noted that the emphasis of WMO in the implementation of a global agenda has grown, and subsequently, new alliances with the Green Climate Fund (GCF) and the World Bank have been cultivated; in this context, he noted on potential funding opportunities in the future through a more integrated coordination with the WMO programmes.

The Coordination Office for Regional Activities (CORA; **Beatriz Balino**, **Paul Bowyer**, **Daniela Jacob**, **Tore Furevik**) was launched in 2018 in order to identify opportunities, resources and partners to promote regional climate science throughout WCRP and the international research community. CORA is jointly hosted by the Climate Service Center Germany (GERICS) and the Bjerknes Centre for Climate Research (BCCR) of Norway. Specifically, CORA plans to support developing joint/integrative activities of Core Projects and CORDEX (**William Gutowski**) (and with other Working Groups) in regions, capacity building efforts and related outreach. In the starting phase, CORA will conduct a survey among the WCRP bodies to investigate what else they can do to support WCRP efforts. The JSC further suggested that The Working Group on Regional Climate Science and Information (WGRC, **Clare Goddess**), which has been stalled since 2016, works with CORA, GC-Extremes and other Core Projects and groups to develop regional aspects or projects within the new Implementation Plan (see also the core projects' proposal, above).

World**C**limate**R**esearch**P**rogramme

Majority of

Geneva

01 Huijun WANG, *JSC, CN*
02 Bo SUN, *support for **01**, CN*
03 Wenju CAI, *CLIVAR, AU*
04 Thomas PETER, *JSC, CH*
05 Xuebin ZHANG, *ETCCDI, CA*
06 Keith WILLIAMS, *WGNE, UK*
07 Neil HARRIS, *SPARC, UK*
08 Ken TAKAHASHI, *JSC, PE*

09 Iréne LAKE, *CORDEX, SE*
10 Jan POLCHER, *GEWEX, FR*
11 Masahide KIMOTO, *JSC, JP*
12 Paul BOWYER, *CORA (GERICS) , DE*
13 Silvina SOLMAN, *CORDEX, AR*
14 Peter VAN OEVELEN, *GEWEX, US*
15 Timothy NAISH, *GC Melting Ice, NZ*
16 Susanna CORTI, *JSC, IT*

17 Tore FUREVIK, *CORA, NO*
18 Daniela JACOB, *CORA , DE*
19 Pascale BRACONNOT, *JSC, FR*
20 Mareike KENNTNER, *SPARC, DE*
21 Jose SANTOS, *CLIVAR, CN*
22 Pedro MONTEIRO, *JSC, ZA*
23 Pavel KABAT, *chief scientist, WMO*
24 Helen CLEUGH, *JSC (vice-chair), AU*

Legend: **#**, given & SUR-name, *unit/role*, country code

Joint**S**cientific**C**ommittee – **S**ession **40**

of Participants

7 / 10 May 2019

25 Susann TEGTMEIER, *WDAC, DE*
26 Michael SPARROW, *JPS, WMO*
27 Michel RIXEN, *JPS, WMO*
28 William GUTOWSKI, *CORDEX, US*
29 Jean-Noël THÉPAUT, *WDAC/WMAC, ECMWF*
30 Igor SHKOLNIK, *JSC, RU*
31 Tercio AMBRIZZI, *JSC, BR*
32 Francisco DOBLAS REYES, *WMAC, ES*

33 Andrew ROBERTSON, *S2S, US*
34 Narelle VAN DER WEL, *JPS (consul.), WMO*
35 Graeme STEPHENS, *GEWEX, US*
36 Gwen HAMON, *CliC (consul.), NO*
37 Beatriz BALINO, *CORA, NO*
38 Lisa ALEXANDER, *JSC, AU*
39 James RENWICK, *CliC, NZ*
40 Hans VOLKERT, *SPARC, DE*

41 Judith PERLWITZ, *SPARC, US*
42 Krishnan RAGHAVAN, *JSC, IN*
43 Martin VISBECK, *JSC, DE (10 May)*
44 Boram LEE, *JPS, WMO*
45 Josefa POTTER, *JPS, WMO*
46 Matthias TUMA, *JPS, WMO*
47 James HURRELL, *JSC, US (10 May)*
48 Detlef STAMMER, *JSC (chair), DE*

Photos, fusion: Josefa Potter, Oliver Lux; Annotation: Hans Volkert

The Joint Scientific Committee (JSC) – the guiding body of the World Climate Research Programme (WCRP) – held its 40th annual session since 1980 at WMO headquarters in Geneva from 6 to 10 May 2019. After lunch on 7 May, 46 persons assembled for their photo opportunity on the staircase in the lobby of the WMO building. Two further JSC members were photographed at not yet taken positions on 10 May in order to construct the enhanced group depicted above. The addition of metadata in two columns (number, given and sur-names, unit within WCRP [cf. **www.wcrp-climate.org***], country code of workplace) helps demonstrate the geographical distribution across all continents and the diversity of the personalities involved in WCRP. The annotated groupphoto prolongs the tradition of similar undertakings of voluntary cooperation as described in a recent article (cf.* **https://doi.org/10.1007/s00376-017-6329-6).**

The CliC project (**James Renwick**) reported a very busy schedule in the current year. Its implementation has been closely linked with that of the Melting Ice and Global Consequences grand Challenge and with various MIPs.CliC has strong links to the CLIVAR and the CORDEX projects, and emphasised the need for fundamental understanding of glacier and ice sheet mass balances for near- and long-term predictions. A new CliC project office will be established this year.

The CLIVAR project (**Annalisa Bracco** & **Wenju Cai**) highlighted several short-term priorities in its future plans. These include (1) the ocean's role in transient climate sensitivity including changes in sea level under anthropogenically induced radiative changes and the ocean's contributions to energy, heat, water and carbon budgets, their perturbations and changes; (2) regional climate variability and change; (3) physical and biogeochemical interactions in the coastal ocean and changes to this vital and vulnerable region of the planet; and (4) variations in the climate mean state and their interaction with teleconnections and climate modes of variability. CLIVAR currently has an open call for a new Research Focus activity.

Jan Polcher and **Graeme Stephens** reported on behalf of the GEWEX project, emphasizing its integrative and multi-disciplinary nature with focus on processes, feedbacks and land-atmosphere coupling. GEWEX fundamentally underpins and strengthens the Earth system process studies, and displays strong regional foci involving many different regional and local communities. The GEWEX activity is well connected with the Water for Food baskets Grand Challenge (**Jan Polcher**), which is built upon the ongoing and planned Regional Hydroclimate Projects (RHPs) around dense agricultural areas. The aim is to better understand the water cycle and its implication to/interaction with the agricultural activities, and to improve understanding on the interactions of human activities (e.g. irrigation) and lower atmospheric system through field campaigns and model development / inter-comparisons. This Grand Challenge has reached out to other core projects for expertise on the Earth system.

The SPARC presentation (**Neil Harris**) emphasised the strength of the SPARC community, that was in part demonstrated at the successful SPARC General Assembly in Kyoto in 2018, and moreover, continuous bottom-up generation of ideas for new initiatives. It further highlighted recent progress of various SPARC activities, and collaborations between SPARC activities and with external partners. Neil Harris also pointed out the need for clarity on WCRP's way forward, as the current discussions on the internal structure of WCRP have put discussions on possible cooperation with other projects on hold. Finally, Neil Harris reminded everyone, that a Research Program focussed on climate change research should define a clear strategy for reducing its own carbon footprint, *e.g.* in the planning of activity meetings.

Catherine Senior described the huge achievement of the CMIP project and the work of the Working Group on Climate Modelling (WGCM). National institutions and centres contribute to CMIP in the order of 3 billion dollars. Most of the work providing input and coordinating the project is carried out on voluntary basis (a special, thankful mention of Veronika Eyring, the CMIP panel chair, was made). The distributed CMIP organisation has proven successful, and there are enough experiments and research questions in CMIP6 to fuel research over the next CMIP phase. Acknowledging that a large pressure has been placed on those volunteers' shoulders, WCRP should urgently seek ways to recognize all the contributors to the CMIP, as well as to secure firmer financial and coordinating support. All agreed that a serious review of the aims and structure of CMIP is needed to ensure that it meets WCRP's and IPCC's broader objectives. The current phase is moving towards its end, in terms of the model output relevant for the IPCC AR6 report. Modelling centres will continue to run CMIP6 experiments into 2020 and MIP analyses will continue over many years.

The Working Group on Numerical Experimentation (WGNE, **Keith Williams**) reports to WCRP and to the Commission for Atmospheric Sciences (CAS). WGNE has developed the AMIP and Transpose-AMIP methodologies, which contribute to the work on seamless prediction. Future science foci include convection, MJO task force work, surface fluxes, surface temperature, microphysics, and uncertainty representation. Other projects will continue their work on drag, aerosols and other topics. Over the last 30 years, many traditional differences between climate- and weather models have disappeared and the purpose of the working group has evolved into "fostering the development of earth system models for use in weather prediction and climate studies on all time scales, and diagnosing and resolving shortcomings". Several of these overlap with SPARC interests, and SPARC scientists should identify opportunities for productive collaboration.

61 articles using data from the Subseasonal-to-Seasonal Project (S2S, **Andrew Robertson**), a joint project of WCRP and WWRP, have been published and are reporting improvements in prediction skills, *e.g.* for MJO, or the Northern Annular Mode (in cooperation with SPARC). S2S, which is now entering its second phase, cooperates with most WCRP groups, as well as many external ones. A request for funding for an NCAR summer school (with SPARC support) in 2020 has been submitted. S2S was praised for its approach to involve scientists and centres from the beginning. It was also proposed that S2S could take a role in risk assessment studies.

The Working Group on Subseasonal to Interdecadal Prediction (WGSIP, **Doug Smith**) reported involvement in conference organisations, contributions to preparing guidance on seasonal forecasting for WMO regions, and basic scientific progress, *e.g.* ENSO influence on global circulation. WGSIP is closely linked with the S2S project. It will initialise new projects to focus on extremes, as well as Asian monsoon and ocean climate forecasting. Furthermore, the group considers becoming involved with CMIP and leading operational prediction assessments. Doug Smith also reported on the Decadal Climate Prediction Project (DCPP), which has been assessing the influence of initialisation in model runs and the prediction of extremes. This project will stay involved with CMIP6 analysis, and contribute to CMIP7. They are prepared to run forecasts to capture volcano impacts, if an eruption happens. He also mentioned the work of the Grand Challenge on Near Term Climate Prediction (GCNTCP), which has prepared its first issue of the Annual-to-Decadal Climate Update.

In 2018 the WCRP Modelling Advisory Council (WMAC, **Francisco Doblas-Reyes**) organised a summer school and awarded its 2018 International Prize for Model Development to Dr. Thomas Melvin (UK Met Office). This year's call for nominations opens in July with a deadline on 1 October. Nominations and applications by Early Career Scientists are strongly encouraged. The council reminds the JSC that managing modelling efforts need to be well coordinated, especially with the new focus in the Strategic Plan on seamlessness and Earth System models.

Francisco Doblas-Reyes suggested the formation of an Earth System model development working group. He also pointed out that "initialized simulations" represent opportunities to consolidate S2S-WGSIP-DCPP and connect more closely to NWP/WWRP towards seamless predictions.

The WCRP Data Advisory Council (WDAC, **Susann Tegtmeier**) has been active over the past years in working as a focal point for all observational and data matters across the program. WDAC has contributed to the CMIP project, and has created a new Surface Flux Task Team, with a white paper just finished. Among other tasks, this team will be a focal point for surface flux observations and analysis, and will establish publication and documentation standards for data and metadata. Furthermore, a proposal is being made to establish a WCRP Earth System Reanalysis Intercomparison and Evaluation group for the coordination of Reanalysis Intercomparison Projects (RIPs). SPARC's S-RIP project was mentioned as exemplary in involving the forecast centres in the work. WDAC calls for explicit inclusion of reanalyses in the WCRP infrastructure discussion. They also propose to write an official WCRP document on observations required for key research and the coordination of targeted field experiments. Finally, concerning data science and data management, WDAC envisions the promotion of transfer of knowledge from other disciplines and the identification of areas for international collaboration on big data and artificial intelligence. During the panel discussion, it became clear that it is important to not only collaborate with GCOS, but also use the Research Data Alliance of the ISC to consult on other possible partnerships.

The Grand Challenge on Extremes (**Jan Polcher**) presented continuous success in advancing scientific understanding, for example, by leading the IPCC AR6 chapter on weather and climate extremes. The presentation pointed out the many remaining questions to pursue, and the need to provide guidance for applications and services (*e.g.* guidance documents on the use of extreme dataset, on future projection of extremes). It was further stressed that interactions with other WCRP groups need to be well-organised to ensure cross-fertilisation and coordinated approaches. At the JSC session in 2018 (Nanjing), the Grand Challenge on Weather and Climate Extremes (GC Extremes) noted the discontinuation of the joint WMO/CCI-WCRP-JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI), which had underpinned many successful research activities on extreme data, analyses, development of indices and relevant attribution studies. At this year's JSC session **Lisa Alexander** and GC-Extremes leaders proposed a light-weight core-project-type activity on extremes (tentatively called Global weather and climate Extremes Project: GEP) to be a central hub to coordinate extreme-related activities toward and within the new WCRP. It could also provide internal science capability in formulating the WCRP position on extreme-relevant and policy-relevant issues such as attribution and prediction/projection of weather and climate extremes.

Following the WCRP workshop "The Earth's energy imbalance and its implications", November 2018 in Toulouse, France, a proposal was made to develop a WCRP-wide project/theme on this subject within a new implementation phase of WCRP. The proposal was based on the work of the CLIVAR research focus CONCEPT-HEAT (Consistency between planetary energy balance and ocean heat storage), Earth energy imbalance uncertainty assessment of GEWEX, and the collective discussions across all core projects and working groups to address the question on "Where does the Energy go?"

Outlook

The conceptual framework of the WCRP implementation plan was agreed at the JSC, and will be further discussed within the JSC and WCRP bodies. A draft structure and outline will be proposed to the WCRP community by April 2020 (at the JSC-41), during which period the focus will be to refine science questions, key elements for delivery and engagement, and the needs for funding and infrastructure. The full Implementation Planning will be an evolving process for 3 years until April 2022 (at the JSC-43). A structure and governance for the new WCRP will be developed and presented through thorough consultation with the full WCRP community, sponsors and partners, academics, and the climate service community. It was reaffirmed that the commitment of WCRP (and its co-sponsors) to Core Projects and their community involvement (*e.g.* Project Offices) will be maintained and further solidified as much as possible. All WCRP the groups (including all Core Projects) may be asked to provide a synthesis of their achievements, for consideration in the "landscape" of the new WCRP.

The initial set of key science questions within the new Implementation Plan will be refined via consultation with Core Projects (referring to their respective Science Plans), and considering various horizon-scanning done by partners and aligned groups (e.g. IPCC); for example, with respect to the needs of mitigation and adaptation strategies relevant for the communities in the post-Paris era.

The JSC discussed the need and possible extent of informing climate policy process of the state and gaps in science/research. As a recognized partner of UNFCCC for science and research, WCRP has been providing science input to the Subsidiary Body for Scientific and Technological Advice (SBSTA) through the Research Dialogue (RD). An EarthInfoDay during the COP-22 (2016) was another good example addressing the Parties of the status of our understanding, knowledge gaps and opportunities in earth observation and global climate (change) science that elevated the Parties' attention to the need for systematic and synthesized reporting on the status of science. And there has been growing expectation on whether WCRP could coordinate a synthesized report on the state of climate research on a regular basis, to complement the peer-reviewed but less-frequent reference of IPCC assessments.

As part of the celebration for WCRP's 40-year anniversary, a climate science week is being organized during the AGU fall meeting in December 2019. It will start with a Symposium on Sunday, 8 December, and will continue throughout the whole week with WCRP science sessions, workshops, and town hall meetings, and ending with a WCRP union session on the Friday. In parallel, an Early Career Scientists (ECS) conference on climate science will be organized together with its community partners and ECS networks. Details of the program can be found at: **www.wcrp-climate.org/wcrp-agu2019**.

SPARC SSG members in 2019:

Neil Harris, co-chair
Centre for Environment and Agricultural Informatics, Cranfield University,
Cranfield, UK

Gufran Beig
Indian Institute of Tropical Meteorology,
Pune, India

Harry Hendon
Bureau of Meteorology,
Melbourne, Australia

Karen Rosenlof
NOAA/ESRL,
Boulder, CO, USA

Hauke Schmidt
Max Planck Institute for Meteorology in
Hamburg, Germany

Donald J. Wuebbles
University of Illinois,
Urbana, IL, USA

Boram Lee
Senior Scientific Officer and SPARC liaison
at the WCRP Joint Planning Staff, WMO,
Geneva, Switzerland

Judith Perlwitz, co-chair
ESRL, NOAA,
Boulder, CO, USA

Wen Chen
Center for Monsoon System Research at
IAP, Chinese Academy of Sciences,
Beijing, China

Nathaniel Livesey
NASA-JPL,
Pasadena, CA, USA

Kauro Sato
Department of Earth and Planetary Science, University of Tokyo,
Tokyo, Japan

Seok-Woo Son
Seoul National University,
Seoul, Republic of Korea

Tianjun Zhou
LASG, Institute of Atmospheric Physics,
Chinese Academy of Sciences,
Beijing, China

The JSC has approved the appointment of **Prof. Nili Harnik** (Tel Aviv University, Israel) and **Prof. Takeshi Horinouchi** (Hokkaido University, Japan), who will join the SPARC SSG in January 2020.

Personal reflections on the outlook for SPARC

The future development of WCRP is beginning to become clearer in practical terms. The constructive discussions at the Joint Steering Committee meeting (above) confirmed the rationale laid out in the new Strategic Plan and, importantly, developed a framework to bring the strategy to life. Our major concern in the past has been the apparent uncertainty on the level of support for communities within WCRP. Their value in both developing new ideas and in training early career scientists is now widely acknowledged: communities will play a major role in the future WCRP. Having said that, WCRP must stimulate the evolution of new communities to meet the new research needs outlined in its Strategic Plan.

The Implementation Plan is now being prepared. An important part of this is the WCRP Climate Science Week at AGU in December (**www.wcrp-climate.org/wcrp-agu2019).** A special WCRP 40th Anniversary Symposium will be held on Sunday 8th December which will celebrate the first 40 years of WCRP as well as launch the new phase of WCRP science. Other WCRP events will be held throughout the week. The aim is for this plan to be refined over the following two and a half years in an extensive consultation period. WCRP is a necessarily complicated structure – it supports the research underlying the ever more complicated climate models. It is critically important that the new Implementation Plan is properly thought through in detail.

From a SPARC perspective, the central role of the atmosphere and its interactions with other components of the climate system in WCRP science is becoming increasingly recognised. The lack of a central activity on tropospheric composition and radiative forcing – and especially the climate forcing agents – is a historical quirk. (SPARC successfully addresses the 'stratospheric' forcings.) Deep understanding of long- and short-lived climate forcing agents will underpin advice on how to minimise increases in radiative forcing in the critical next 40 years: WCRP has to help achieve this. This will require cooperation with many existing activities outside WCRP (WMO's GAW and Future Earth's IGAC, SOLAS, ILEAPS to name but four). A similar situation exists for the larger scale atmospheric dynamics in which SPARC plays the leading role. For example, addressing sub-seasonal to decadal prediction is requiring the input from many current disciplines and activities. S2S is an exemplar in bringing the expertise of many interests to address this issue.

