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SPARC

Stratosphere-troposphere Processes And their Role in Climate

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This spectacular image of sunset on the Indian Ocean was taken by astronauts aboard the International Space Station (ISS). The image presents an edge-on, or limb view, of the Earth's atmosphere as seen from orbit. The pink to white region above the clouds appears to be the lower stratosphere. The ISS was located over the southern Indian Ocean when this picture was taken, with the astronaut looking towards the west. Astronauts aboard the ISS see 16 sunrises and sunsets per day due to their high orbital velocity (greater than 28,000 km per hour). The multiple chances for photography are fortunate because at that speed, each sunrise or sunset only lasts a few seconds. (Image: NASA/JSC).

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WCRP World Climate Research Programme
WMO
UNESCO
IOC
ICSU International Council for Science

Report on the 24th SPARC Scientific Steering Group Meeting
1-4 November 2016, Berlin, Germany

Fiona Tummon[1], Neil Harris[2], and Judith Perlwitz[3]

[1]SPARC Office, ETH Zurich, **fiona.tummon@env.ethz.ch**, [2]Centre for Atmospheric Informatics and Emissions Technology, Cranfield University, UK, [3]Physical Sciences Division, NOAA Earth System Research Laboratory, Boulder, CO, USA.

The 24th SPARC Scientific Steering Group (SSG) meeting was hosted at the Max Planck Institute's Harnack House in Berlin, Germany, from 1-4 November 2016. The meeting followed a one-day science workshop focused on SPARC's contribution to the WCRP Grand Challenges (see page 8, this issue).

WCRP update

The WCRP continues to focus on its mission of facilitating analysis and prediction of the Earth system through its core projects and grand challenges, which now include two recently approved grand challenges on near-term climate predictions and carbon cycle-climate interactions (Boram Lee, WCRP/SPARC liaison). The WCRP will undergo a major review by its sponsors in 2018 and so a document outlining WCRP's achievements and future strategic direction is currently being drafted. All WCRP projects, working groups, and grand challenges will provide input to this document, which is to be completed by the 38th session of the WCRP Joint Scientific Committee to be held in April 2017. Part of this process will be to establish best practices for assessing progress of the grand challenges as well as core projects. Furthermore, WCRP is working to refresh its communications, both internal and external, and is currently carrying out a survey to establish where to make effective improvements. Participation in the survey is most welcomed at: **www.wcrp-climate.org/wcrp-communication-survey**.

WCRP recently held a scoping meeting on regional activities, which highlighted the fundamental gap in the availability of data for providing regional climate information, as well as the difficulty in doing so even when data is available. A call for a regional climate information coordinator has been made, with the hope of establishing a clear contact point for all WCRP regional activities. These activities are strongly linked with WCRP's capacity development strategy, which has also recently focused on supporting early career researchers by actively engaging them in WCRP strategic discussions and officially endorsing YESS (the Young Earth System Scientists community). This group has been very active, recently having published a white paper on the frontiers of Earth system science, and helping to organise a very successful early career symposium at the CLIVAR Open Science Conference, amongst other things.

The WCRP Data Advisory Council (WDAC) coordinates all data and observation activities across WCRP and ensures cooperation with major partners such as the Global Climate Observing System (GCOS). Over the past few years SPARC has continuously highlighted the possible looming gap in limb-sounding observations (**Susann Tegtmeier**) and this has now been noted in the new GCOS implementation plan. This plan also includes several action items, two of which are relevant to this issue: a review of the availability of climate data records, and the identification of gaps in the availability of these records. Together with WDAC, GCOS has established a data prize to recognize an early- to mid- career scientists for outstanding work in data generation, management, preservation or monitoring. WDAC has also recently established a Task team on the Intercomparison of Reanalysis (TIRA), with Masatomo Fujiwara serving as the SPARC representative. First results from this effort will be presented at the 5th WCRP international reanalysis conference, which will take place from 13-17 November 2017 in Rome, Italy.