Our view is that WCRP will need discipline-centred themes into the foreseeable future. Given the strength of existing infrastructure, it is hard to see what can successfully replace core projects in the medium term. Offices, newsletters, General Assemblies, focussed workshops and conferences all play a central role in coordinating global climate science. SPARC has a special role in view of its support for the Montreal Protocol as well as UNFCCC process. Issues such as the unreported CFC-11 emissions and the ozone trend in the lower stratosphere show that the area is still very much alive.

However, SPARC and the other core projects must continue to evolve in order to support WCRP's aims. The core project-led initiative at the JSC is a good example of collaborative generation of new, broad initiatives. Such cross-cutting science activities are likely to become the norm, not the exception, in future. Generating cutting edge ideas and clear plans for these is critical.

In the case of SPARC, we are starting to prepare the strategy for 2021-2025. It will be based around the continued existence of SPARC, but will have clearer emphasis than before on how the SPARC strategy supports the WCRP strategy and society's needs more generally. A large number of studies presented at the General Assembly directly address challenges faced by society. In addition to working with a wider a range of natural scientists, more work with economists, social scientists, private sector, *etc.* is likely with co-design of projects becoming a standard approach to proposal development - not the only one, but a widely used one. Having said that, it is critical that the type of high quality scientific research promoted by SPARC remains the bedrock of WCRP. Successfully achieving this balance between doing excellent research and addressing practical societal questions is an exciting challenge for SPARC scientists in the coming years.

Neil Harris and Judith Perlwitz (SPARC co-chairs)

Report on the International Symposium on the Unexpected Increase in Emissions of Ozone-Depleting CFC-11

Neil R.P. Harris[1], Stephen A. Montzka[2], Paul A. Newman[3], with generous contributions from the Symposium attendees

[1]Centre for Environmental and Agricultural Informatics, Cranfield University, UK, [2]ESRL, NOAA, Boulder, CO, USA, [3]NASA/GSFC, Greenbelt , MD, USA.

DATES:
25 - 27 March 2019

ORGANIZING COMMITTEE:
Geir Braathen (WMO), Neil Harris (SPARC), Paul Newman (SAP), Bella Maranion (TEAP), Sophia Mylona (Ozone Secretariat)

SCIENTIFIC PROGRAMME COMMITTEE:
Tina Birmpili (Ozone Secretariat), Geir Braathen (WMO), Neil Harris (SPARC), Jianxin Hu (Univ. Beijing), Ken Jucks (NASA), Bella Maranion (TEAP), Steve Montzka (NOAA), Sophia Mylona (Ozone Secretariat), Paul A. Newman (SAP), Sun Young Park (Korea), Stefan Reimann (Empa), Matt Rigby (Univ. Bristol), Takuya Saito (Japan), Helen Tope (TEAP)

MEETING VENUE:
United Nations, Vienna, Austria

NUMBER OF PARTICIPANTS: 71

SPONSORS:

WEBSITE:
https://www.sparc-climate.org/meetings/meetingscfc-11-workshop-march-2019-in-vienna/

1. The state of understanding before the Symposium

Recent findings of an unexpected emission increase of chlorofluorocarbon-11 (trichlorofluoromethane, CFC-11, CCl_3F) [Montzka *et al.*, 2018][1] has raised important issues within the atmospheric sciences and policy communities. CFC-11 is a long-lasting man-made compound (52-year lifetime in the atmosphere) that is not only a powerful ozone depleting substance (ODS) but also a powerful greenhouse gas with a 100-year global warming potential of 5,160. Growth of emissions could indicate that releases from CFC-11 banks are accelerating, that the atmospheric circulation is changing such that our estimates of emissions based on observed concentrations increase, or that unreported production is leading to increased CFC-11 emissions.

Global CFC-11 emissions in the 2014-2016 period derived by Montzka *et al.* [2018] were shown to be about 13 gigagrams per year (Gg/yr) higher than the 2002-2012 average. Montzka *et al.* further showed that emissions from eastern Asia had also increased during this period. The "Scientific Assessment of Ozone Depletion: 2018" [WMO, 2018] provided additional information to that from Montzka *et al.* [2018] using both NOAA and AGAGE CFC-11 observations, along with some simple model simulations of impacts of these emissions. The independent AGAGE observations also showed CFC-11 emissions increased after 2012. The combined networks indicated an annual increase of 10 Gg/yr in the 2014-2016 period over the 2002-2012 baseline, consistent with the Montzka *et al.* estimate. While such an emission increase was highly unexpected given the reported production phase-out, the discrepancy between expected and observationally-derived emissions may have begun as early as 2007 (Figure 1). These emission increases slowed the otherwise steady decrease in atmospheric concentrations reported in previous Assessments. The global decline in CFC-11 concentration over 2014 to 2016 was only $2/3^{rds}$ as fast as it was from 2002 to 2012. While the CFC-11 emissions from eastern Asia have increased since 2012, the contribution of this region to the global emission rise was not well known, and the country or countries in which emissions have increased had not been identified.

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[1] Citations are indicated by square brackets []. Italicized citations denote Symposium presentations with only the lead presentation author given, while regular font citations are peer-reviewed publications.

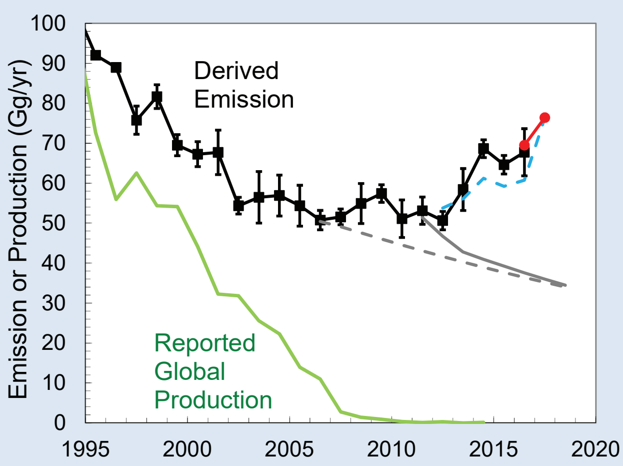

***Figure 1:** Global CFC-11 emissions derived from NOAA atmospheric observations with a three-box model (black squares) considering a 57.5-year lifetime[2], and production magnitudes reported to the United Nations Environment Programme (UNEP, green line). Red points represent updated values to Montzka et al. [2018] presented at the Symposium [Montzka], while the dashed blue line represents emissions approximately corrected for the upper end of estimated circulation changes. The dashed grey line shows expectations given measured global changes through 2005 using a data derived release fraction of 3.2 % per year of CFC-11 from the bank extrapolated forward, and the solid grey line is a WMO scenario projection [WMO, 2014] that was constrained by observational data through 2012 (rescaled here to be consistent with a 57.5 yr lifetime) [as in Montzka et al., 2018].*

Subsequent on-the-ground investigations by different organizations suggested ongoing use of CFC-11 in China for the production of foams in 2018, but it was not clear if the activities they identified could account for the observed global changes [*Perry*].

CFC-11 production usually begins with carbon tetrachloride (CCl_4 or CTC) as feedstock (Figure 2, left) [*Sherry*]. The main commercial-scale production involves the fluorination of CTC using a liquid-phase antimony catalyst and anhydrous hydrogen fluoride (Figure 2, left middle) [*Tope*]. In addition to CFC-11, there is typically some co-production of CFC-12 (CCl_2F_2) [*Tope*]. Before its phasedown, CFC-11 was mainly used in foams; other uses included aerosols, limited refrigeration and air conditioning units (R/AC), metered-dose inhalers, tobacco processing, and as solvents (Figure 2, middle right). Use in aerosols and solvents resulted in the emission of the CFC-11 shortly after production; but when used to produce foams, only a small fraction of the CFC-11 escapes to the atmosphere rapidly while the majority remains in the foam cells in building insulation or in foam products. Collectively, the CFC-11 that is not immediately released is referred to as a "bank" (Figure 2, right). While some of this "banked" CFC-11 is readily available for disposal and can be incinerated or destroyed in anaerobic processes in landfills[3], a substantial fraction remains and is slowly released to the atmosphere at an estimated rate of 0.5 %[4] per year (e.g., the CFC-11 in foam cells of building insulation). The schematic representations of plumes in Figure 2 collectively shows the multiple paths by which CFC-11 is emitted to the atmosphere. Once in the atmosphere, CFC-11 eventually reaches the stratosphere, where it breaks down and releases its chlorine atoms to catalytically destroy ozone. Further, the increased atmospheric CFC-11 increases the radiative climate forcing.

The implications from the increased CFC-11 emissions are potentially serious. Under the Montreal Protocol on Substances that Deplete the Ozone Layer (hereafter, MP), the global consumption and production for controlled uses of CFC-11 was mandated to cease from 2010 onwards. In response to these recent observational findings concerning CFC-11, the Parties to the MP approved "Decision XXX/3: Unexpected emissions of CFC-11." This decision formally asked the Scientific Assessment Panel (SAP) to provide a summary report on this "… unexpected increase of CFC-11 emissions ..." A preliminary summary report is required for the 41st Open-ended Working Group (July 2019), a further update is requested at the 31st Meeting of the Parties (Nov. 2019), and a final report to the 32nd Meeting of the Parties (Nov. 2020). The decision also asked the Technology and Economic Assessment Panel (TEAP) to provide the parties with information on potential sources of emissions of CFC-11 in a preliminary report to the 41st Open-ended Working Group and a final report to the 31st Meeting of the Parties.

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[2] The 57.5-year lifetime is consistent with coupled-chemistry-climate model lifetimes [Montzka *et al.* 2018]. The 52-year lifetime is from WMO [2018], and is a combined estimate of atmospheric observations and models.

[3] Although a few tests were completed from 2003-5 that showed some biodegradation of CFC-11 in anaerobic conditions, no large-scale or long-term in situ testing was completed to confirm that this would occur in landfill operating conditions. Additional detail can be found in the May 2005 volume 3 Technical and Economic Assessment Panel (TEAP) Report of the Task Force on Foam End-of-Life Issues. Evidence for CFC-11 loss in a limited number of landfills is also provided in Hodson *et al.* [2010]. CFC-11 destruction does occur in anoxic marine waters [*e.g.* Bullister and Lee, 1995].

[4] The Intergovernmental Panel on Climate Change estimates that the release rate from landfills is 0.5 % per year as extrapolated from foam degradation. Additional detail can be found in the May 2005 volume 3 TEAP Report of the Task Force on Foams End-of-Life Issues [TEAP, 2005].

The science community responded to this CFC-11 emissions increase by holding the "International Symposium on The Unexpected Increase in Emissions of Ozone-Depleting CFC-11" at the United Nations Office in Vienna, Austria on 25-27 March 2019. More than 70 participants from the science and technical communities from 22 different countries attended the Symposium, with 37 presentations. Representatives of the MP's SAP, TEAP and the Environmental Effects Assessment Panel (EEAP) were also present.

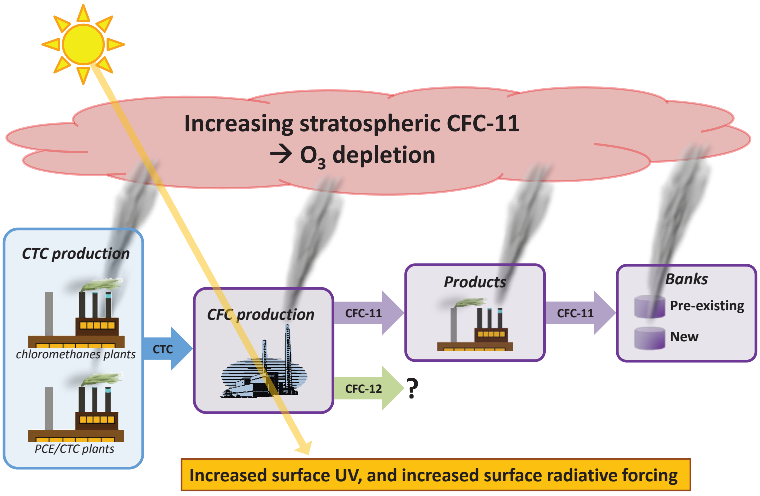

Figure 2: *Schematic of CFC-11 emission routes (and also CTC). The left blue box shows production of CTC, which is used as the feedstock (blue arrow) for CFC-11 production (left middle box; PCE = perchloroethylene or C_2Cl_4). The produced CFC-11 feeds into (purple arrow) the manufacturing of products (e.g., foams), as indicated in the middle box. Some traditional CFC-11 products are directly emissive (e.g., aerosols). Foams and other less emissive products collectively form the CFC-11 bank (right hand purple box). Life-cycle emissions of CTC and CFC-11 from these sources (represented as grey cloud plumes) contribute to the atmospheric burden of chlorine that leads to ozone depletion, allowing increased penetration of ultraviolet radiation to the Earth's surface and increased surface radiative forcing.*

2. Unravelling the puzzle

Additional evidence for unreported production

Updated measurements of atmospheric CFC-11 concentrations and additional consideration of CFC-11 emission from banks that were presented at the Symposium make it more certain that the recent excess in emissions inferred for the past few years (see Figure 1) is caused by unreported CFC-11 production. The major uncertainties in quantifying the excess emissions to unreported production are (i) a possible increase in the leakage from banks; and (ii) the influence of atmospheric variability.

A preliminary estimate of CFC-11 emissions for 2018 suggests that they remained comparable with 2014-2017 rates when inferred from NOAA observations [Figure 1; update of Montzka *et al.*, 2018]. New results presented at the Symposium based on observations conducted in eastern Asia also confirmed that emissions from this region had increased from 2012, during the 2013-2017 period [*Western*; *Park*; and now Rigby *et al.*, 2019].

Other work presented at the Symposium further confirmed that enhanced atmospheric concentrations of CFC-11 have been observed recently in Asia in both focussed studies [*Benish*; *Simpson*; *Fang*] and in analyses of longer-term measurements [*Arduini*; *Adcock*; *Dang*; Lin *et al.*, 2019]. These studies have potential for more precisely identifying the location of sources in eastern Asia and quantifying their magnitude. Observations of other ODS potentially related to CFC-11 production (e.g., CFC-12, HCFC-22) do not show comparable global emissions behaviour [*Laube*; *Vollmer*]. However, significant emissions of CTC (the CFC-11 feedstock) are found in eastern China in the last decade [Park *et al.*, 2018; Lunt *et al.*, 2018], with these CTC emissions shifting northward to Shandong province after 2012 [Lunt *et al.*, 2018].

Considering the major uncertainties in turn: analysis of bank release rates indicates that it is unlikely that bank emissions could have increased by the amount required to explain the observations. Specifically, it seems improbable that emissions from the breakdown of insulating foams expressed as a fraction of the global CFC-11 bank could have tripled in recent years and now be as large as 10% per year. Even larger increases in the bank leakage rate (by 10 times) would be required if the increased global source was the result of enhanced releases from foams only in eastern Asia [*Western*; Rigby *et al.*, 2019]). This is compounded by the fact that even when foams are crushed or shredded, a significant portion of the blowing agent (e.g., CFC-11) remains in the foam matrix[5]. Other traditional CFC-11 applications (e.g., aerosols, refrigeration and air-conditioning and associated banks) also appear to be unlikely sources of the increased emissions [*Walter-Terrinoni (b)*].

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[5] The 2005 TEAP report on End-of-Life of Foams estimates that 50% of the blowing agent remains in the foam matrix after crushing or shredding.

The main processes other than emission variations that can lead to interannual variations in CFC-11 concentrations are the quasi-biennial oscillation, El Niño-Southern Oscillation, and other large-scale dynamical changes that typically operate on time-scales of a few years. Both the multi-year period during which excess CFC-11 emissions have continued (now including 2018) and especially the identification of substantial increases in CFC-11 from eastern China (see below) [*Western*; Rigby *et al.*, 2019] put tighter bounds on the possible contribution of changing atmospheric dynamics on the observed concentration anomalies. The updated observations provide additional confidence that the influence of dynamical variability cannot account for more than half of the inferred emissions and further imply that the excess emissions are attributable in large part to unreported production. Several presentations examined how atmospheric variability could impact CFC-11 concentrations and global emissions when derived with simple model approaches [*Laeng*; *Mueller*; *Nuetzel*; *Portmann*; *Prather*; *Schuck*; *Sheese*].

Where do the increasing emissions come from?

Global CFC-11 emissions can be estimated using annual global concentrations and the CFC-11 lifetime (as shown in Figure 1). The difference between the northern hemisphere (NH) and southern hemisphere (SH) average concentrations (the inter-hemispheric difference or IHD, North minus South) provides additional information on anthropogenic emission magnitudes. If there are no emissions, global mixing by atmospheric weather systems over a 1-2 year time-scale makes the IHD quite small or even slightly negative. Increasing emissions primarily in the NH would cause a temporary increase in the IHD, since the tropics inhibit rapid mixing between the hemispheres. After 2012, the IHD in both NOAA and AGAGE measurements rapidly increased [Montzka *et al.*, 2018 and WMO 2018], and updates for 2018 presented at the Symposium show that this larger IHD persists, implying that elevated NH emissions continued through that year [*Montzka*].

Temporarily enhanced CFC-11 concentrations above background ('pollution events') can be easily identified in station observations made downwind of and relatively near sources. Owing to the long CFC-11 lifetime, pollution events are indicative of recent emissions from one or more specific upwind sources (e.g., chemical plants, production facilities, landfills, and building demolition). The Gosan station (South Korea) observations show many such events, and the concentration of CFC-11 in these events has increased since 2012 [*Park*; *Western*; Rigby *et al.*, 2019]. As with smoke plumes, mixing by the atmosphere causes the CFC-11 concentrations in these plumes to eventually dilute to background levels. Hence, measurements made far downwind contain reduced quantitative information about emission magnitudes and locations in these upwind regions. Many stations outside of eastern Asia (*e.g.*, Mace Head, Ireland) show a decreasing frequency and strength of events, suggesting fairly constant or reduced emissions in regions surrounding these sites over these same years [Rigby *et al.*, 2019]. Station and aircraft observations in eastern Asia also suggest a continued regional source of emissions [*Adcock*; *Benish*; *Dang*; *Simpson*; Lin *et al.*, 2019].

In contrast to global emission estimates, quantitative estimates of regional emissions are more difficult to obtain because they depend on a sufficient number of hourly-to-daily observations from regional stations, along with detailed knowledge of atmospheric air motions that bring air to a station. Emissions have been estimated for several areas of the world, with a recent estimate of emissions from eastern Asia, using observations from Gosan Station (S. Korea) and Hateruma (Japan) [*Western*; Rigby *et al.*, 2019; *Park*].

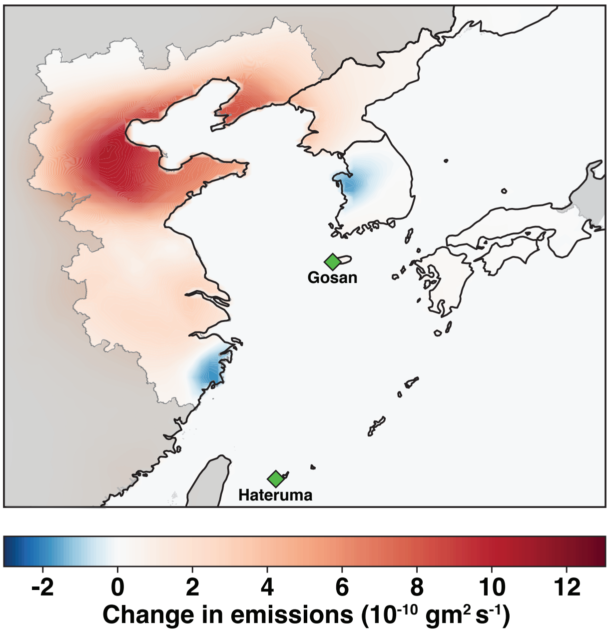

Figure 3: *Spatial distribution of the changed CFC-11 emissions from 2008-2012 to 2014-2017 from an inverse analysis of the data from observations at Gosan and Hateruma (diamonds) with the NAME-HB inversion framework. The shaded areas indicate regions with low sensitivity, and therefore, are not included in the estimates of emissions and emission changes [adapted from Western; and Rigby et al., 2019].*

These two stations are mainly sensitive to emissions only from South Korea, North Korea, southern Japan, and the eastern portion of China that accounts for about 38 % of its population. Figure 3 shows the difference between emissions derived for 2014-2017 and for 2008-2012. The majority of these emission increases come from Shandong and Hebei provinces in NE China, and the integrated total increase is 7.0 ± 3.0 Gg/yr, which accounts for at least 40 - 60 % of the global rise in CFC-11 emission over these years [*Western*; Rigby *et al.*, 2019].

While these regional inversions provide the best information about the location and strength of the emissions in this region, they require high quality measurements within or closely downwind of this region. Given that such measurements are made in only some regions, the value of this approach to sum over all potential emission regions to obtain global increases is limited (Figure 4). In addition to eastern China, estimates of CFC-11 emissions have been made for recent years for Western Europe [*Manning*; Manning *et al.*, 2003], Australia [*Fraser*; Fraser *et al.*, 2015], and the U.S. [Hu *et al.*, 2017]. While these are important regions, many other important areas are not covered. Indeed, Rigby *et al.* [2019] point out that any unreported production and resulting emission from eastern China is unlikely to have contributed substantially to the slower than expected global decrease in atmospheric CFC-11 from 2002 to 2012. Understanding the observations during this earlier period requires further work from both a scientific and a technical perspective [*Solomon*] - one possible explanation is continued unreported CFC-11 emission from unknown locations outside of eastern China.

More geographic, though less quantitative, information is available from short-term field studies using aircraft and ground-based sampling. In India, for example, emission estimates are available from a 2-month aircraft campaign in 2016 [Say *et al.*, 2019]. Such studies, which have been performed in China, Korea, Pakistan, Saudi Arabia and Taiwan [*Adcock*; *Dang*; *Simpson*], can (a) identify emissions hotspots, as well as areas with low emissions, and (b) provide detailed information on the gases which are co-emitted with CFC-11, and possibly also on the potential CFC-11 sources and/or co-located emissive activities. Such studies are flexible, can be quickly organized, and the information gained can be used to identify priority areas for further research.

Do we understand the source(s)?

The possibility that unexpected increased emission rates from banks could lead to a rise in emissions was explored in multiple ways. A new "bottom-up" model was developed and a sensitivity analysis was used to bound the range of possible emissions related to production reported to AFEAS and the Ozone Secretariat changing the relative sizes of the market sectors and emissions rates from production, installation, and banks. The best fit corresponded to the highest emissions rates up to 2002. After that time period, none of the scenarios aligned with the derived emissions.

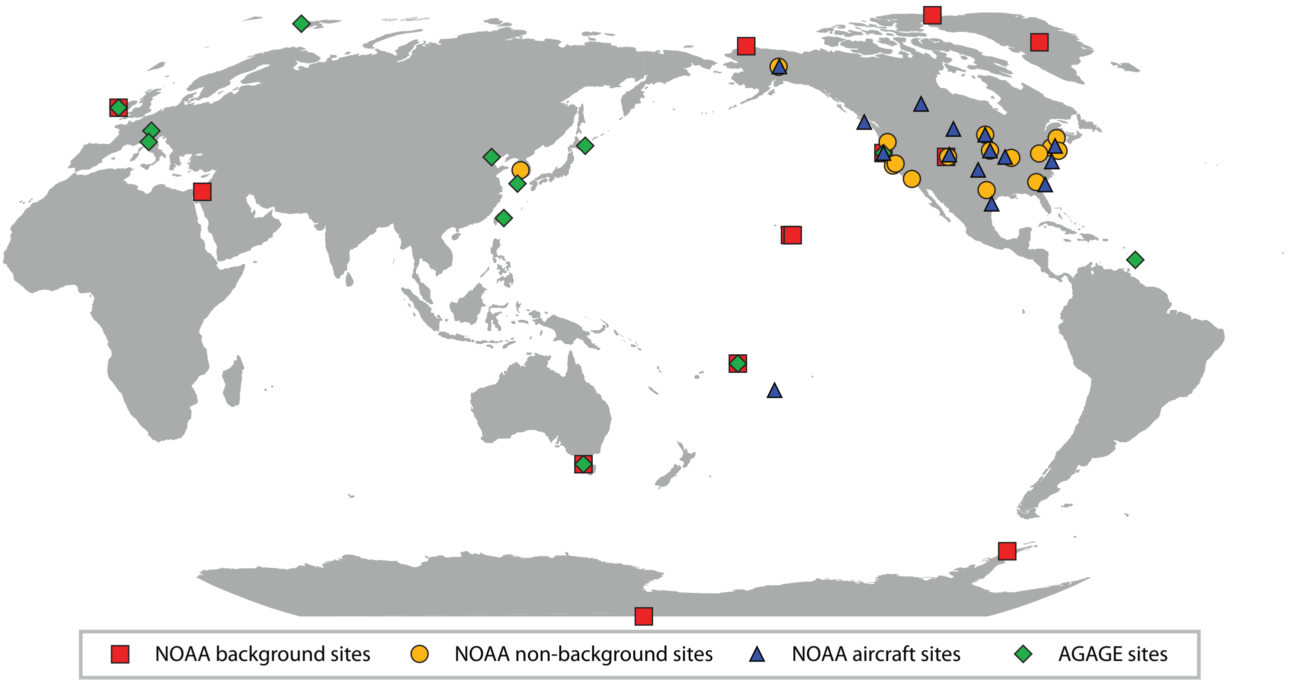

Figure 4: *Global map of CFC-11 surface measurement stations. Green diamonds show AGAGE and AGAGE-affiliated site locations.*

Emissions rates and banks were also explored for North-Western Europe to better understand bank behaviour relative to atmospheric emissions. The time period of greatest interest (1996 through the latest available data) was used to develop combinations of banks and emissions rates for this region, including an iterative analysis that was found to be consistent with a total CFC-11 bank of 100 to 120 Gg for North-Western Europe. Given this bank size and the atmosphere-derived emissions, a total emissions rate of 3-4% from the bank in 1996 is calculated, which does not align with the global emissions rate of CFC-11 during the period of the global unexpected emissions [*Walter-Terrinoni (a)*].

More extreme scenarios were developed, and scenarios related to newly produced CFC-11, were also explored. More extreme historic emissions rates did not result in scenarios that fit the currently derived emissions profile. Very high emissions rates in recent years were required (24% emissions from the global foams bank for multiple years in a row) to align with the unexpected emissions. Additional usage as a refrigerant did not produce enough emissions either. However, these are extreme scenarios related to direct emissions from production or inventory release, which seems unlikely given economic considerations [*Walter-Terrinoni (b)*].

Scenarios that include additional foam production did align with the global atmospheric top-down emissions in both closed and open cell foams. The competing low cost of dichloromethane, which is used in open-cell foams, makes those open-cell foams scenarios improbable, but the possible use of CFC-11 in closed cell foam could not be eliminated through the sensitivity analyses or due to commercial reasons or based on the analysis of replacement blowing agents [*Walter-Terrinoni (b)*].

The global top-down emissions from the foam blowing agents that replaced CFC-11 were examined and found to align with normal foam uses prior to 2002, but they did not align after 2002 without the inclusion of CFC-11. Further exploration into the potential use of CFC-11 in closed cell foams, and the economic impact of the use of CFC-11 in open cell foams, would help address remaining questions, but to date no plausible process involving emissions from banks has been found to explain the unexpected emission increase [*Walter-Terrinoni (b)*].

Finally, there was a good deal of discussion about whether the CFC-11 was being made in converted large-scale facilities [*Tope*], as would make sense based on standard economic arguments, or whether it is occurring in new small-scale plants as have been suggested in China [*Perry*]. Understanding the technical as well as the economic rationale for the production is required to understand this better.

What is the expected impact?

As would be expected, additional CFC-11 emissions over our baseline expectations result in higher future levels of chlorine in the stratosphere. In turn, larger ozone depletions can be expected in the future, with delays in the recovery of ozone to pre-1980 levels. A major problem with understanding the impact of the unexpected increased emissions is to create a realistic projection of future CFC-11 levels [*Daniel*]. As noted earlier, these projections depend on CFC-11 production estimates, emissions from the manufacture of products, and emissions from CFC-11 banks [*Kuijpers*; *Pons*; *Reimann*; *Solomon*; *Walter-Terrinoni (a)*; *Tope*; *Walter-Terrinoni (b)*]. These bank emissions depend on the magnitudes of the banks, and the rates of CFC-11 loss from those banks. All of these factors have significant uncertainties, and therefore CFC-11 projections are also poorly understood [*Daniel*; *Solomon*]. A better understanding of foam banks and emissions rates would also help to further quantify the unexpected emissions of CFC-11 [*Walter-Terrinoni (a)*].

A number of simulated CFC-11 scenarios were shown at the Symposium. The primary results were that increased CFC-11 emissions lead to increased stratospheric ozone depletion as expected, and that the additional accumulated emissions over the next few decades will control the level of additional ozone depletion [*Chipperfield*; *Eleftheratos*; *Fleming*; *Keeble*, *Liang*; *Nuetzel*]. At present, a temporary increase of 10-13 Gg/yr will not have a detectable impact on ozone levels, particularly if the emissions quickly decrease [*Chipperfield*]. Ground-based and satellite ozone measurements do not provide evidence yet as to an observational effect of increased CFC-11 emissions to ozone profile trends in middle latitudes [*Eleftheratos*]. However, sustained emissions over decades, e.g., of a total at the 60-80 Gg/yr level, would have a large impact.

A major uncertainty was identified with respect to the potential influence on ozone of co-production of CFC-12 with CFC-11, and the use of CCl_4 as a feedstock for CFC-11 [*Sherry*; *Tope*].

The consequent growth of emissions from these additional chemicals, including from a possible delayed release from an increased bank of CFC-12, would add to the impact on the ozone layer.

Model simulations of enhanced CFC-11 emissions provide a variety of estimates on the impact to stratospheric ozone to 2100. All models found that recovery was delayed depending on the emission levels [*Chipperfield*; *Fleming*; *Keeble*, *Liang*; *Nuetzel*]. For various scenarios of continuing high emissions of CFC-11 (*e.g.* continuing current values of 72.5 Gg/yr until 2100), the ozone hole persists until 2100 [*Keeble*; *Liang*]. There is a linear dependence of ozone depletion on the cumulative CFC-11 emissions to the year 2100, with a global ozone change of -0.29 DU (-0.1%) per 1000 Gg of emitted CFC-11, and an Antarctic spring depletion of -2.4 DU (-0.9 %) per 1000 Gg of CFC-11 [*Fleming*].

Future global ozone depletion is also sensitive to the climate scenario, the depletion per 1000 Gg emission was less (-0.25 DU) for the high-GHG RCP8.5[6] than for the lower-GHG RCP2.5 (-0.3 DU) [*Fleming*]. In contrast to global ozone, the Antarctic ozone hole was minimally affected by GHG scenarios, with no perceptible difference in ozone depletion sensitivity to CFC-11 between RCP8.5 and RCP2.5. However, the ozone depletion caused by sustained CFC emissions into the future had significant impacts on the Antarctic stratospheric temperature, the Southern Hemisphere jet strength, and the Brewer-Dobson circulation [*Liang*].

Until the source and, ultimately, the likely future trajectory of the unexpected increased CFC-11 emissions becomes clearer, it will not be possible to provide more constrained emission scenarios for the atmospheric models to explore expected future impacts on stratospheric ozone depletion and climate forcing.

Suggested research directions

Two categories for future research emerged during the Symposium: (1) short-term activities that will inform the various reports to the Parties in the next two years; and (2) longer-term requirements to ensure that the community can respond to this and similar situations in the future. The latter could be related to the controlled HCFCs and HFCs in the Montreal Protocol or to other gases controlled for other purposes (*e.g.*, greenhouse gases).

In the short term (1), the main aims identified are to better bound the problem based on analyses of existing information and to prioritize and perform any quick-response activities that can reduce the major uncertainties. These are scientific and technical in nature and include the following:

a) *Updates based on recent observations.* It is quite possible that this issue's significance will lead to actions that will then bring about rapid emissions reductions. Providing timely feedback to the Parties on any changes in emission rates is highly relevant to their decision making.

b) *Identify other possible areas of CFC-11 emissions.* While the unreported emissions were initially detected at the global scale, the sparseness of existing measurement sites means that little is known about possible emissions from many parts of the world. Analysis of existing measurements and organising focussed, internationally recognised measurement campaigns in priority areas (*e.g.* those with the capacity for CFC production) could rule in and/or rule out locations reasonably quickly.

c) *Providing improved knowledge on the time history of emissions.* There is clearly more that can be derived from atmospheric observations that have already been made, from new analyses of CFC-11 emissions from banks (*e.g.* emission rates from the disposal of foams, including breakdown rates in different types of landfill) and from foam production, *etc.* Further modeling work to better understand the influence of atmospheric dynamics in interannual changes in CFC-11 concentrations could better constrain global emission estimates.

d) *Review known plant capacities and other pathways for CFC-11 production.* Some plants can in principle be switched to produce CFC-11. Identifying these and their potential capacities could provide insights into how CFC-11 could be produced using established techniques in the quantities required to supply potential new foam production.

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[6] RCP (Representative Concentration Pathway) is a future greenhouse gas concentration trajectory adopted by the IPCC for its 5th Assessment Report [AR5] in 2014. The number (e.g., 8.5) is the expected radiative forcing in Watts per meter squared expected for those concentrations.

This would complement analyses of potential new or less common CFC-11 production pathways.

e) *Improved assessment of unreported CFC-12 co-production.* Given current understanding of the production of CFC-11, there is a good chance that additional CFC-12 is being co-produced. If so, it has not been detected in atmospheric measurements as yet, so either it is not being released or any amount produced and subsequently released cannot currently be detected by the observational system. Addressing this requires a mixture of analyses of near-source atmospheric observations and new assessments of possible CFC-12 uses and banks.

f) *Improved understanding of the relationship between the locations of production and emissions.* CFC-11 containing products, such as foams, can be found in dispersed locations, including those well away from production plants. Better knowledge of the geographic distribution of foams and other products would further constrain our understanding of where emissions may occur.

Addressing these short-term research goals has the potential to put bounds on the nature and scale of the overall CFC-11 emissions problem and provide a more rounded scientific and technical basis for possible policy responses.

The emergence of the unexpected increased CFC-11 emissions raises questions about the completeness of our understanding of the ODS banks and new production and provides valuable lessons that can be taken into account when considering how to monitor emissions of other gases with restricted production. This applies to substances controlled under the Montreal Protocol and other greenhouse gases.

In the longer term (2), the main goals identified were to ensure on-going effective responses to this and similar future situations. These include the following:

a) *Improve the current monitoring system to provide quantitative estimates of regional emissions throughout the world.* Unmonitored regions include the Western and central China, India, Russia, Eastern Europe, Southeast Asia, South America, Africa and some of North America. Maintaining a robust system with better coverage, scientific expertise, and long-term continuity is critical.

b) *Pursue a mix of atmospheric monitoring approaches.* Increasing the coverage of the monitoring network requires developing and maintaining international capabilities for short-term, intensive field studies. These include static, spot or mobile measurements near source locations that ideally are coordinated with available observational systems (*e.g.* local government air quality networks) which can provide ancillary information. It will be important to identify priority areas for such intensive studies.

c) *Reduce uncertainties in emission estimates from global and regional inversion studies.* This topic is already a priority due to its importance for other greenhouse gases; nonetheless, it is important to recognise its broad importance.

d) *Develop a set of more plausible CFC-11 and other ODS emission scenarios.* These emission scenarios are highly dependent on production estimates, total amounts in banks, and emission rates from those banks. Constraining these scenarios would enable more realistic estimates of the possible impact on O_3, UV radiation, and radiative forcing.

e) *Assess similar issues that could result from the implementation of the Montreal Protocol.* The production and consumption of CFCs, HCFCs and HFCs are controlled under the Montreal Protocol. It will be helpful to continue to identify and analyse potential 'pinch-points' where unreported production might be more likely to occur, *e.g.* when the cost of producing the replacement is more than the cost of producing the banned substance. For CFC-11, with major replacements HCFC-141b, HFC-365mfc and HFC-245fa, this could involve modelling emissions rates (to cross check with other foam blowing agent types) and to reverse engineer banks and examine transitions and compare them to production and consumption.

f) *Improve our understanding of emissions from banks.* Updated emissions rates from foams and further exploration of the timing of emissions from banks by region to further quantify the unexpected emissions geographically (see (d) above).

3. Summary

The Symposium brought together an international community of experts with technical and scientific expertise to update the understanding about the unexpected emissions of CFC-11. A wide range of results were presented including a review of previous work, new or updated estimates of emissions based on atmospheric measurements, field studies of the mixture of gases emitted by a number of sources, technical assessment of possible new sources of CFC-11 emissions, and atmospheric modelling studies of the impact of continuing new emissions on stratospheric ozone.

One major conclusion is that the evidence that a substantial fraction of the unreported emissions are from eastern China is now stronger. This evidence is consistent with the increase in the IHD. Conversely there is no evidence for unreported emissions from other regions, though that can certainly not be ruled out as the coverage of other regions by existing observational studies is incomplete. Sustained emissions at current rates would lead to a delay in ozone recovery.

The most likely use of the newly produced CFC-11 is thought to be in manufacturing foams as there is large global demand for insulating materials. However, it is hard from a technical perspective to explain how the CFC-11 is being produced, whether in re-conversion of large production plants or the use of new micro-scale plants. Questions underlying this aspect are the subject of the TEAP report being produced for the 31st Meeting of the Parties in November 2019.

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Symposium Presentations:

Adcock, K.E. *et al.*, 'The origin of high concentrations of CFC-11 observed in Taiwan'. (03/25/19, 12:00 CET).

Arduini, J. *et al.*, 'CFC measurements from Nepal Climate Observatory - Pyramid (Nepal), GAW global station'. (03/25/19 12:20 CET).

Benish, S.E. *et al.*, 'Aircraft Measurements of Elevated CFC-11 Concentrations over the North China Plain in Spring 2016'. (03/25/19 14:00 CET).

Chipperfield, M. *et al.*, 'Determination of the Sources and Implications of Increased CFC-11 Emissions using Inverse and Forward 3-D Modelling'. (03/27/19 14:00 CET).

Dang, G. *et al.*, 'Long-term spatiotemporal variations and source changes of halocarbons in the greater Pearl River Delta region, China'. (03/25/19 14:20 CET).

Daniel, J., and Carpenter, L., 'A path towards more useful future CFC scenarios'. (03/26/19 11:20 CET).

Eleftheratos, K. *et al.*, 'A note on possible effects of the unexpected increase in global CFC-11 to ozone profiles and erythemal doses at ground level'. (03/27/19 14:20 CET).