The WCRP Model Advisory Council (WMAC) plays a similar role to WDAC, but is focused on modelling (**Judith Perlwitz**). After a very successful model development summer school held in 2015, the group is organising a second school in 2017 in Brazil. The next WMAC meeting will be held together with several other WCRP modelling working groups to facilitate planning for the next 5-10 years and provide input to WCRP's future strategic plans. They will also work on tying to coordinate several of activities within WCRP focused on making decadal predictions, including the new grand challenge on near-term climate predictions. Discussion during the SPARC SSG meeting also focused on raising awareness about the relevance of including chemistry in models on various timescales. How important chemistry is for various prediction purposes is still very much an open research question, and one that WCRP, together with the World Weather Research programme (WWRP), should certainly continue to focus on.

Quentin Errera represented SPARC at the 2016 meeting of the Working Group on Numerical Experimentation (WGNE), which is joint between WCRP and the WMO Commission for Atmospheric Sciences. This link could prove useful to encourage more climate modelling groups to get involved in the WGNE focus areas, particularly as more and more modelling centres are moving towards seamless models that can be used across all timescales. In this regards, WGNE is organising a systematic errors workshop that will be held from 19-23 June in Montreal, Canada, and hopes to bring representatives from both the weather and climate modelling communities together.

SPARC activity reports

The Stratospheric Network for Atmospheric Predictability (SNAP) has concluded the first phase of the project, which produced several well-cited papers examining the influence of the stratosphere on climate predictability at various timescales (**Andrew Charlton-Perez**). They have also been encouraging cooperation with other projects, including the SPARC DynVar and QBOi activities (see below) as well as the WCRP/WWRP Sub-seasonal to Seasonal (S2S) project. Their revamped website (**www.sparcsnap.org**) now has real-time diagnostics of annular modes and the probability of occurrence of sudden stratospheric warmings. Amy Butler will be joining Andrew as new co-lead of the activity, while Greg Roff, who steps down, is warmly thanked for his leadership of the activity.

The Stratospheric Reanalysis Intercomparison Project (S-RIP) also has new co-leads, with Gloria Manney and **Lesley Gray** joining Masatomo Fujiwara in running the activity. The group has been working hard on the interim S-RIP report, which is nearing completion and will be published in 2017. To complement the report, which will include many technical details, there is an S-RIP special issue open in Atmospheric Chemistry and Physics that includes papers that serve as an "entry point" to the reanalyses and science covered in more depth in the report.

S-RIP has held joint meetings with the Data Assimilation Working Group (DAWG; **Quentin Errera**) for the past two years, and will do so again in 2017 with a workshop that will be held in Reading, UK, from 23-27 October 2017. The themes of the workshop are yet to be decided, but may focus on things such as the representation of the stratosphere and mesosphere in data assimilating models or novel assimilation techniques. John McCormack will join Quentin to co-lead and further develop the activity.

The second Water Vapour Assessment activity (WAVAS-II) is finalising much of its work, with several papers having been or going to be submitted to a special joint journal issue between Atmospheric Chemistry and Physics, Atmospheric Measurement Techniques, and Earth System Science Data (**Gabriele Stiller**). These papers include descriptions of the various satellite and *in situ* water vapour products available, comparisons of these data, and analyses of variability and trends. The group have also been cooperating with the GEWEX G-VAP activity, which also focuses on comparing and understanding water vapour records, but mainly for the troposphere.

The Chemistry-Climate Modelling Initiative (CCMI), a joint SPARC-IGAC (International Global Atmospheric Chemistry) activity, has worked hard over the last year to ensure most of the phase-1 model data are available on the British Atmospheric Data Centre (BADC) server (**Michaela Hegglin**). They have also refreshed the steering committee, with Bryan Duncan replacing Jean-François Lamarque as co-lead with Michaela, and improved communication within the activity by issuing quarterly news emails. The group contributed to the overview paper describing the Coupled Model Intercomparison Project – Phase 6 (CMIP6) AerChemMIP project, and are working to finalise the CCMI ozone forcing dataset in support of CMIP6. CCMI will continue analysing the available model data over the coming year, with results being presented in a joint special issue between Geophysical Model Development, Atmospheric Chemistry and Physics, Atmospheric Measurement Techniques, and Earth System Science Data. This work has been facilitated by three focus groups that will produce key publications on tropospheric OH and ozone budgets, the specified dynamics simulations, and an overview of the entire CCMI activity. The group will hold its next workshop from 12-17

June 2017 in Toulouse, France.