Fang, X. *et al.*, 'Rapid increase in ozone-depleting CHCl3 emissions from eastern China'. (03/25/19 14:40 CET).

Fleming, E. *et al.*, 'The impact of continuing emissions of CFC-11 on the stratospheric ozone layer'. (03/27/19 11:40 CET).

Fraser, P. *et al.*, 'Chlorofluorocarbon (CFC-11, CFC-12, CFC-113) emissions in Australia: 1962-2017'. (03/26/19 13:40 CET).

Pons, J., 'Aerosol, solvent and other misc. uses of CFC-11 and CFC-12'. (03/25/19 16:50 CET).

Keeble, J. *et al.*, 'The Impact of Recent East Asian Emissions of CFC-11 on Ozone Recovery'. (03/27/19 11:20 CET).

Kuijpers, L. *et al.*, 'Considering total bottom-up emissions and comparisons with top-down numbers'. (03/26/19 12:00 CET).

Kuijpers, L. *et al.*, 'CFC refrigerant banks and emissions 1990-2010-2018 '. (03/25/19 16:40 CET).

Laeng, A. *et al.*, 'On natural atmospheric variability of CFC-11'. (03/27/19 10:00 CET).

Laube, J. *et al.*, 'Distributions and correlations of CFC-11 and other trace gases in the upper troposphere and stratosphere'. (03/26/19 16:20 CET).

Liang, Q. *et al.*, 'GEOSCCM simulations of the Antarctic ozone hole changes due to continuing CFC-11 emissions'. (03/27/19 13:40 CET).

Manning, A. *et al.*, 'Estimating CFC-11 emissions over Western Europe from atmospheric observations'. (03/26/19 14:00 CET).

Montzka, S. *et al.*, 'Atmospheric measurements of CFC-11 through 2018: Are global CFC-11 emissions back on the decline?'. (03/25/19 10:20 CET).

Mueller, R. *et al.*, 'Stratospheric loss of CFC-11 and age-of-air in the Chemical Lagrangian model of the Stratosphere (CLaMS)'. (03/27/19 09:20 CET).

Nützel, M. *et al.*, 'Implications of constant CFC-11 concentrations for the future ozone layer'. (03/27/19 12:00 CET).

Park, S. *et al.*, 'Identifying potential CFC-11 emission sources in China based on atmospheric observations from 2008 to 2016'. (03/25/19 10:40 CET).

Perry, C., 'Understanding and Mitigating the Impacts of Illegal CFC-11 Use in the Production of Polyurethane Foams'. (03/26/19 09:40 CET).

Portmann, R. *et al.*, 'Interannual Stratospheric Transport Variability Impacts on Surface Trace Gas Concentrations'. (03/26/19 16:40 CET).

Prather, M., Ruiz, D., 'Understanding the role of the stratosphere on the lifetime and surface variability of CFC-11'. (03/26/19 15:00 CET).

Reimann, S., 'Additional CFC-11 emissions: Foam is the only answer, is it?'. (03/26/19 10:00 CET).

Schuck, T. *et al.*, 'New Long-term Measurements of CFC-11 and other halocarbons at Taunus Observatory'. (03/26/19 14:20 CET).

Sheese, P. *et al.*, 'Recent changes in CFCs in the upper troposphere – lower stratosphere from the ACE-FTS satellite instrument'. (03/27/19 09:40 CET).

Sherry, D., 'Production pathways and usages of CFC-11 from carbon tetrachloride'. (03/26/19 09:20 CET).

Simpson, I. *et al.*, 'Recent CFC-11 enhancements in China, Korea, Saudi Arabia and Pakistan'. (03/25/19 15:00 CET).

Solomon, S. *et al.*, 'Evaluation of Chlorofluorocarbon Banks, Uncertainties, and Implications for Emissions'. (03/26/19 11:00 CET).

Tope, H., *et al.* 'Understanding the production of CFC-11, associated chemicals, and related emissions'. (03/25/19 16:00 CET).

Vollmer, M. *et al.*, 'Increasing Emissions of Montreal Protocol Substances Other than CFC-11'. (03/26/19 14:40 CET).

Walter-Terrinoni, H. *et al.*, (a), 'Foam Uses'. (03/25/19 16:20 CET).

Walter-Terrinoni, H. *et al.*, (b), 'Emissions & Hypothetical Release Scenarios'. (03/26/19 11:40 CET).

Western, L. *et al.*, 'Estimates of CFC-11 emissions from eastern Asia based on atmospheric measurements and inverse modeling'. (03/25/19 11:40 CET).

Acknowledgements

The organizers wish to thank the Parties to the MP for their financial support along with thanks to the Ozone Secretariat of the MP, NASA, and the WCRP/SPARC program for their logistical support. Financial support for attendee travel was also provided by the MP, NASA, WCRP/SPARC, NOAA, USGCRP, and WMO. We also acknowledge the Symposium participants for their active contributions at the Symposium and assistance with the preparation and review of this article, in particular Helen Tope and Helen Walter-Terrinoni.

Report on the 2nd LOTUS workshop

Irina Petropavlovskikh[1,2], Sophie Godin-Beekmann[3], Daan Hubert[4], Robert Damadeo[5], Birgit Hassler[6], Viktoria Sofieva[7]

[1]Cooperative Institute for Research in Environmental Sciences, Univ. of Colorado, USA, [2]NOAA ESRL Global Monitoring Division, USA (**irina.petro@noaa.gov**), [3]LATMOS, Paris, France, [4]BIRA-IASB, Brussels, Belgium, [5]NASA Langley Research Center, USA, [6]DLR, Oberpfaffenhofen, Germany, [7]Finnish Meteorological Institute, Finland.

DATE:

17 - 19 September 2018

ORGANISERS:

Daan Hubert (BIRA-IASB, Belgium), Irina Petropavlovskikh (Univ. of Colorado, USA), Sophie Godin-Beekmann (LATMOS, France), and Geir Braathen (WMO, Switzerland)

HOST INSTITUTION:

WMO, Geneva, Switzerland

NUMBER OF PARTICIPANTS: 28

SPONSORS:

SPARC Stratosphere-troposphere Processes And their Role in Climate

WCRP World Climate Research Programme

GLOBAL ATMOSPHERE WATCH

IO3C International Ozone Commission

WORKSHOP WEBSITE:

https://events.spacepole.be/event/56

ACTIVITIY WEBPAGE:

www.sparc-climate.org/activities/ozone-trends

https://lotus.aeronomie.be

LOTUS (Long-term Ozone Trends and Uncertainties in the Stratosphere, **https://www.sparc-climate.org/activities/ozone-trends** and **https://lotus.aeronomie.be**) is an international research initiative endorsed by WMO, IO3C and WMO (GAW). Driven by the schedule of the WMO/UNEP 2018 Ozone Assessment our efforts were focused and intense these past few years, culminating in a peer-reviewed assessment of ozone profile trends (SPARC/IO3C/GAW, 2019). Celebrating this achievement was one of the motivations for a second workshop on 17-19 September 2018. Organised at the WMO premises in Geneva, Switzerland by the LOTUS coordinators (D. Hubert, I. Petropavlovskikh, and S. Godin-Beekmann) and the WMO GAW scientific officer for ozone (G. Braathen), this workshop welcomed 28 international participants including three postdocs and several early career scientists (Figure 5).

The activity Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS) was initiated in 2016, with the following objectives:

- to update and extend stratospheric ozone observations to recent years,
- to improve our understanding of crucial yet poorly known sources of uncertainties in trend retrieval,
- to investigate how uncertainties interact and propagate through the different stages of analysis chain,
- to re-evaluate current best practice(s) and possibly establish more suitable alternatives.

The driving scientific question behind these objectives is whether stratospheric ozone concentrations are currently increasing, or not. Finding evidence of ozone recovery is of great societal importance to ensure that the measures taken by the Montreal Protocol and subsequent amendments to reduce ozone depleting substances (ODSs) continue to adequately protect the ozone layer. The first stage of LOTUS (2016-2018) aimed at revisiting the estimates and understanding of long-term ozone profile trends in the stratosphere, in support of the WMO/UNEP 2018 Ozone Assessment.

Figure 5: *Participants of the second LOTUS Workshop in Geneva, Switzerland.*

Concerted efforts by a team of 30+ LOTUS participants over a two year period have led to several crucial achievements. Using a single "LOTUS regression" model, past and recent trends were assessed in the vertical distribution of stratospheric ozone from updated individual and merged satellite and ground-based data records, as well as from an ensemble of CCMI REF-C2 models. Our estimate of stratospheric ozone decline rates over the January 1985 – December 1996 period confirm those reported in earlier assessments. Measurements by satellite and ground-based instruments show a coherent picture with ozone increases between January 2000 and December 2016 throughout the upper stratosphere. LOTUS estimates the recovery rate at 2 - 3 % per decade between ~5 - 1 hPa at Northern Hemisphere (NH) mid-latitudes, 1 - 1.5 % per decade between ~3 - 1 hPa in the tropics and ~2 % per decade near 2 hPa at Southern Hemisphere (SH) mid-latitudes. Confidence is largest for positive trends – and hence ongoing recovery– in the NH mid-latitude upper stratosphere. For altitudes below the 4 hPa level, ozone trends in the post-2000 time period are not significant. While the 2000 - 2016 trends derived from observations and from CCMI simulations agree fairly well in the upper and middle stratosphere, larger differences are found in the NH middle latitude lower stratosphere where merged satellite records indicate negative trends and model simulations positive trends. The consolidation of trends in the lower stratosphere is clearly more challenging, due to large uncertainties in the combined ozone records and the large natural variability.

In general, the LOTUS assessment of stratospheric ozone trends agrees with recent studies, however the uncertainties and hence significances of the combined trends in broad latitude bands differs substantially (Figure 6). LOTUS developed a new approach to compute the uncertainty of the combined trend from individual satellite records. It incorporates information from the propagation of regression errors and from the observed standard error of the mean, and explicitly accounts for correlations between the trends from the different data sets as well. This method results in more conservative uncertainty estimates and thus lower but, arguably, more realistic confidence in positive upper stratospheric trends compared to other recent assessments. The LOTUS report was peer-reviewed and accepted in May 2018, then published in February 2019 (available at **www.sparc-climate.org/publications/sparc-reports**), thus completing the main objective of the first phase of the activity.

Besides celebrating this feat, the participants at the second LOTUS workshop discussed unresolved issues regarding trends and trend uncertainties remaining from the first phase of the LOTUS activity. These could not be addressed in the first phase due to the tight deadline associated with the publication of the WMO/UNEP 2018 Ozone assessment. One of the pressing open issues is a re-assessment of ground-based ozone data and trends since our LOTUS analyses indicate inconsistencies in the trends derived from time series by different ground-based measurement techniques and by satellite data in broad latitude bands.

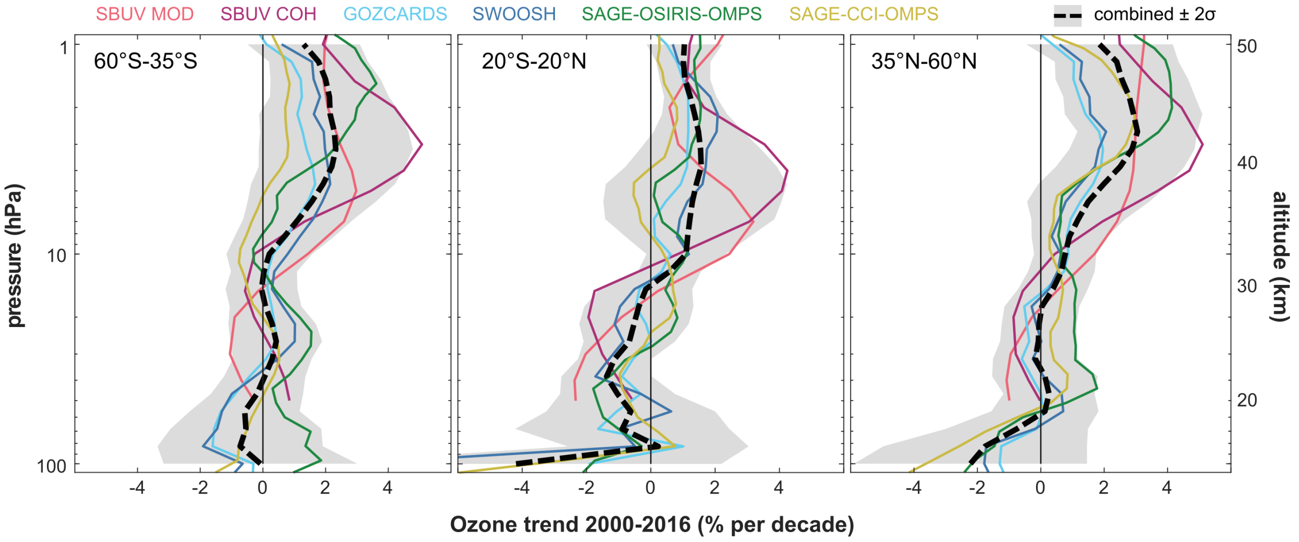

Figure 6: *Combining 2000-2016 trends and trend uncertainties of six ozone profile data sets (coloured lines) in three broad latitude bands. The combined trend and its 2-sigma uncertainty are shown as a black dashed line and grey shading respectively. Redrawn from Figure 5.7 of the LOTUS Report.*

Updated ground-based ozone profile records will be considered for this analysis, *e.g.* the recently homogenized ozonesonde records that were not available for the first phase and thus were not included in the LOTUS Report. In order to improve the assessment of trend uncertainties, techniques are needed to directly estimate or correct for inhomogeneities in the merged records resulting from possible step changes, spikes and long-term drift in the used data records. Additional uncertainties can occur from the conversion between geometric altitude and pressure-based vertical coordinates and from differences in sampling properties. Phase 2 of the LOTUS activity will continue with the evaluation of long-term stability in satellite (*e.g.* BASIC approach, Ball *et al.*, 2017) and ground-based data records (*e.g.* Bernet *et al.*, 2019). The impact of short-term dynamical variability on ozone changes over regions of limited spatial extent (such as a ground-based station) requires optimization of the LOTUS multiple linear regression (MLR) trend model (**https://arg.usask.ca/docs/LOTUS_regression/Technical%20Note.html**) for analyses of the ground-based records. The application of a dynamical linear model (DLM; Laine *et al.*, 2014; Alsing, 2019) to regress atmospheric time series was discussed as well. The workshop participants expressed interest in exploring ozone trends in polar regions and in the lower stratosphere. The latter will be done in conjunction with the SPARC/WMO Observed Composition Trends And Variability in the Upper Troposphere and Lower Stratosphere (OCTAV-UTLS, **www.sparc-climate.org/activities/octav-utls**) activity dedicated to the assessment of atmospheric composition and its decadal changes in the UTLS region. This research will support comprehensive evaluation of the coherence between stratospheric and total column ozone trends.

More detailed information on LOTUS can be found at **http://lotus.aeronomie.be**, and a detailed programme of our second workshop at **https://events.spacepole.be/event/56**.

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SPARC/IO3C/GAW, 2019: SPARC/IO3C/GAW Report on Long-term Ozone Trends and Uncertainties in the Stratosphere. I. Petropavlovskikh, S. Godin-Beekmann, D. Hubert, R. Damadeo, B. Hassler, V. Sofieva (Eds.), SPARC Report No. 9, GAW Report No. 241, WCRP-17/2018, doi: 10.17874/f899e57a20b, available at **www.sparc-climate.org/publications/sparc-reports.**

Report on FISAPS Workshop on Atmospheric Turbulence

Marvin A. Geller[1], Thomas Birner[2], Hye-Yeong Chun[3], David C. Fritts[4], and Franz-Josef Lübken[5]

[1]Stony Brook Univ. (retired), Stony Brook, NY, USA, [2]Ludwig-Maximilians-Univ., Munich, Germany, [3]Yonsei Univ., Seoul, Korea, [4]GATS, Inc., Boulder, CO, USA, [5]Leibniz-Institute of Atmospheric Physics, Kühlungsborn, Germany.

Date:
6 - 8 November 2018

Organisers:
Marvin Geller (Stony Brook Univ., USA), Franz-Josef Lübken (IAP, Germany), Hye-Yeong Chun (Yonsei Univ., South Korea) and David Fritts (Gatts Inc. USA).

Host Institution:
Leibniz-Institute of Atmospheric Physics (IAP), Kühlungsborn, Germany

Number Of Participants: **25**

Sponsors:

Activitiy webpage:
www.sparc-climate.org/activities/fine-scale-processes/

Figure 7: *Participants at the FISAPS Workshop on Atmospheric Turbulence held in Kühlungsborn, Germany during November 6-8, 2018.*

In October 2017, the inter-activity QBOi, SATIO-TCS and FISAPS workshop (Anstey *et al.*, 2018) suggested a specialised FISAPS Workshop on Atmospheric Turbulence to be held in 2018. This workshop took place November 6-8, 2018, at the Leibniz-Institute of Atmospheric Physics (IAP) in Kühlungsborn, Germany. Workshop goals were to discuss recent modeling and observational research on atmospheric turbulence, as well as applications, such as turbulence forecasting for aviation. 25 scientists, from 7 countries, attended and gave 22 oral presentations. Time was allotted for discussion of the science, observational needs, modeling needs, and future activities of FISAPS, including follow-up activities to the workshop. Here, we provide a summary.

As an introduction, Marvin Geller highlighted background and goals and Franz-Josef Lübken provided an introduction to relevant activities at IAP.

Deriving turbulence from observations

Peter Love and **Marvin Geller** opened the first session presenting the status of operational high vertical-resolution radiosonde data (HVRRD). About 39 % of worldwide radiosonde stations are now transmitting high vertical-resolution profile data (*i.e.*, profiles with more than 300 data points up to 30 km) to operational weather forecasting agencies (*c.f.* Figure 8). Plans are underway to archive them separately and make them available to the research community.

Jorge Chau dealt with atmospheric turbulence parameters derived from radar remote sensing. He reviewed two alternative derivations of the turbulent kinetic energy dissipation rate, ε, from radar vertical velocity measurements, one assuming $\varepsilon \sim w^2_{turb}$, while the other $\varepsilon \sim w^3_{turb}$. Recent comparisons of radar and in-situ data (Global Hawk; Luce *et al.*, 2018) indicate the latter as being more accurate.

Richard Wilson spoke on the so-called Thorpe method to derive turbulent parameters from high vertical-resolution radiosonde data. The method distinguishes stable and unstable section in the measured temperature to derive the Thorpe scale, L_T.

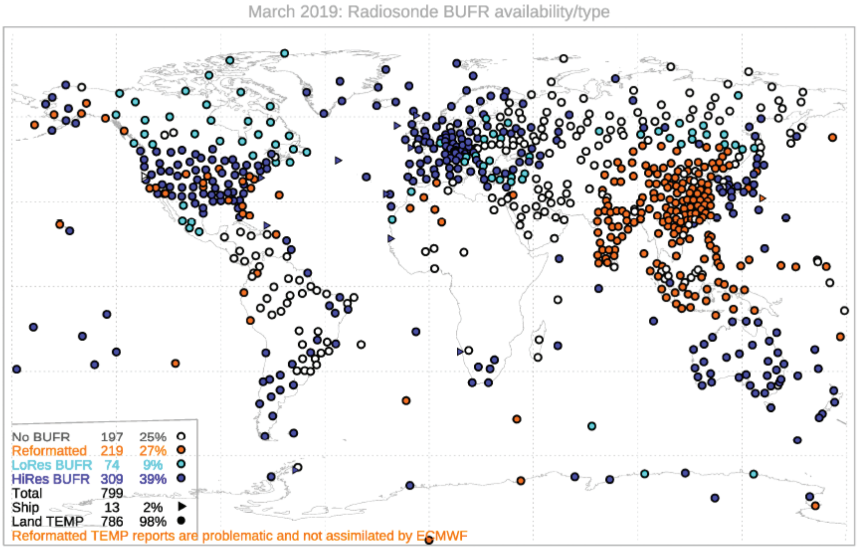

Figure 8: *Status of worldwide radiosonde network toward operational transmission of BUFR and high vertical-resolution data.*

A linear relation is then assumed between L_T and the Ozmidov scale, L_O, from which various turbulence parameters can be calculated. A number of pitfalls was identified, among them: (i) noise in the profile can be mistaken for turbulent layers; (ii) humidity effects must be taken into account at tropospheric levels; (iii) evaporation from a moist temperature sensor contaminates the temperature measurements; (iv) radiosonde wake effects should not be regarded as atmospheric turbulence. In conclusion, after paying proper attention to the pitfalls, the Thorpe methodology provides valuable information about atmospheric turbulence.

Masashi Kohma compared kinetic energy dissipation rates obtained from radar retrievals (assuming $\varepsilon_R \sim w^2$) to those based on collocated radiosonde profiles (ε_T, Thorpe method). For the lower stratosphere good correspondence was found between average values of ε_R and ε_T , while in the troposphere ε_R was generally smaller than ε_T. This can be due to shear instability being a predominant source of turbulence in the lower stratosphere, whereas convective instability dominates at tropospheric levels.

Han-Chang Ko used HVRRD at 68 US mainland stations (4 years; Sep. 2012 to Aug. 2016) plus for 4 of them (> 10 years, between Oct. 2005 and Sep. 2017) to infer the geographical distribution of atmospheric turbulence. The findings included on average: (i) in the lower stratosphere, the Thorpe scales, L_T, attain less than half of the tropospheric average; (ii) the Brunt-Väisälä frequency in the lower stratosphere is more than twice as in the troposphere; (iii) the dissipation rate of turbulent kinetic energy (ε) is about 20 % greater in the troposphere than in the lower stratosphere, with maxima just below the tropopause; (iv) ε in the troposphere is substantially larger over mountainous terrain, and less so in the lower stratosphere. Finally, the relevance of such analyses to aviation operations was mentioned.

In the last presentation on Tuesday, **Jens Söder** noted that many of the LITOS (Leibniz-Institute Turbulence Observations in the Stratosphere) measurements are contaminated by wake turbulence effects induced by the balloon and the rope connecting to the payload. He suggested to focus on data gathered during balloon-descent rather than ascent. He called for special scrutiny in the analysis of radiosonde to suppress such contamination.

Turbulence and Aviation

Dale Lawrence presented observations obtained by DataHawk, a small, unmanned aircraft containing sensors measuring fine-scale wind and temperature structures, from which atmospheric turbulence parameters can be derived. He presented information on three DataHawk campaigns: ShUREX (the Shigaraki UAV Radar Experiment), which compared MU radar and DataHawk measurements in June of 2015, 2016, and 2017; IDEAL (the Instabilities, Dynamics, and Energetics accompanying Atmospheric Layering) up to 1.8 km in November 2017; and HYFLITS (Hypersonic Flights in the Turbulent Stratosphere) experiment to take place in Kühlungsborn right after the workshop and involving direct comparison of the LITOS and DataHawk measurements on the same balloon payload.

Hye-Yeong Chun focused on atmospheric turbulence for aviation operations. She distinguished mountain-induced turbulence, convectively produced turbulence, and near-convection turbulence, and clear-air turbulence (CAT), discussing the nature and causes of CAT. Various turbulence events were presented, including model simulations and, finally, prediction models for aviation turbulence.

Dave Fritts introduced DNS (Direct Numerical Simulation) results obtained by his group during the past years. He mentioned as key questions for atmospheric turbulence: (i) what are the dominant energy sources for instabilities and the resulting turbulence? and (ii) What are the characteristics of atmospheric instabilities and the resulting turbulence? Sample results addressed gravity wave-produced instabilities, deep overturning associated with mountain waves, as well as vortex rings that appeared with horizontal dimensions of about 40% of the vertical wavelength of the gravity wave that initiated the turbulence.

Marvin Geller discussed obtaining reliable derivation of turbulence parameters via averages of Thorpe analyses. Results from DNS were used to infer the Thorpe scale, L_T, during wave breaking and related that to the Ozmidov scale, L_O. The dependence of the ratio $C = L_O/L_T$ on the actual turbulent state was discussed, also by using synthetic profiles taken through the DNS multiscale modeling results of Fritts *et al.* (2016). Finally, it was suggested that environments with larger Reynolds Numbers likely exhibit larger values of Cs and that these values are dependent on the actual sources for the turbulence.

Peter Love presented a climatology of unstable layers derived from analyses of HVRRD, by, e.g., identifying altitude ranges exhibiting static instability within individual radiosonde soundings. His results included: (i) in the troposphere thicker unstable layers are found in comparison with to the lower stratosphere; (ii) the "population" of unstable layers clearly differed between 00 and 12 UT ascents at each station, exhibiting also distinct inter-station variability, (iii) a tropical station had larger diurnal than seasonal variability, (iv) a systematic bias was detected apparently linked to transitions between instrumentation (older Lockheed Martin LMS-6 and newer Väisälä RS92-NGP sondes).

Almut Gassmann's presentation started from the equations of motion for numerical simulations of gravity wave breaking. The grid-dependent, resolved scales describe reversible energy transformations, while the unresolved motions induce irreversible energy conversions feeding back on the resolved scales through dissipation. Results for modelling of gravity wave breaking were presented, in which these energy and entropy conversions were treated more realistically, and comparisons were made to conventional simulations.

Paul Williams showed in a remote presentation how climate change is expected to change the turbulence experienced by aviation. Climate models tend to simulate enhanced vertical wind shear in the UTLS. Consistent with this, NCEP and ERA re-analyses indicated a wind shear increase in the 300-to-200-hPa-band over the past 35 years. This is also consistent with the increase of severe injuries due to turbulence encounters of aircraft as reported for the period 1982-2003. Also presented were measurements from radiosondes equipped with accelerometers.

Modelling turbulence

Raffaele Marino dealt with "intermittency and mixing in stratified turbulent flows" showing modeling and observational results including rotation as well as stratification. Strong and intermittent large-scale updrafts were found for flows within a distinct range of Froude numbers, apparently linked to those regions in space and time where the flow is more unstable and prone to develop overturning. He showed that observations could be reproduced in a simple one-dimensional model, a truncated version of the full system of the equations in a Boussinesq framework. The irreversible mixing efficiency parameter increased by about one order of magnitude, and scaled linearly with the Froude number in the range $0.05 < Fr < 0.3$.

Erich Becker addressed the parameterization of macro-turbulence in a high-resolution general circulation model, specifically the Kühlungsborn Mechanistic general Circulation Model (KMCM), a hydrostatic model designed to study the dynamical interaction between different scales and altitude regions, with a physically consistent parameterization of unresolved scales using a Smagorinsky formulation where horizontal and vertical diffusivities are functions of the resolved flow's Richardson number. This approach yielded realistic gravity wave drags and dissipation rates for the extratropical middle atmosphere. Both large- and small-scale secondary gravity waves were simulated in contrast to model runs using conventional gravity wave parameterization schemes.

Additional KMCM results were presented by **Victor Avsarkisov**, who focused on stratified turbulence in the MLT (Mesosphere/ Lower Thermosphere) region. Simulation results of MLT turbulence compared well with observations. Such model results facilitate the explanation of the neutral turbulence nature of rare PMWE (Polar Mesosphere Winter Echoes). They also confirm the relevance of high Schmidt number values to analogous summer echoes (PMSE).

Turbulence near the Tropopasue

Thomas Birner spoke on turbulence near the tropopause and started with GPS occultation analyses by Randel and Wu (2005), who had found enhanced temperature variances near the tropical tropopause. Several processes could induce turbulence in that region: (i) a static stability reduction due to latent heating in the upper tropical troposphere, combined with cooling above and (ii) the sharp increase of Brunt-Väisälä- frequency across the tropopause can induce a reduction of vertical gravity-wave-length along with enhanced probability for wave breaking. Glanville and Birner (2017) postulated more turbulent mixing at the tropical tropopause than previous work suggested. Clearly, this issue calls for more systematic studies.

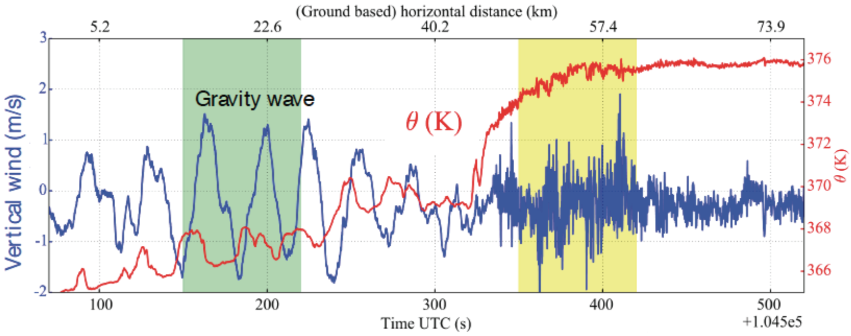

Figure 9: *Example of Global Hawk measurements of vertical wind and temperature during ATTREX, showing both gravity wave and turbulence activity. From Podglajen et al., 2017.*

Martina Bramberger introduced observations made with the HALO research aircraft in October, 2016, on a day when extreme mountain wave activity was forecast by ECMWF. At 13.8 km, the aircraft encountered such strong turbulence that the pilot had to disengage the automatic thrust control. In general, the forecast agreed well with observations except that vertical velocities were forecast around one order of magnitude smaller than observed. The NCAR GTG forecasts agreed well regarding location and magnitude of the observed turbulence, but did not describe corretly its intermittency. Finally, estimates of the turbulent kinetic energy and wave fluxes were provided for the event.

For his presentation, **Aurélien Podglajen** returned to the tropical tropopause and pointed to the uncertainty about the turbulent vertical mixing strength. He recalled that NASA's Global Hawk aircraft had performed some 300 hours of during the winters 2013 and 2014 over the tropical Pacific, focusing on the altitude range from 14 to 19 km. Gravity wave and turbulence events had been probed (*cf.* the example displayed in Figure 9.) Statistically it was determined that the turbulent kinetic energy dissipation rate exceeded $\varepsilon > 0.001$ in MKS units approximately 1 % of the time. The derived turbulent diffusivities were also compared to the mixing rates in CLaMS (Chemical Lagrangian Model of the Stratosphere) simulations.

In the last scientific presentation, **Dave Fritts** showed results of DNS numerical experiments corresponding to an observed mountain wave event over the southern Andes. A striking simulation result was the violence of mountain wave breaking which unexpectedly launched acoustic waves in addition to the secondary gravity waves.

Recommendations after general discussions

Toward the end of the workshop, discussions were held on FISAPS observational needs, FISAPS modeling needs, and future FISAPS activities. The following both briefly reviews those discussions, and also is meant to serve as a record of them.

Observational Needs

1. Radar/Thorpe analyses of radiosonde comparisons should be carried out at more locations in order to see the robustness of the results.
2. Meetings should be held involving both the radar and turbulence communities.
3. A limited number of LITOS measurements are available for comparison with radiosonde measurements. Higher resolution, cheaper sondes need to be developed for more studies.
4. Compare lengths scales from radiosondes, $L_{T,}$ L_O, and $L = U^3_{rms}/\varepsilon$. Are they consistent?
5. Studies should be carried out to see if turbulent available potential energy dissipation might be easier to measure and easier to compare with radar C^2_T.
6. Increased international cooperation is needed to collect information of aviation turbulence. Perhaps a data center?
7. Studies need to be carried out to evaluate how aviation turbulence is changing in a changing climate from pilot reports.
8. More studies are needed on turbulence in the vicinity of the tropical tropopause.

Modeling Needs

1. More studies on Thorpe, Ozmidov, and turbulent energy dissipation rates should be carried out by instrument comparisons (*e.g.*, LITOS and DataHawk) and by comparing DNS results with measurements.
2. More modeling is needed to understand differences in the evolution of L_T, L_O, and $C = L_T/L_O$ for different classes of instabilities.
3. Better understanding of the statistics for ε is needed. How common are strong events?
4. Better understand turbulent spectra for different turbulence initiation mechanism and stages of turbulence.
5. DNS assessments of mixing efficiency, heat, and momentum fluxes, enhanced turbulent diffusion should be tested against observations.
6. Explore GCM resolutions, secondary gravity wave sources, with observational comparisons.
7. Evaluate ability to capture "realistic" gravity wave behavior as climate model resolutions increase. What types of gravity wave parameterizations, if any, might still be needed in these high resolution models?

FISAPS Future Activities

FISAPS science is broader than the more specialized topic of the workshop, which was atmospheric turbulence. There was definitely the concept that atmospheric turbulence should remain one of the mainstream topics for FISAPS; however, it was agreed that the next FISAPS meeting should cover a wider range of topics, but there also would be future workshops focused on atmospheric turbulence. The proposed future activities are:

1. A paper on gravity wave treatments in high-resolution models, which resolved a great deal of gravity wave activity. This should be pursued jointly with SPARC's Gravity Wave Activity.
2. FISAPS should expand its range of topics to deal with understanding fine-scale chemical constituent structures, and how their presence should be dealt with in chemistry-climate models. This likely should be pursued jointly with an IGAC group.
3. There should be a focused effort to document and understand fine-scale structures in the vicinity of the tropopause.

Another topic that FISAPS should focus upon is the nature of dissipative processes in the atmosphere and their treatment in global models. It is clear that energy dissipation in the atmosphere occurs at very fine scales. How is this being treated in global models? Are the details of how dissipation is being treated important in those models?

Preliminary plans were discussed for a paper on fine-scale structures and processes in the atmosphere. Topics to be treated include (i) chemical constituent fine-structures; (ii) instability constraints on gravity wave amplitudes; (iii) filamentary structures of tratosphere-troposphere exchange and their radiative impact; (iv) ultimate energy dissipation at small scales; and (v) clear-air turbulence.

It was noted that the 17th Annual AOGS meeting is scheduled to be held June 28 – July 4, 2020 in Gangwon, Korea. Tentative plans were discussed for a 3-day FISAPS meeting occurring either before or after that AOGS meeting at Yonsei University, in Seoul, Korea.

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Report on the second SPARC OCTAV-UTLS meeting

Peter Hoor[1], Irina Petropavlovskikh[2], Luis Millán[3], Daniel Kunkel[1]

[1]Johannes Gutenberg Univ., Mainz, Germany, **(hoor@uni-mainz.de)**; [2]NOAA, CIRES, Boulder, CO, USA, **(irina.petro@noaa.gov)**, [3]NASA Jet Propulsion Laboratory, Pasadena, CA, USA **(lmillan@jpl.nasa.gov)**.

Date:

7 - 9 November 2018

Organisers:

Peter Hoor & Daniel Kunkel (Johannes Gutenberg Univ., Mainz, Germany), Irina Petropavlovskikh (NOAA, USA), and Louis Millán (NASA JPL, USA).

Host Institution:

Johannes Gutenberg University, Mainz

Sponsors:

Activitiy webpage:

www.sparc-climate.org/activities/octav-utls

The OCTAV-UTLS (Observed Composition Trends And Variability in the Upper Troposphere and Lower Stratosphere) second workshop was organised by Peter Hoor and Daniel Kunkel at the Johannes Gutenberg University of Mainz, Germany (November 7-9 2018) with support from Irina Petropavlovskikh (CIRES) and Luis Millán (JPL). The SPARC OCTAV-UTLS activity aims at improving the quantitative understanding of the UTLS's role in climate and the impacts of stratosphere-troposphere exchange (STE) processes on air quality. Climatologies of observations of ozone and water vapor exhibit the largest uncertainties in the UTLS at the tropopause, which feeds into large uncertainties of their radiative forcing estimates. OCTAV-UTLS objectives are to reduce the large variability of the observational variability by using a consistent reference frame for all observational data types. The intent of the second OCTAV-UTLS workshop was to identify the most appropriate coordinate systems and metrics to apply to different data sets in the UTLS region. This included first results from newly available JETPAC (Manney *et al.*, 2011) processed output.

More than 20 scientists from EU, UK, and USA supported the workshop. Invited talks discussed observational data (focussing mainly on ozone, but also water vapor) in varying coordinate systems (using different altitude and latitude coordinates) to identify regions of enhanced variability. That is to say, the data was mapped into absolute as well as tropopause or jet relative coordinates, as well as, geographical, equivalent or jet relative latitudes. The first consistent application of this set of coordinates for the various observational platforms was based on MERRA-2 reanalysis fields within the JETPAC analysis tool. On the basis of the workshop discussions focus groups for the analysis of the individual data sets were identified.

Figure 10: *Group photograph of the OCTAV-UTLS 2nd workshop participants. From left to right: Martin Wirth, Jörn Ungermann, Christiane Voigt, Irina Petropavlovskikh, Stefan Kaufmann, Viktoria Sofieva, Harald Bönisch, Gabriele Stiller, Peter Hoor, Luis Millán, Christian Rolf, Thierry LeBlanc, Susanne Rohs, Johannes Speidel, Andreas Zahn, Michaela Hegglin, Herman Smit, Mihal Rütimann, Daniel Kunkel, Yann Cohen, and Robert Damadeo.*

Further comparisons will be based on specific templates which should facilitate the initial systematic comparison between the various observations. A key metric is the analysis and potential reduction of ozone variability in different coordinate systems. First results were presented at the 2019 EGU meeting in Vienna, Austria (**https://meetingorganizer.copernicus.org/EGU2019/EGU2019-12206-2.pdf** and **https://meetingorganizer.copernicus.org/EGU2019/EGU2019-13580.pdf).**

Peter Hoor opened the meeting by welcoming all participants, presented the objectives of OCTAV-UTLS and identified the goal of the workshop; to find the most appropriate coordinate systems and metrics to apply to the different data sets in the UTLS region.

Partner projects

OCTAV-ULTS has strong connections to other activities from SPARC, ESA, and the Horizon 2020 programme. Several talks discussed these interconnections during the meeting. **Irina Petropavlovskikh** reported insights from the Long-Term Ozone Trends and Uncertainties in the Stratosphere (LOTUS) SPARC activity. **Gabriele Stiller** summarized the general findings from the Water Vapor Assessment (WAVAS) phase II SPARC activity pointing out the large uncertainties in the UTLS. Similarly, **Alexandra Laeng** reported insights from the Towards Unified Error Reporting (TUNER) SPARC activity. **Gloria Manney** discussed findings from the SPARC Reanalysis Intercomparison Project (S-RIP). **Andreas Zahn** reported on CLIMATO. **Viktoria Sofieva** presented an overview from the ESA Ozone Climate Change Initiative (Ozone_cci), and, lastly, **Michaela Hegglin** from the ESA Water Vapor Climate Change Initiative (WV_cci).