The SOLARIS-HEPPA activity is also actively engaged in analysing the CCMI output (see also page 30, this issue), with five different working groups focusing on aspects ranging from the stratospheric solar signal to the impact of energetic particles on climate (**Katja Matthes**). Over the past year SOLARIS-HEPPA has produced the solar forcing dataset for CMIP-6, as well as a number of key papers outlining the impact of the solar signal on climate variability and predictability. This includes an overview paper of the DAMIP, a CMIP-6 project, that will cover experiments looking at the impact of solar forcing on detection and attribution of climate change. The activity will hold their next workshop in Paris, France, from 6-8 November 2017.

Michelle Santee provided an overview of progress made by the Polar Stratospheric Clouds Initiative (PSCi). So far the group has met three times, with the last two meetings being focused on a review paper that they are aiming to submit to Reviews of Geophysics by January 2018. The paper is being led by Michael Pitts and Ines Tritscher, and will provide a comprehensive overview of the distribution, formation processes, composition, and chemical processing of polar stratospheric clouds.

During 2016 the Atmospheric Composition in the Asian Monsoon (ACAM; also joint with IGAC) activity transitioned its formation committee into a scientific steering committee, which includes members from the four ACAM working groups (**Laura Pan**). ACAM helped organise a very successful workshop on Dynamics, Transport, and Chemistry in the Asian Monsoon Upper Troposphere/Lower Stratosphere in March 2016 and is working on organising the third biennial workshop to be held in Guangzhou, China, from 5-9 June 2017. Associated with this workshop will be the second ACAM training school. The group continues to work on developing capacity in the Asian Monsoon region, particularly through involvement in various field campaigns.

The Stratospheric Sulfur and Its Role in Climate (SSiRC) activity has, similar to several other SPARC activities, been involved in developing CMIP-6 projects (**Claudia Timmreck**). Their focus has been on VolMIP, which aims to understand the climatic responses to volcanoes. In 2016, SSiRC also produced a review paper on stratospheric aerosols and worked on a paper regarding the atmospheric sulfur budget, which is to be submitted soon. The group has also been very involved in several observational campaigns and in developing a response plan for a future campaign in the event of a major volcanic eruption. SSiRC is hoping to organise a Chapman Conference focused on "Stratospheric aerosols during the past 20 years" in 2018 on the island of Tenerife, Spain.

Amanda Maycock presented the Atmospheric Temperature Changes (ATC) activity, which she is co-leading with Andrea Steiner and Bill Randel. The activity is focused on understanding atmospheric temperature variability and trends in climate records and attribution of changes to radiative and dynamical drivers. Recent progress was presented at the group's first workshop in April 2016. This includes the production of new long-term merged temperature records for the stratosphere and mesosphere, comparison of model and satellite observations in terms of the magnitudes of tropospheric temperature changes, and an analysis of the consistency of GPS radio occultation observations. The group is organising a session at the European Geophysical Union's 2017 Conference and will likely plan a second ATC workshop for 2018 as well.

This year the Dynamical Variability (DynVar) activity held a major workshop in Helsinki, Finland, from 6-10 June 2016, which brought together the DynVar community, including representatives from various modelling centres (**Alexey Karpechko**; see page 26 for a full report). DynVar were also heavily involved in developing the DynVarMIP as part of CMIP-6. This MIP specifies and extra list of output diagnostics that will be used to help understand consistent model biases of various aspects of atmospheric dynamics, such as sea level pressure change or the mean position of the mid-latitude jets.

The Quasi-Biennial Oscillation initiative (QBOi) has largely focused on their phase one experiments over the past year (**Scott Osprey**). These experiments were designed to better understand differences between models able to reproduce the QBO and will serve as a basis for several papers to go into a special collection of the Quarterly Journal of the Royal Meteorological Society in 2017. The background work already done made it possible to very quickly put together a paper in response to the disruption in the QBO in mid-2016 (Osprey *et al.*, 2016). Together with SNAP and the Gravity Waves activity, QBOi would like to organise a joint workshop on the 2016 QBO disruption event, likely to be held in Asia in late 2017. More news on this workshop will be posted on the

SPARC website and in the eNews bulletin.

The SPARC Gravity Waves activity organised one of its major five-year conferences in 2016 at Penn State University (**Joan Alexander**). The symposium brought together a large number of scientists from both the weather and climate communities to focus on topics ranging from convective gravity wave generation to new observational results from the DEEPWAVE campaign and PANSY radar system (see page 22 for more details). Results from recent studies indicate that typical gravity wave parameterisations underestimate the amplitudes of these waves by up to a factor of 10, with even the most advanced parameterisations still underestimating amplitudes by up to a factor of 3. They also found that vertical resolution and numerical schemes play a very important role in accurately resolving waves and reducing dissipation in models. In the coming years the group, with Fuqing Zhang joining as a third co-lead, will focus on model predictability, particularly through encouraging modelling groups to incorporate newer gravity wave parameterisations.

Marv Geller presented progress made by the emerging FIne-Scale Atmospheric Processes and Structures (FISAPS) activity. Over the past year they have been developing an overview paper outlining recent progress made using high-resolution radiosonde observations as well as areas for new research that the activity will focus on. This includes, for example, recovering higher resolution signals from lower resolution historical data using spline-fitting techniques to extend records back to the 1960s. In addition to completing the paper, the group will be working on extending membership, in particular to help obtain further data, and will be organising a joint workshop together with the QBOi in 2017. The SSG accepted FISAPS as a full activity given the progress made over the past year.

New SPARC activities

A record number of five proposals for new SPARC activities were presented, on various topics across SPARC's three scientific themes. **Daan Hubert** gave an overview of the Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS) activity, which developed in response to issues raised in the last WMO/UNEP Ozone Assessment and the completed SPARC Si2N activity. These include differences in trend estimates as well as the uncertainties associated with these estimates. The activity will be coordinated by Daan, Irina Petropavlovskikh, and Sophie Godin-Beekman, with two science teams focused on "multi-instrument dataset integration" (MIDI; led by Viktoria Sofieva and Robert Damadeo) and on "regressions of ozone analysed for stratospheric trends" (ROAST; led by Robert Damadeo and Birgit Hassler). The MIDI team aims to extend and update ozone profile datasets to correct them as best as possible before running trend analyses, while the ROAST team will then use these datasets to assess the impact of using different statistical techniques to estimate long-term trends. Overall, it is hoped that an ensemble of datasets (including uncertainties) and techniques will be developed to provide a much better estimate of long-term ozone trends in the stratosphere. The activity will publish its results in peer-reviewed journals in time for the WMO/UNEP 2018 Ozone

Figure 1: Participants at the 24th SSG meeting held in Berlin, Germany. (Photo: Hans Volkert, DLR).

Assessment. It was accepted as a full activity.

An activity focused on Short-Lived Climate Forcers (SLCFs; **Bill Collins**) aims to understand the climate system's physical response to changes in radiative forcing from SLCFs. This includes aspects of the surface climate, such as surface temperature and precipitation, as well as other large-scale atmospheric features such as circulation patterns. For the moment, most of the planned activities are model-based, with experiments loosely based on the protocols developed for the Precipitation Driver Response Model Intercomparison Project (PDRMIP). There is however, plenty of scope to combine investigations with observational estimates of radiative forcing and emissions studies. The activity is very much in the development phase, with planning of experiment design to follow on from the CMIP-6 AerChemMIP project in 2018 and model simulations to be started in late 2018. The activity would clearly link with IGAC (see below) as well as the WCRP grand challenges on Clouds, Circulation, and Climate sensitivity; Carbon-climate interactions; and near-term climate predictions. Results from the activity would also be highly relevant to understanding the climate impacts of various air quality policies around the world.