Instruments and data

Several talks focused more on instruments specifics and their validity/utility/calibration for UTLS studies. **Adam Bourassa** presented a tropopause-based analysis of the Ozone Mapping Profiler Suite (OMPS) Usask-2D ozone product, **Herman Smit** reported ozonesonde data quality assessment, **Susanne Rohs** discussed in-flight calibration for the In-service Aircraft for a Global Observing System (IAGOS) relative humidity data. Newly available two-dimensional airborne curtain data sets for potential use in OCTAV-UTLS were presented by **Jörn Ungermann** showing observed ozone and tropopause curtains from the Gimballed Limb Observer for Radiance Imaging of the Atmosphere (GLORIA). **Martin Wirth** presented simultaneous water vapor and ozone curtain data from the Water Vapor Lidar Experiment in Space (WALES), an airborne differential absorption Lidar from a research aircraft. **Stefan Kaufmann** discussed model deficiencies in representing water vapor in the UTLS and planned analyses of water vapor form various research aircraft campaigns based on the DLR HALO database. **Thierry LeBlanc** discussed the impact of apriori in lidar retrievals.

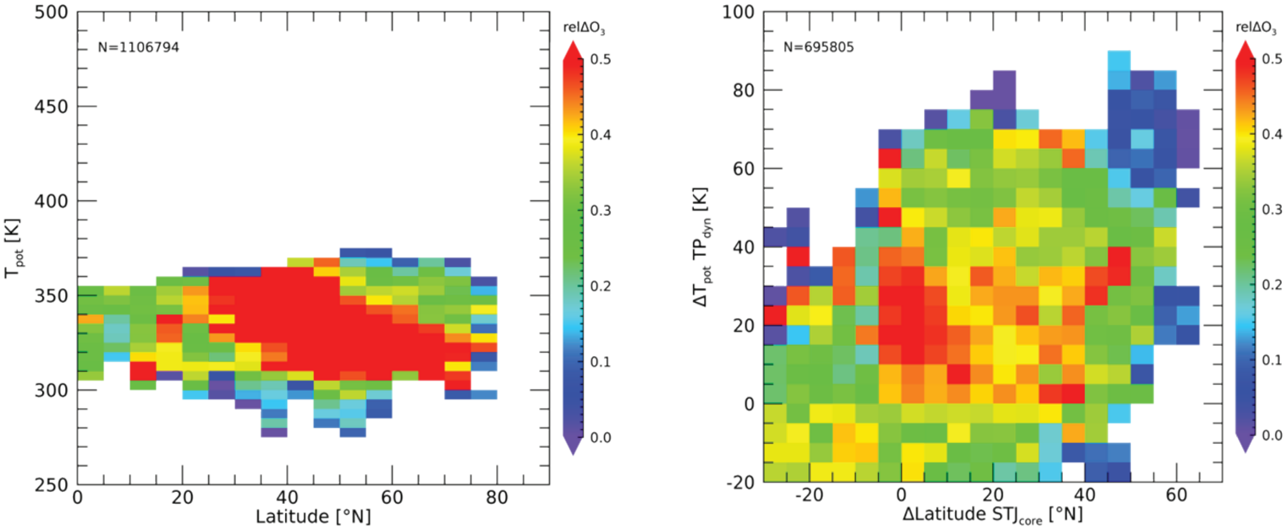

Figure 11: *Variability of ozone from IAGOS-CARIBIC measurements from 2005-2016 in different coordinate systems based on JETPAC processing with MERRA-2 showing the reduction of variability combining jet- and tropopause based coordinates (data from H. Bönisch and A. Zahn, KIT).*

UTLS

Other talks discussed an assorted variety of UTLS topics. **Yann Cohen** showed trends and climatologies using airborne IAGOS in-situ observations of ozone and carbon monoxide. **Christian Rolf** discussed water vapor climatologies using the Jülich In-Situ Airborne (JULIA) database, which combines IAGOS and other research aircraft data. Water vapor and mixing case studies by mountain waves were presented by **Christiane Voigt**. **Sophie Godin-Beekmann** discussed the latest results of long-term trends of ozone from lidar. **Johannes Speidel** discussed the distribution of water vapor and δD during the Asian summer monsoon using the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS).

JETPAC

Luis Millán presented an update on the JETPAC processing while others provided first results using the results of the JETPAC diagnostics. **Irina Petropavloskikh** showed the impact of dynamics on the ozone distribution over Boulder using different coordinates. **Thierry LeBlanc** discussed the impact of double tropopauses upon the lidar retrievals. **Harald Bönisch** presented the impact of dynamics over the IAGOS-CARIBIC measurements (*c.f.* Figure 11), and **Daniel Kunkel** reported results for the SPURT (acronym in German for trace gas transport in the tropopause region) campaign.

Workshop outcome

Discussions during the workshop lead to the suggestion of developing templates for future comparisons of different observational records in the same coordinate systems. These templates were based upon the slides of **Daniel Kunkel**. Platform-specific challenges remain for comparisons of results due to profile smoothing, limited sampling, and data quality. The participants agreed to use those templates for follow ups discussions during the next OCTAV-UTLS meeting. The next meeting will be held in Table Mountain, CA, USA, to discuss ozone variability from various observations in the UTLS based on the different coordinates provided by JETPAC/MERRA-2 and to discuss the potential impacts on trend estimates in the UTLS from these observations. Also, Luis Millán was introduced as a new co-lead replacing Gloria Manney.

OCTAV-UTLS contributes to the research lead by a number of programmes (WCRP and GAW of WMO and IUGG), sponsored by the IO3C (International Ozone Commission) under the IAMAS (International Association of Meteorology and Atmospheric Sciences) and collaborates with other SPARC activities, such as LOTUS, SSiRC, S-RIP with links to FISAPS.

Partners for this activity are: SPARC, WMO and GAW.

Acknowledgements

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Links to partner organisations

GAW - **www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html**
IAMAS - **www.iamas.org**
IO3C - **www.io3c.org**
IUGG - **www.iugg.org**
SPARC - **www.sparc-climate.org**
WCRP - **www.wcrp-climate.org**
WMO - **https://public.wmo.int/en**

Links to other SPARC activities

FISAPS - **www.sparc-climate.org/activities/fine-scale-processes**
LOTUS - **http://lotus.aeronomie.be**
SSiRC - **http://www.sparc-ssirc.org**
S-RIP - **http://s-rip.ees.hokudai.ac.jp/**
TUNER - **www.imk-asf.kit.edu/english/304_2689.php**
WAVAS - **www.sparc-climate.org/activities/water-vapour**

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:

3 - 7 December 2018

1 - 5 April 2019

Organisers:

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

Host Institution:

Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

ISSI, Berne, Switzerland

Number Of Participants: 12

Sponsors:

Activitiy webpage:

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

www.imk-asf.kit.edu/english/304_2689.php

TUNER aims to provide recommendations on how uncertainties and other metadata such as vertical resolution shall be reported in a unified way for satellite measurements of atmospheric composition and temperature. Since TUNER became a regular SPARC Activity in 2018, two project meetings have been held. The first was open to the entire TUNER team and was held at the Karlsruhe Institute of Technology from 3 to 7 December 2018. The second meeting took place at ISSI Berne, from 1 to 5 April 2019, within the framework of an ISSI International Team.

The major topic of both these meetings was the discussion of a draft paper that lays down a methodical framework for error estimation and guidelines on how uncertainty estimates shall be reported. The challenge is contained within the fact that the amount of metadata, including all covariance matrices and averaging kernel matrices, is larger by orders of magnitude than the atmospheric state, and that a compromise between scientific rigor and practicality has to be found. Because of the large differences between various instruments and retrieval schemes it was agreed that it is of no use to prescribe details related to how data characterization shall be performed. Such technical decisions should remain the responsibility of the retrieval scientist. However, the error estimates should have empirical significance in that they can be tested by validation experiments. Accordingly, random error estimates are considered adequate if they explain the standard deviation of the differences between the data sets under comparison. Conversely, estimates of the systematic error are considered adequate if they explain the biases between the data sets intercompared. Another major issue is how to make best use of representative error estimates in cases where full error analyses for each vertical profile are not available. For example, rescaling error estimates for application to a different data set than that for which the uncertainties have been evaluated, requires knowledge related to whether the uncertainties are additive or multiplicative in nature. In general, we have agreed that it is important that data users be provided with all information to propagate the uncertainties onto higher level data products in a manner that does not require without detailed technical knowledge of the instrument or retrieval scheme used to generate the data.

Figure 12: *Participants of the TUNER ISSI workshop.*

Further issues under discussion were consideration of atmospheric variability in the comparison of less than perfectly collocated data sets; estimation of random errors from inter-comparison of different measurement systems; and guidelines for the data user on how to make best use of the uncertainty estimates.

The next Activity Meeting will take place in Helsinki from 10 to 12 September 2019.

Seeking New Quantitative Constraints on Orographic Gravity Wave Stress and Drag to Satisfy Emerging Needs in Seasonal-to-Subseasonal and Climate Prediction

An Update from the SPARC Gravity Wave Activity

M. Joan Alexander[1], Julio Bacmeister[2], Manfred Ern[3], Sonja Gisinger[4], Lars Hoffmann[3], Laura Holt[1], Christopher Kruse[2], Riwal Plougonven[5], Inna Polichtchouk[6], Petr Sacha[7], Kaoru Sato[8], Ryosuke Shibuya[8], Annelize vanNiekerk[9], and Corwin Wright[10]

[1]NorthWest Research Associates, Boulder, CO, USA, **(alexand@nwra.com)**, [2]NCAR, Boulder, CO, USA, [3]Forschungszentrum Jülich, Germany, [4]DLR, Oberpfaffenhofen, Germany, [5]Laboratoire de Meteorologie Dynamique, Palaiseau, France, [6]ECMWF, Reading, UK, [7]Univ. of Natural Resources and Life Sciences, Vienna, Austria, [8]Univ. of Tokyo, Japan, [9]UK Met Office, Exeter, UK, [10]Univ. of Bath, UK.

Dates:
1 - 5 April 2019

Organisers:
M. Joan Alexander (NorthWest Res. Ass., USA),
Lars Hoffmann (FZ Jülich, Germany), and
Corwin Wright (Univ. of Bath, UK).

Host Institution:
ISSI, Berne, Switzerland

Number Of Participants: 14

Sponsors:

SPARC Stratosphere-troposphere Processes And their Role in Climate
WCRP World Climate Research Programme
INTERNATIONAL SPACE SCIENCE INSTITUTE

Activitiy webpage:
www.sparc-climate.org/activities/gravity-waves

www.issibern.ch/teams/consonorogravity

Orographic gravity wave (OGW) drag is one of the fundamental physics parametrizations employed in every global numerical model across timescales from weather to climate. Orographic waves are part of the complex dynamical interaction of winds with topography, and one piece in that puzzle is topography's effect on global circulation. Parametrized OGW drag provides an important control on model wind biases at levels from the surface through to the middle atmosphere, and these alterations in winds in turn affect stationary and synoptic Rossby wave propagation and dissipation. Thus, properly tuned OGW drag parameterizations can improve weather model prediction skill from synoptic to seasonal timescales. Climate models have long relied on OGW drag parameterizations for improved representations of both the mean climate and variability. In the stratosphere in particular, the circulation changes associated with OGW drag reduce winter temperature biases that affect ozone chemistry, so OGW drag is also fundamental to chemistry-climate modelling.

Despite its importance in global models, OGW parametrization tuning is still only weakly constrained by observations in today's models, while new issues related to shortcomings in OGW parametrization are arising. OGW parameterizations have been employed in global models for over 30 years, yet new parameterization methods are still being developed (e.g. Bacmeister *et al.* 2019). Unlike some atmospheric processes that are fully unresolved across most atmospheric model resolutions, such as microphysics or turbulence, larger-scale mountain waves can be partly resolved by the model dynamics, while sub-grid effects of smaller-scale waves must be parametrized. Modern orographic drag parametrizations attempt to be 'scale-aware' by reducing their sub-grid variance and OGW horizontal scale with increasing resolution (e.g. Vosper *et al.* 2016).

Are the newer parameterizations and scale-aware tunings more realistic? Evaluations are generally based on zonal-mean wind changes or global forecast skill scores, but these do not tell the whole story. Such parameterization changes also affect global distributions of drag in models and therefore regional and seasonal circulation patterns in the stratosphere and troposphere.

In a new project jointly supported by SPARC and the International Space Science Institute (ISSI), the Gravity Wave Activity began a new focus on using satellite observations to constrain OGW drag in global models.

The interaction of winds with mountainous terrain leads to both drag forces in the boundary layer as well as exchanges of momentum between the surface and the overlying atmosphere. Part of the momentum is carried vertically by OGWs, which grow in amplitude exponentially with height to conserve energy, and somewhere aloft, the waves break or dissipate. This exerts forces on the flow we call OGW drag. The key variable in this momentum exchange is the wave stress (or momentum flux). These OGW stresses and forces can be locally quite large with important nonlinear circulation and/or instability effects. Observing the stress directly requires observation of 3D wind anomalies (u',v',w'), which are historically difficult to measure from space, particularly for the vertical wind, which can be orders of magnitude smaller than horizontal wind. Ern *et al.* (2004) related the stress to the more directly measured wave temperature anomalies, which requires measurement of the local 3D wave properties: horizontal wavenumber vector, vertical wavenumber, and wave amplitude. OGW with horizontal wavelengths as short as ~20 km are important, so the satellite measurements must have very high resolution. Earlier attempts with limb-viewing satellite measurements from CRISTA, HIRDLS, SABER, and MLS provided only 2D measures of an apparent horizontal wavenumber and crude measures of stress magnitude. A 2010 SPARC/ISSI team found these 2D limb-viewing estimates to not only be low-biased, as expected, but also highly uncertain depending on the analysis method (Geller *et al.* 2013). Specialized high-resolution stratospheric temperature retrievals from hyper-spectral infrared nadir sounding instruments with cross-orbital scan patterns like the Atmospheric Infrared Sounder (AIRS) and the Infrared Atmospheric Sounding Interferometer (IASI) can provide the necessary information on the 3D structure of OGW (Hoffmann and Alexander 2009), and advanced wave analysis methods have been developed for computing global gravity stresses (Ern *et al.* 2017; Hindley *et al.* 2019). However, uncertainty in these methods is still difficult to quantify. The observations have many additional limitations including horizontal and vertical resolution limits and limitation to stratospheric levels only (Figure 13). What is more, while OGW stresses may be computed directly from the observations, the drag forces cannot be observed due to observational filter effects (Alexander and Sato 2015).

In addition to uncertainties in the observations, there remain important uncertainties also in high-resolution model representations of gravity waves. Issues include model resolution (both horizontal and vertical), numerical scheme and implicit numerical dissipation, explicit scale-dependent dissipation, parameterization of moist processes, surface topography and boundary layer specifications, and partitioning of parametrized gravity wave drag between orographic and nonorographic sources (Holt *et al.* 2017; Polichtchouk *et al.* 2018). Studies also suggest that straight-forward scale-aware parameterizations that scale with model resolution do not result in consistent representation of OGW drag across resolutions (vanNiekerk *et al.* 2016) and that resolved waves are strongly influenced by boundary layer treatments.

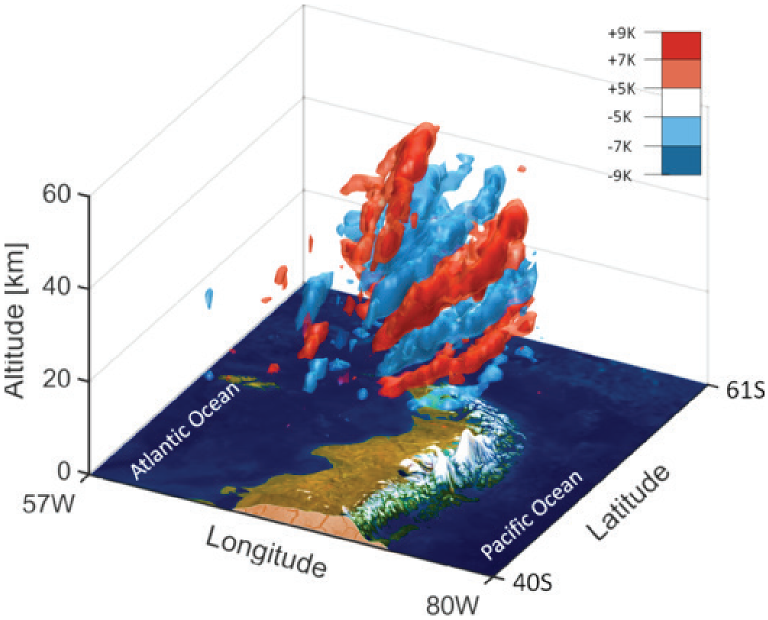

Figure 13: *Gravity wave temperature anomalies from AIRS high-resolution stratospheric temperature retrievals [Hoffmann and Alexander 2009], showing the 3d structure of orographic waves over the Southern Andes. Figure from Wright et al. 2017.*

In a first meeting 1-5 April 2019, our team of 14 experts in OGW observations, drag parameterizations, and global and regional modeling assembled at ISSI in Bern, Switzerland to discuss how best to use the global observations, despite their limitations, to provide new constraints on the problem of OGW drag. In addition to the evaluation of uncertainties in available observations, discussions also focused on OGW drag parameterizations and high-resolution modeling.

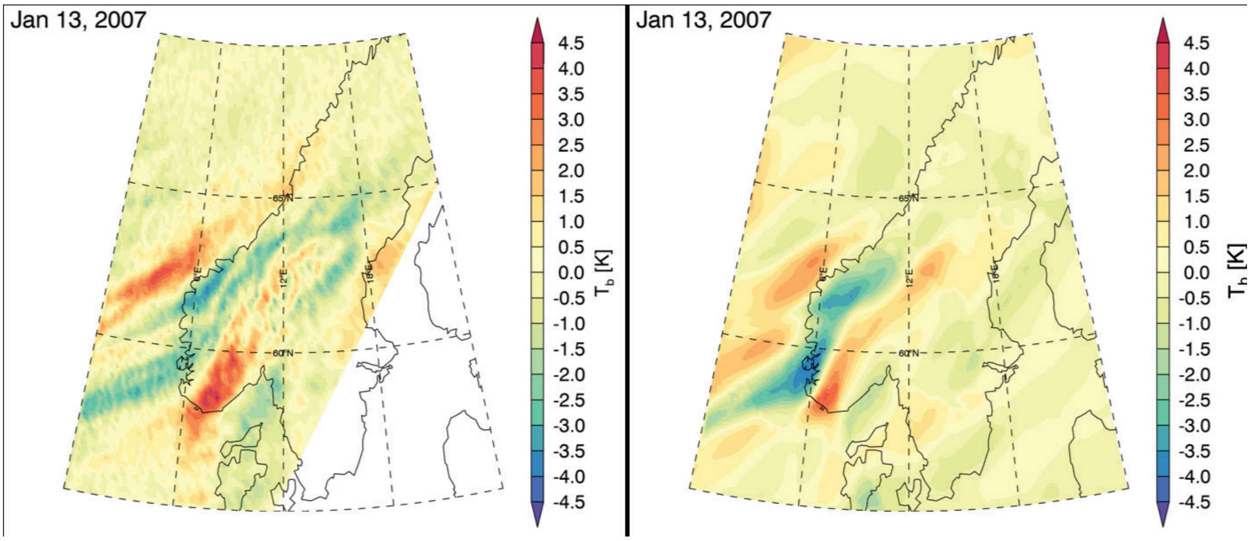

Figure 14: *Brightness temperature anomalies from (left) AIRS and (right) MERRA-2 12.5-km Replay for January 13, 2007.*

Discussion on Parametrization Limitations

Current state-of-the-art OGW drag parametrizations make several simplifying assumptions, a few of which were discussed as being of a particular importance: i) instantaneous vertical propagation of waves, ii) lack of horizontal wave propagation, and iii) saturation assumptions for wave dissipation with height. Observational and high-resolution modelling results indicate that OGWs can be located far from their source region, emphasizing the need to revisit these assumptions. Importance of advection and refraction of GWs by the background flow, and the dependence of the vertical group velocity on the horizontal wavenumber was stressed by several working group members (Kruse and Smith 2018; Shibuya and Sato 2019). Therefore, relaxing these simplifying assumptions implies that the spatial distribution and the partitioning of OGW drag between zonal and meridional components will change. OGW reflection from the tropopause and heating by OGW drag was discussed as being potentially important for the circulation.