Peter Hoor presented a proposal for an activity on Observing Composition Trends And Variability in the Upper Troposphere/Lower Stratosphere (OCTAV-UTLS). The region is very sensitive to changes in radiatively active gases such as ozone, methane, and water vapour and thus has a significant impact on much of the atmosphere. However, the UTLS is a highly variable region and definitions of the tropopause can have significant results on estimates in trends of chemical species. The activity aims to address the issue of understanding which tropopause definitions are ideal for various radiatively active species and using this information to reconcile and better understand limitations in the available observational datasets. They will use data from satellites, balloon- and aircraft-borne instruments, as well as ground-based remote sensing.

The fourth proposed activity called Towards UNified Error Reporting (TUNER) was presented by **Thomas von Clarmann** on behalf of his co-leads Doug Degenstein and Nathaniel Livesey. The activity aims to assess the best ways to report satellite measurement uncertainty estimates, since currently there is a very wide range in how these are reported. The activity team so far includes investigators from 12 satellite missions who will then implement the recommendations developed into their datasets. TUNER thus provides a key link between data providers and users, with strong links to many of SPARC's other activities as well as NDACC (see below), who have faced similar challenges in terms of their ground-based observational networks.

Historically, SPARC activities on stratosphere-troposphere exchange have focused on the mid-latitude regions, where balanced dynamics prevail. The Stratospheric and Tropospheric Influences On Tropical Convective Systems (SATIO-TCS; **Marv Geller**) activity aims to focus rather on the tropical regions, where weather systems involved multi-scale interactions with moist convection. Many studies over the past decade have shown that the stratosphere can significantly influence tropospheric variability in the tropics, and vice versa. This activity aims to better understand and predict stratosphere-troposphere interactions in the tropics using coordinated observational data analyses, theoretical studies, and experiments with a hierarchy of numerical models. SATIO-TCS links well with the WCRP Grand Challenges on Clouds, Circulation, and Climate Sensitivity; Near-term Climate Predictions; and Climate Extremes. The activity will also help develop capacity, particularly in the Asian region, where they already organized one training school in 2016. SLCFs, OCTAV-UTLS, TUNER, and SPATIO-TCS were all accepted as emerging activities.

Partner projects

The International Global Atmospheric Chemistry project (IGAC; **Mark Lawrence**) has been redefining itself, particularly in light of IGBP's move to Future Earth. The project continues to facilitate atmospheric chemistry research across the globe and functions in a similar way to SPARC, with two joint activities between both projects: CCMI and ACAM. A major focus for IGAC in 2016 was its biennial science conference, held in Breckenridge, Colorado, in late September. Of almost 500 participants, 200 were early career researchers and a very successful early career programme was organised both before and during the conference. The 2018 IGAC conference will be held the week prior to the 2018 SPARC General Assembly and also in Takamatsu, Japan, just 2.5 hours away from Kyoto, the location of the SPARC conference. The science programmes will be developed to encourage participation from the SPARC and IGAC communities in both conferences.

Martine de Mazière presented an overview of the Network for the Detection of Atmospheric Composition Change (NDACC), whose observations are used widely throughout the SPARC community. Most recently, measurements of carbon tetrachloride and carbonyl sulfide were used in SPARC Report No. 7 ("Solving the Mystery of Carbon Tetrachloride") and the SSiRC stratospheric sulfur overview paper, respectively. New products from the network include temperature and wind profiles from microwave radars, which can be obtained under most atmospheric conditions and therefore provide good data coverage. NDACC are completing an activity homogenising long-term ozonesonde records, and hope that the data will be made available soon. NDACC is maturing as a reference network and recognised as a key data provider for supporting validation activities around the globe, including by the Copernicus Atmospheric Monitoring System. Finally, to celebrate 25 years of NDACC/NSDC (the NDACC precursor network) observations, a joint special issue has been opened in Earth System Science Data, Atmospheric Chemistry and Physics, and Atmospheric Measurement Techniques.