Discussion on Scale-aware Parametrizations

Several talks highlighted the fact that the behavior of orographic waves and the drag that they impart on the atmosphere depends on their horizontal scale (Smith and Kruse 2018), such that the relative importance of representing certain processes in parametrizations varies across resolutions. For example, the vertical phase velocity of the mountain waves is proportional to their horizontal wave number. This means that, as the model horizontal resolution decreases and more of the waves become unresolved, the assumption of instantaneous propagation, a common approximation amongst OGWD parametrizations, becomes more severe. If the model's vertical resolution is too coarse, the vertical variations of the OGW may then also be sub-grid, which is an aspect not currently well represented by parametrizations. In fact, a series of gravity-wave permitting model experiments indicate that simulated gravity wave stresses highly depend on the vertical resolution (Watanabe *et al.* 2015). It became evident that we do not have a good understanding of how the stress should increase or decrease with increasing vertical resolution and, as a result, how the parametrizations should account for this.

Understanding the scales (in both the vertical and horizontal) that are contributing to the OGW stresses and drag, and their horizontal as well as vertical distributions, therefore, seems to be paramount to developing improved scale-aware parametrizations. This motivates the need for a more detailed description of the global statistics of the wave fields from observations and models, so that we may judge the importance of different aspects of waves and their propagation in the real atmosphere. Namely, the horizontal and vertical wavelengths and propagation directions of the waves, as well as their geographic distribution and magnitudes and dependence on the background winds, may help to inform the development of scale-aware parametrizations.

Discussion on Global High-resolution Data Assimilation/Forecast Tools

Output from high-resolution data assimilation systems and forecast models contain many realistic signatures of gravity waves (e.g. Holt *et al.* 2017).

However, even at resolutions < 10 km, only a portion of the gravity wave spectrum is resolved. So these model systems are best described as gravity wave 'permitting' rather than 'resolving'. One major advantage of data assimilation is that large-scale wind and temperature are well-constrained by observations, so smaller-scale waves propagate in realistic conditions (Gisinger *et al.* 2017). For OGW, where surface topography defines the wave sources, this can potentially yield highly realistic simulation of OGW (Figure 14). However, topographic smoothing and various forms of dissipation from the boundary layer to the stratosphere may conspire to give poor comparisons between simulated OGW and observations despite sufficient model resolution. Combining different types of observations at different levels, *e.g.* satellite, radar, lidar, and balloon measurements, permits a more complete evaluation of all the scales of waves simulated.

Discussion on Comparing Models and Observations

Before using observations to validate models, we first need to evaluate uncertainties in those observations and carefully consider which parts of the wave spectrum are included/excluded. Waves are always first isolated as perturbations on some larger-scale background value, and the method for defining the background needs to be considered carefully in any comparison. Comparing waves in satellite observations and models is best accomplished by sampling the models with the satellite sampling pattern and kernel functions or by applying a radiative transfer model to simulate satellite observations for direct comparison.

Some important issues discussed include:

(a) Are line-of-sight slant paths important, or can they be neglected to first order?

(b) What model resolution is sufficient for the comparison to the observations? Issues include model numerical scheme and implicit and explicit dissipation at small scales.

(c) How representative are case studies to the global problem? If regional comparisons are planned, the locations and times will depend on availability of other observations besides the satellite data. Will these locations/times permit characterization of important OGW properties globally?

(d) How important is it to include non-hydrostatic waves? This is an issue for comparisons to global gravity wave permitting models.

(e) How do we best evaluate model/observation differences (*e.g.* strength versus shifts in location)?

(f) Can we use observations to determine the relative importance of different scales of waves?

(g) Can observations help to constrain compensation between Rossby waves and gravity waves that is observed in models?

(h) If we only have stratospheric wave observations, can these help with tropospheric factors in OGW parameterizations?

(i) Are there significant differences in OGW stress in models with different dynamical cores due to the different methods in calculating the stress, or can intermodel differences be understood solely in terms of implicit/explicit dissipation?

Discussion on Intercomparison of Satellite-based OGW Stresses

Different methods used for satellite analysis appear to give quite different gravity wave stress results, both for individual cases and global means. Methods agree well qualitatively, but closer quantitative comparisons reveal significant differences. Considerations that are not commonly discussed in the literature include important differences between conditional versus unconditional mean stresses. Analogous to other intermittent phenomena like precipitation, the mean values and global patterns in gravity waves can be significantly different for conditional and unconditional averages. This likely contributed to differences among observations reported by Geller *et al.* (2013). The intermittent nature of gravity waves also leads to the question of how best to report on their global properties. For example, distributions in gravity wave amplitudes show that infrequent values, 10 - 100 times larger than the mean, contribute most of the mean stress (*e.g.* Hertzog *et al.* 2012). Directional stresses are another important issue that require more attention. Particularly for global observations that will include both OGWs and waves from moving sources like convection, averaging may obscure important directional stresses with cancellation of positive and negative values across different wave events. One goal may be to formulate, as a group, general recommendations for how gravity wave activity should be reported, both for observational and modeling studies.

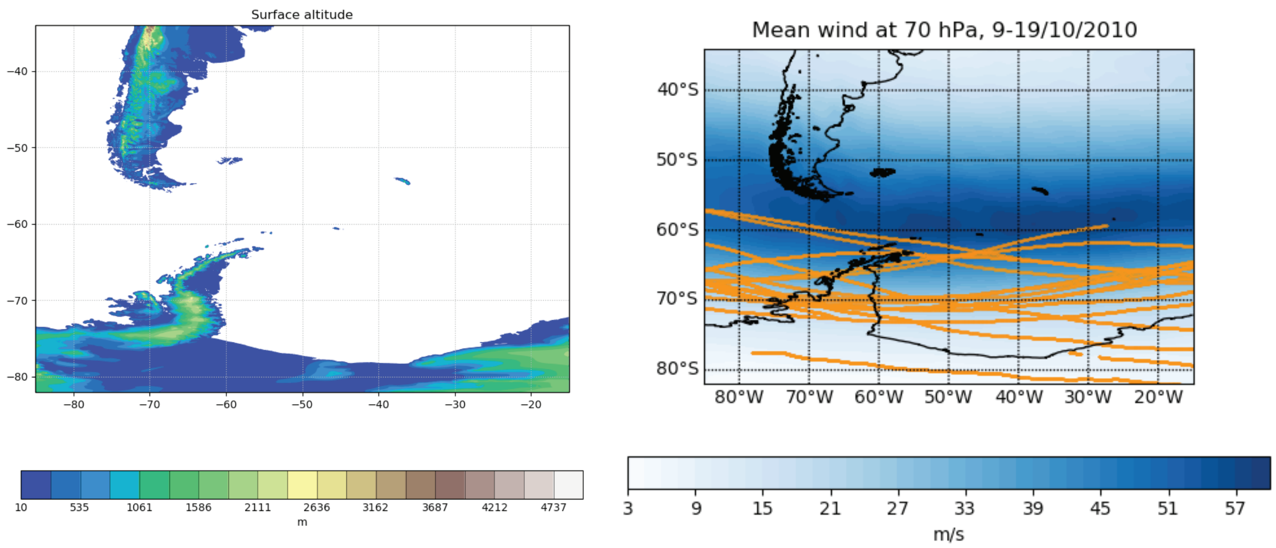

Figure 15: *(a) Regional domain and topography for the first OSSE experiment. (b) Coverage of Concordiasi super-pressure balloon tracks (orange) during the OSSE period 9-19 October 2010.*

Focused Research Questions

The team defined a set of focused research questions to jointly address:

Q1. How well do methods used for computing gravity wave stress from satellite temperatures represent the true stress derived from 3-dimensional winds?

Q2. How well does satellite-computed stress compare between different analysis methods?

Q3. How well do different high-resolution, limited-area models reproduce satellite and other observations of OGW?

Q4. How can we use answers to 1 - 3 to improve parameterization of OGW drag in coarser-resolution global forecasting models?

Observing System Simulation Experiments (OSSE) for gravity waves

In order to address these questions, the team has planned a set of regional simulations to address questions 1 through 3. In the spirit of the OSSE, the simulations are designed for the AIRS and IASI satellite sampling and kernel functions in order to create a simulated set of satellite observations of OGW. Different wave analysis methods will be applied to these simulated satellite data from model temperatures and resulting wave stresses can be compared to those calculated from simulated winds (u',v',w') for evaluation of the analysis method uncertainties (Q1). This also affords a direct comparison of the different analysis methods (Q2). European Center for Medium-range Weather Forecasts (ECMWF) analysis or Modern-Era Retrospective analysis for Research and Applications (MERRA-2) will serve as initial and boundary conditions for the OSSE, so we can also compare the simulated satellite observations to the real satellite observations on the same days/times in order to validate the realism of the simulations (Q3). The simulation locations and dates have further been chosen to permit comparison of simulated gravity waves to other observational datasets in order to validate portions of the simulated gravity wave spectrum that are not visible in the satellite data (Q3). As a first step towards answering Q4, the high-resolution simulations and validating observations will also be compared to parameterizations of OGW drag in coarser resolution global models, with the expectation that this will either validate the parameterizations or suggest new tuning parameters or appropriate modifications to the parameterization methods. While portions of these research tasks have been performed previously by individual research groups, we hope our coordinated international collaboration will provide new and meaningful constraints for global prediction models.

The first set of simulations targets the Southern Andes and Antarctic Peninsula region (Figure 15) during October 2010, when super-pressure balloon observations of gravity waves are available through the Concordiasi field campaign (Jewtoukoff *et al.* 2015). These data observe the full spectrum of gravity waves from the inertial frequency to the buoyancy frequency at levels in the lower stratosphere. Measurements from radiosondes and radio-occultation are also available. Additional foci are planned for Scandinavia, New Zealand, and Syowa Station in Antarctica.

Within the limits of the model resolutions, the validated simulations can also be used to study other aspects of the interaction between the atmosphere and complex surface topography at levels from the surface through the stratosphere. These include surface stress, form drag, turbulence, and other nonlinearities. Once the simulations are carefully validated against observations as described above, additional studies to examine these aspects of the simulations are planned. The OGW OSSE datasets will be made publicly available for any further studies by the scientific community. We hope these further studies will provide natural links to a parallel project on Surface Drag and Momentum Transport that is sponsored by GEWEX/GASS. A joint workshop on orographic stress and drag from the surface to the middle atmosphere (Sandu *et al.* 2019) with participation from these two projects and an open invitation to the broader community may be planned for late 2020.

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SSiRC Science Steering Group Meeting

Larry Thomason[1] and Stefanie Kremser[2]

[1]NASA Langley Research Center, Hampton, Virginia, USA, [2]Bodeker Scientific, New Zealand.

DATE:
2 - 5 April 2019

ORGANISERS:
Marc von Hobe (FZ Jülich, Germany), Larry Thomason (NASA Langley Research Center, USA), Claudia Timmreck (Max-Planck-Institute for Meteorology in Hamburg), and Stefanie Kremser (Bodeker Scientific, New Zealand).

HOST INSTITUTION:
Forschungszentrum Jülich

NUMBER OF PARTICIPANTS: 12

SPONSORS:

ACTIVITIY WEBPAGE:
www.sparc-ssirc.org

The Stratospheric Sulfur and its Role in Climate Science Steering Group meeting was held at the Forschungszentrum Jülich from 2-5 April 2019. The meeting was focused on the status of on-going activities within SSiRC, the implementation of new activities and science discussions focused on where SSiRC may have an impact. The SSG membership has undergone some changes with Markus Hermann leaving the SSG and Claudia Timmreck stepping down as a co-leader of SSiRC. L. Thomason and S. Kremser remain the co-leaders of SSiRC and the current SSG has 12 members from different scientific backgrounds, combining measurements and modelling expertise. There are no immediate plans to add additional members. However, as current activities evolve, we may choose to add new members such as members that would provide expertise in non-sulfur stratospheric aerosol. In consultation with the SSiRC community (**https://listserv.gwdg.de/mailman/listinfo/ssirc**), the SSG updated the SSiRC Implementation Plan (SIP) to highlight areas where significant knowledge gaps are recognized and to outline current SSiRC activities. The new SIP will be published on the SSiRC web site at **www.sparc-ssirc.org.** The current SSiRC web site is in the process of being updated, which should be completed over the next few months. It will communicate current SSiRC activities and SSiRC initiated future events. SSiRC is currently planning to hold its fifth workshop in Leeds, UK in April/May 2020 with Graham Mann (University of Leeds) being the host. An organizing committee has been convened consisting of Graham Mann, Landon Rieger, Stefanie Kremser and Larry Thomason. We are keen to provide travel support for early career scientists and scientists from developing countries to attend this SSiRC workshop and to encourage wider participation in SSiRC sponsored activities. We recognize that expanding our inclusivity may require SPARC financial support in a period when the potential for support is increasingly limited and that we will need to be more creative in how we acquire support in the future.

The SSiRC project to compile a sulfur burden climatology, led by **Terry Deshler**, is progressing now that major revisions to some key data sets are completed. The goal of this project is to develop as complete as possible climatology of sulfur bearing gases and sulfur in particulate form for the stratosphere, combining satellite and in-situ measurements of both gas phase and particulate components of the stratospheric aerosol layer. This effort focuses on the period between 1996 and 2012 where measurements of the gas phase components of the sulfur burden are most broadly available. Recent improvements to key data sets including the University of Wyoming optical particle counter measurements and the OSIRIS aerosol extinction coefficient data sets will enable a more robust inference of sulfur in particulate form.

The Asian Monsoon has the capacity to affect stratospheric aerosol composition and several recent studies have suggested varying degrees to which human-derived sulfur may impact the development of the Asian Tropopause Aerosol Layer (ATAL) and on which pathways that material may find its way into the stratosphere. Ongoing investigations of aerosol and trace gas measurements made during the StratoClim (**www.stratoclim.org**) field campaigns are helping us to better understand and constrain the role of the Asian Monsoon Anticyclone in transporting sulfuric and non-sulfuric aerosols and precursors into the stratosphere (**Fred Stroh**). **Jean-Paul Vernier** suggested that SSiRC should consider an activity focused on distinguishing between the contribution of natural and human-derived sources of aerosol in the upper troposphere/lower stratosphere (UTLS). The SSG will coordinate with other SPARC activities to avoid any overlap in effort. Background stratospheric aerosol is strongly influenced by the tropospheric sulfur cycle. **Marc von Hobe** discussed efforts to better quantify OCS sources/sinks and resolve a debate on the OCS budget. He pointed out evidence for larger anthropogenic OCS emissions and described plans to revisit the DMS-to-OCS conversion. Detailed understanding of such processes and trends is necessary to assess the impact of climate change on sulfur cycling and stratospheric aerosol abundances, making it worth SSiRC's attention.

The Volcanic Response activity (led by **Jean-Paul Vernier** and **Claudia Timmreck**) developed a wiki page as an interactive way to communicate when a volcanic eruption happens. This page is used by observationalist and modelers to communicate about volcanic activity with the potential to impact climate (**https://wiki.earthdata.nasa.gov/display/volres/Volcano+Response**). This has already been successfully used when Mt Agung and Krakatau erupted in 2018, leading to various model simulations and estimates of SO_2 injected into the stratosphere. While these eruptions did not result in significant injections of sulfur into the stratosphere, the largest volcanic event in recent years, the July 2018 eruption of Mt Aoba, was not caught in a timely fashion by the VolRes wiki. A lessons-learned process is underway to prevent missing future eruptions. A BAMS paper is in preparation that uses the Mt Aoba eruption as an example of how a volcanic response could evolve. We also plan to develop an easily accessible document that will be updated annually and that will be available for reference by measurement and modeling communities that specifies strategies to promote the capture of the most important information in the short term following a major volcanic eruption.

Larry Thomason discussed recent activities of developing the GloSSAC data set (**https://eosweb.larc.nasa.gov/glossac**) that provides a long-term, measurement-based data set of aerosol optical properties to be used for global climate model simulations. He outlined changes from version v1.0 to v1.1 that corrected an error in the data set associated with the use of CLAES data. In addition, he discussed changes associated with v2.0 that extend through to 2018 and is expected to be released in mid-2019. A significant improvement in the use of OSIRIS (**www.asc-csa.gc.ca/eng/satellites/odin.asp**; updated to version 7.0) and CALIPSO (use of the CALIPSO stratospheric aerosol product) data that significantly reduce the enhanced aerosol that was apparent in the lower stratosphere in GloSSAC v1.0 and v1.1. **Thomas Peter** noted that even with the corrected aerosol properties in v1.1, SOCOL simulates too much heating in the lower stratosphere (by about 3-4K) after the Mt Pinatubo eruption. This is a significant issue that we need to understand and that needs to be addressed. **Landon Rieger** pointed out that there is growing interest in calculating uncertainties on aerosol radiative forcing, such as those produced by ETH using GloSSAC in combination with CMIP6 data. While the inclusion of uncertainties in measured quantities will improve in GloSSAC v2.0, it is not currently clear how to propagate these uncertainties into radiative forcing uncertainty.

New versions of SAGE III (**https://sage.nasa.gov**; **Larry Thomason**) and OSIRIS (**Landon Rieger**) have been released both of which are substantial improvements over previous versions. The correspondence between these data sets is good above the tropopause and suggests that the stability of the long-term stratospheric aerosol data record (based on satellite observations) is in good shape into the near future.

Figure 16: *The SSiRC SSG from left to right: (front) Juan-Carlos Antuña, Survarna Fadnavis, Thomas Peter, Marc von Hobe, Terry Deshler, (back) Graham Mann, Landon Rieger, Jean-Paul Vernier, Larry Thomason, Stefanie Kremser, Claudia Timmreck, Peter Hoor (OCTAV ULTS), Matthew Toohey (visitor). Not pictured: Alan Robock.*

A new stratospheric aerosol product produced by the CALIPSO team was also discussed (**Larry Thomason**). While this product is in reasonable agreement with other observational data sets in mid and low latitudes and above 20 km, it has substantial biases outside this region. **Terry Deshler** discussed a long-duration balloon experiment, Strateole 2, planned for 2020 to 2024 (**https://strateole2.cnes.fr/en/home-105**). This experiment is focused on observations in the tropical tropopause layer and includes in situ optical particle counter observations, which will be of significant interest to the stratospheric aerosol community.

A historical data rescue activity led by **Juan-Carlos Antuña Marrero** and **Graham Mann** has begun with data recovered from a Russian ship-borne lidar record during transects of the tropical North Atlantic from Cuba to North Africa in the initial months after the June 1991 Mt Pinatubo eruption. This is a period where the SAGE-II satellite data sets was saturated, the lidar providing valuable new information on the mid and lower parts of the tropical Pinatubo aerosol plume. Dr. Antuña Marrero is discussing with the PI of this data set for where to host the dataset and register a doi for the datasets. An initial collaboration by Mann and Antuña is comparing interactive stratospheric aerosol model simulations to the data set which will be a very useful new observational constraint for the early progression of the Pinatubo aerosol cloud. Earliest lidar measurements from Lexington and balloon measurements from Minneapolis and Panama have also been gathered as benchmark observational dataset for the 1963 Mt Agung aerosol plume. Mann and Antuña are considering how best to archive these older data sets where they are not already in a recognized public data center. We are keen to seek dialogue with others in SPARC to plan how best to proceed to make the datasets available to the wider science community.

Peter Hoor from SPARC's OCTAV UTLS activity gave a presentation on the use of alternative coordinate systems in the vicinity of the tropopause for atmospheric measurements. The SSiRC SSG felt that this was extremely relevant to activities within SSiRC and further collaborations with the OCTAV UTLS seem promising. A particular point of agreement was the need for more data sets to have dynamical coordinates (e.g., equivalent latitude) tied to measurements. Of particular interest to the SSiRC SSG was the OSIRIS data set and getting these data tagged with other coordinates. Landon Rieger and Larry Thomason agreed to follow up on this idea. Whether this develops into an SSiRC activity (coordinated with OCTAV UTLS) has not been decided at this stage.

The GMD paper presenting the rationale and experiments in the Interactive Stratospheric Aerosol Model Intercomparison Project (ISA-MIP) was published in July 2018, with the initiative now co-led by **Valentina Aquila** and **Graham Mann**. This activity defined experiments investigating background conditions, the post-2000 stratospheric aerosol increase and the radiative effects from the Mt Agung, El Chichón and Mt Pinatubo major eruptions. A fourth "PoEMS" experiment will quantify and attribute sources of uncertainties in each model's simulated Pinatubo aerosol cloud, and producing probability density functions of the radiative forcing time series to compare between the different interactive stratospheric aerosol models.

Claudia Timmreck discussed a new project, Vollmpact, which is of significant relevance to SSiRC. Vollmpact is a multi-institutional Deutsche Forschungsgemeinschaft program to improve the capacity to model the impact of major volcanic eruptions on the atmosphere and climate. This program will focus on modeling volcanic plumes and the impact of volcanic eruptions on radiative forcing, clouds, atmospheric dynamics, climate and the tropical hydrological cycle.

The SSiRC SSG has initiated an activity to investigate the idea of formulating a new index that relates the input of material in the stratosphere by a volcano to its subsequent impact on climate. This effort recognizes that while the Volcanic Explosivity Index (VEI) has been used throughout the climate community used as a proxy for the climate impact of an eruption, it is, in fact, an inadequate predictor. The goal is an index that can convey to the scientific community (and beyond) the scale of climate impact of an eruption. It could also play a role in defining what is meant by 'major' or 'minor' eruptions; concepts that have been vague for far too long. SSiRC's plan is to create an index based on simple modeling that relates altitude, latitude, and size of an SO_2 injection with the resulting radiative forcing. Other parameters such as time of year and phase of the QBO may be considered if they do not overly complicate the process. The most likely outcome is a look up table that relates the above parameters to a simple index. While it is not directly intended that the index serve as a trigger for a concerted measurement campaign, it is possible that it will play a role in such decisions. The intention is produce this index for at least a cross section of historical events as this is likely to be a necessary step in its development and provides context for future eruptions. It is possible that the VolRes wiki can help disseminate index values in the short term as well. Landon Rieger and Matthew Toohey have agreed to lead this effort.

Latest news: WMO and SPARC at IUGG-2019 in Montréal

Hans Volkert

SPARC Office, DLR, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany, (**Hans.Volkert@DLR.de**)

The International Union of Geodesy and Geophysics (IUGG) held its 27th General Assembly from 9 to 17 July 2019 in Montréal, Canada, attended by just under 4000 participants from all continents. The event also marked IUGG's centennial, the Union having been founded in July 1919 in Brussels when structures of international scientific cooperation were re-established after World War I.

David Grimes, head of the Meteorological Service of Canada and past-president of WMO (2011-19), delivered the prestigious IUGG Union lecture. He claimed that Earth sciences provided underlying pillars to meet future societal challenges and underscored the proven complementary roles of WMO and IUGG as inter-governmental and non-governmental partners in advancing applicable knowledge in the various geophysical compartments, atmosphere and oceans in particular.

In the celebratory IAMAS symposium M25, **James R. Fleming** put a century of atmospheric research challenges and accomplishments into a historical perspective, with special foci on the periods after the first and the second world-war, respectively, and three inter-linked generations of influential researchers (*cf.* Fleming, 2016), while **John P. Burrows** recalled the increase of satellite observations addressing the temporal development of atmospheric chemistry and global pollution in the Anthropocene, a new geological epoch, currently under consideration.

In the Union symposium *"Centennial of the international cooperation in Earth and space sciences"*, **Huw C. Davies** provided a fast and tightly packed ride through decades of dynamical meteorology under the modest sounding title *"A flavour of IAMAS-related achievements"* and underscored the decisive role of small research groups for past breakthroughs. Figure 17 assembles the four exemplary speakers as they appeared at IUGG-2019.

Several colleagues, who are active in SPARC, participated in a number of IAMAS-symposia, *e.g.* M06 – *"Middle atmosphere science"*, M07 - *"Stratosphere couplings to the troposphere and the ocean"*, M08 - *"Air quality in the changing Anthropocene"*, M11 – *Advances in atmospheric dynamics"*, M15 – *"Frontier challenges in data assimilation and ensemble forecasting"*, M20 - *"El Niño-Southern Oscillation and its regional and global impacts"*, and M21 - *"Celebrating the Montreal Protocol in Montreal"* (for details *cf.* IUGG, 2019). M15 contained a commemorative session about the achievements of William Lahoz (1960-2019) and, rather spontaneously, a dinner of William's colleagues and his close family.

From four bids for hosting the next general assembly, the IUGG council selected Berlin, Germany. IUGG-2023 will take place during the second half of July in the City-Cube conference centre.

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IUGG, 2019: Final program, 486 pp., online **http://iugg2019montreal.com/assets/iugg2019-final-full-program.pdf**.

Figure 17: *Advocating non-governmental research efforts for WMO and SPARC (from left): David Grimes (Canada; WMO president 2011-19), James R. Fleming (USA; atmospheric physicist and historian of science), John P. Burrows (Germany; principal investigator of Envisat; photos: IUGG-2019), Huw C. Davies (Switzerland; long-term contributor to and reviewer of atmospheric dynamics; photo: Hans Volkert).*

The SPARC newsletter welcomes historical notes. Background information about previous endeavours to obtain atmospheric data, to build comprehensive analyses, and to infer general characteristics can help to put current SPARC activities in perspective. Contributions and comments should be submitted to the SPARC International Project Office at **office@sparc-climate.org.**

Previous SPARC newsletter articles with historical topics include:

A. Brewer, 2000: The stratospheric circulation: A personal history. *SPARC Newsletter* No. **15**, 28-32.
M.-L. Chanin, 2004: A Short History of the Beginning of SPARC and its Early Development. *SPARC Newsletter* No. **22**, 10-12.
S. Brönnimann *et al.*, 2015: Bicentenary of the great Tambora Eruption. *SPARC Newsletter* No. **45**, 26-30.
K. Hamilton, 2018: James Sadler and the Discovery of the Stratospheric Quasi-biennial Oscillation.
SPARC Newsletter No 51, 32-35.

Ernest Hovmöller's diagram – the illustrative link of time with longitudes and altitudes is turning 70

Hans Volkert

SPARC Office, DLR, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany, (Hans.Volkert@DLR.de)

This note recalls the first publications of Hovmöller-diagrams seventy years ago, partly addressing stratospheric data, alongside with international cooperation and newly established scientific journals during the years following the end of the Second World War.

The protagonist is the Danish meteorologist Ernest Hovmöller (1912-2008) who, in 1946, had started working for the Swedish meteorological and hydrological institute SMHI after a move from its Danish counterpart DMI (Persson, 2017). Soon after he began cooperating with Carl-Gustaf Rossby (1898-1957), arguably the most prominent dynamical meteorologist of the time, who permanently returned to Sweden in 1947, after two decades in the United States, and who started the research journal *Tellus* in 1949. Another cooperation partner of Hovmöller's was the Italian geophysical all-rounder Mario Bossolasco (1903-1985), founding and long-standing editor (1939-73) of the journal *Pure and Applied Geophysics* and in 1950 instigator of the biennial International Conferences on Alpine Meteorology (ICAM; Volkert, 2009; the 35th realization is scheduled for September 2019). Portraits of the three colleagues are juxtaposed in Figure H1.

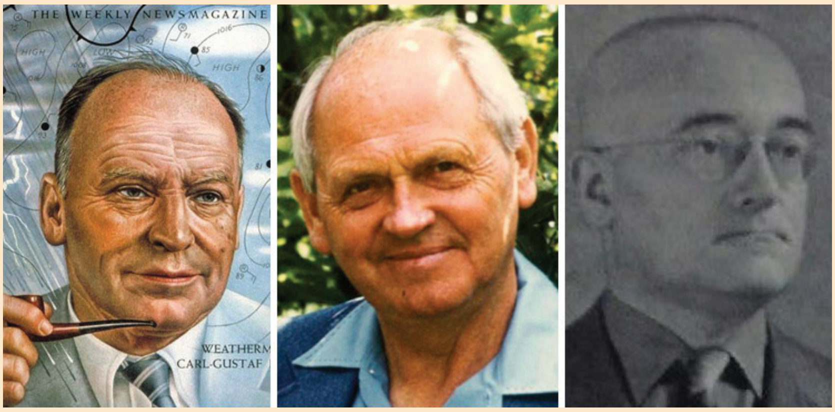

Figure H1: Three geophysical all-rounders, who cooperated around 1950 (from left): Carl-Gustav Rossby (1898-1957; depicted as "Weatherman Carl-Gustav Rossby" on the front page of TIME magazine, 17 Dec. 1956 [© TIME USA, LLC.]), Ernest Hovmöller (1912-2008; from Persson 2017), and Mario Bossolasco (1903-1985; from the web).

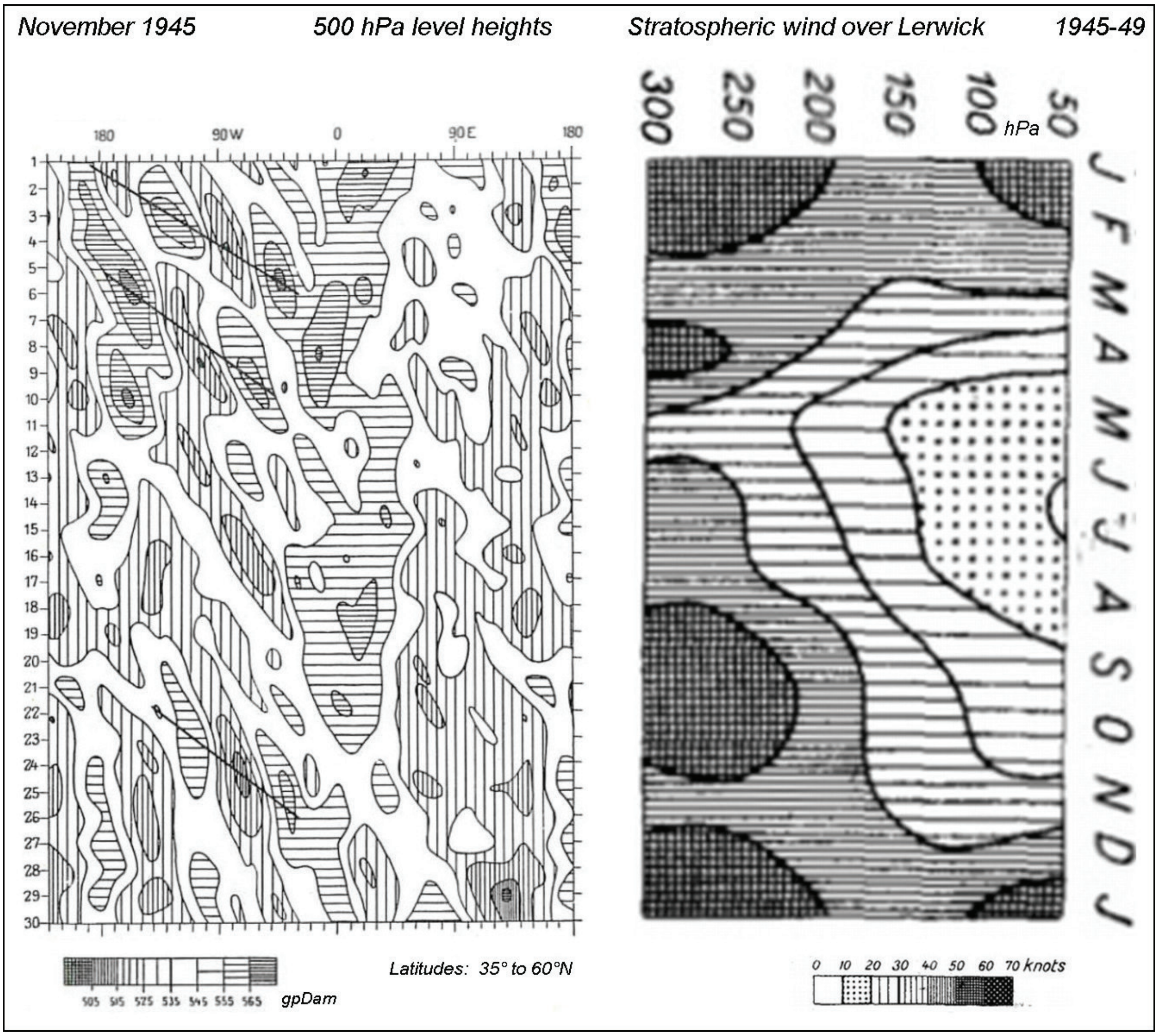

Figure H2: The two earliest published realizations of Hovmöller diagrams: time-longitude variations of 500 hPa geopotential heights during November 1945, averaged over 6 latitudes in a 25°-wide band (left; from Hovmöller, 1949) and mean annual variation of stratospheric wind speed from a five-year dataset of Lerwick sounding station (60°N, 1°W; right; adapted from Hovmöller 1950).

Not only nowadays, but also during the 1940s, data measured along the five dimensions of atmospheric research began to abound. It was, and continues to be, a considerable intellectual challenge to sufficiently reduce the observations made of (i) different physical quantities, (ii) over time, and (iii) to (v) along the three spatial dimensions in order to gain a general understanding of atmospheric motions and their dynamics. In a shorter contribution of less than five pages, Hovmöller (1949) introduced a through-ridge diagram which condensed a month-worth of 500-hPa-level heights as observed within the latitude belt 35° to 60°N roundabout the Earth. What then appeared as Figure 1 is reproduced here as the left part of Figure H2. Time proceeds downwards along the ordinate while geographical longitudes run along the abscissa. The latitudinal averaged height band from 5350 to 5450 gpm is left white, while the adjacent bands of lower (higher) values are given vertical (horizontal) hatching of increasing density. Due to this ingenious design three (or even four) trains of quasi-uniformly progressing anomaly patterns become visible to the west of the Greenwich meridian within the otherwise rather arbitrary fluctuations. Hovmöller determined average progression speeds and related them to Rossby's previously described concept of group velocities for planetary waves.

In September 1950, Hovmöller was an invited participant at the inaugural ICAM in Milano (Bossolasco, 1950). In the afternoon of the first day, he presented his study entitled "*Zonal and meridional air currents in the stratosphere over Europe*", which focused on the average annual variation of stratospheric winds, *i.e.* in the height range 300 to 50 hPa, obtained from regular radiosondes ascents made at the stations Larkhill and Lerwick, in southern England and northernmost Scotland, respectively. The study was published in the 1950 autumn edition of the journal founded by Bossolasco (Hovmöller, 1950) and contained in its Figure 1 the diagram on the right side of Figure H2 here. The diagram was rotated by 90° in order to have the months along the ordinate and pressure levels along the abscissa. Striking is the wind speed maximum extending also to the higher levels during the winter months, which was found more pronounced at the higher latitude. Additionally, time-series over selected months were used to depict the considerable day-to-day fluctuations.

Anticipating the routine of meeting reports about conferences and workshops in the SPARC newsletter (no less than four in this issue), Hovmöller (1951) reported about the inaugural ICAM in *Tellus*, without relating to his own contribution. In the following issue, his mentor Rossby (1951) explicitly mentioned the cooperation with Bossolasco, involving Hovmöller, as an encouraging sign that extended working relations between various institutes started to increase also within post-war Europe. UNESCO and WMO were mentioned as possible sponsors. As WCRP is approaching its 40th anniversary and SPARC having started its second quarter of a century, the visionary, yet clear and also critical thoughts of Carl-Gustav Rossby about cooperative projects continue to be fascinating reading.

And finally, we note that Rossby was preparing his trip as president of IAMAS to the IUGG general assembly scheduled in Toronto, when a heart attack in his office at the University of Stockholm ended his life on 19 August 1957. This month, IUGG and IAMAS are remembering their centenary (*cf.* MacCracken and Volkert, 2019) at the 27th general assembly in Montréal (see note on page 40) and, later, with a special celebration at UNESCO in Paris. The three cooperation partners depicted in Figure H1, their published achievements and easily accessible reports about their meetings, are to be regarded as still relevant parts of the ever growing mosaic of knowledge derived from the atmospheric sciences, very often by international cooperation on a voluntary basis.

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SPARC meetings

4 - 9 August 2019
CCMi Summer school and workshop
Hong Kong

9 - 13 September 2019
TUNER workshop
Helsinki, Finland

11 – 13 Sept. 2019
Data Assimilation Working Group Meeting
Boulder, Colorado, USA

18 - 19 September 2019
SOLARIS-HEPPA working group meeting
IAA, Granada, Spain.

22 - 25 October 2019
Workshop on Atmospheric Circulation in a Changing Climate
Universidad Complutense, Madrid, Spain

4 - 6 December 2019
SPARC SSG meeting
Boulder, Colorado, USA

SPARC related meetings

28 July - 2 August 2019
AOGS 16th Annual Meeting
Singapore

9 - 13 September 2019
2nd GOTHAM international summer school on: Global Teleconnections in the Earth's Climate System
Beijing, China

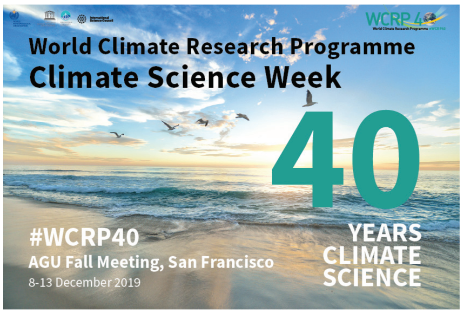
9 - 13 September 2019
HEMERA summer school
Heidelberg, Germany

14 - 18 October 2019
ICRC-CORDEX 2019
Beijing, China

12 - 16 January 2020
100th AMS Annual Meeting
Boston, MA, USA
including:
1-day Middle Atmosphere Symposium
Susan Solomon Symposium

WCRP climate science week during AGU 2019:
7 Dec. 2019 - Early Career Workshop
8 Dec. 2019 - WCRP 40th Anniversary Symposium
9 - 13 Dec - Organised sessions during the wole week
San Francisco, USA

www.wcrp-climate.org/wcrp-agu2019/wcrp-csw-overview



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

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SPARC Office

Director
Hans Volkert

Office Manager
Brigitte Ziegele

Project Scientist
Mareike Kenntner

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