Space observations

The issue of a looming gap in limb-sounding observations of atmospheric composition was touched on again by **Joan Alexander**. These observations are vital for monitoring essential climate variables such as water vapour, as well as for assessing the efficacy of the Montreal Protocol. Although the SAGE-III instrument will be launched on board the international space station soon, its sampling will be very sparse. The only instrument that is planned to continue into the future is OMPS, which measures ozone and aerosols, however, there are no firm plans for any instrument that could measure water vapour, methane, or other species important in the stratosphere and UTLS. The SPARC community has kept advocating for the continuation of limb-sounding observations wherever possible, including most recently as input for the NASA decadal survey.

To discuss this survey and give an update on a wide range of other NASA activities, **Kenneth Jucks** joined the meeting remotely. The Aura science team will be reviewed in the coming months as part of the regular biennial "senior review" process. There is also an ongoing review of the SAGE-III launch system, which was found to have a fault preventing it from launching as planned in November 2016. NASA is currently selecting a commercial telecommunications satellite for launch of the TEMPO instrument, the first of Earth Venture instrument series and which is aimed at observing air pollution around the globe. Several other missions stemming from the last NASA decadal survey will launch in the near future, including NI-SAR, SWOT, GEI, ECOSTRESS; CLARREO-pathfinder, and the OCO-3 which will be installed on board the international space station. The final report for the upcoming NASA decadal survey will be released in late 2017 and it is possible to still provide input to the various committees involved in providing the report. NASA has also conducted a large number of airborne campaigns over the past year, including KORUS-AQ, focused on air quality; POSIDON; ATOM, which has obtained global-scale cross-sections of atmospheric constituents including several reactive gases; ORACLES, focused on aerosols and their interaction with clouds and impacts on radiative forcing; and ACTA, aimed at measuring greenhouse gas fluxes over the Americas.

Quentin Errera briefly outlined the Altius mission, which will go some ways to 'fill the gap' in limb-sounding observations of the stratosphere. The mission was officially recognised as part of the ESA Earth Watch programme in December 2016 and will be based on PROBA micro-satellites on a polar orbit making both limb and occultation observations. The team expects to measure ozone and hopefully also water vapour, methane, aerosol, and polar stratospheric clouds. A third group of constituents, including OClO, BrO, and NO_3, will be measured if possible. The aim is to launch the instrument in late 2020 with a proposed lifetime of approximately three years.

Other SPARC news

2016 was a busy year in terms of SPARC's capacity development efforts (**Fiona Tummon**). The SPARC website now includes a 'How to get involved' page, which also provides a useful page of links to SPARC-related online courses and teaching material. SPARC has been actively promoting the Young Earth System Scientists (YESS) community and, as usual, has supported many early career researchers to attend SPARC workshops and a training school on atmospheric composition and dynamics, held on Réunion island. The Asia-Pacific working group is still growing and was involved in the "Southeast Asia School on Tropical Atmospheric Science (SEASTAS)", which was held joint with a workshop on Extreme

Weather in a Changing Climate in the Maritime Continent (Seok-Woo Son). Work is underway to develop a university-level course on middle atmosphere dynamics in southern Africa, which will hopefully stimulate interest across the region in SPARC-related science (Thando Ndarana). Several activities are planned for 2017, including the 2nd ACAM training school (Guangzhou, China), an atmospheric dynamics training school (Cape Town, South Africa), the 3rd SEASTAS school in Singapore, as well as regional science workshop joint with the 25th SPARC SSG meeting, which will be held in Seoul, Korea, in September or October 2017.

In other good news, the Deutsches Luft- und Raumfahrt (DLR; German space agency) have offered to host the international SPARC project office as of mid-2017. **Hans Volkert** will serve as director and, together with the current team in Zurich, will help ensure a smooth transition to the new location in Oberpfaffenhofen. The DLR team will take over all duties as of 2018.

The 2018 SPARC General Assembly will be held from 1-6 October 2018 at the Miyakomesse, a major conference centre in Kyoto, Japan (**Kaoru Sato**). Organisation of the event is already underway, with the science programme to be made public in mid-2017. Various early career researcher events are also being planned, potentially in collaboration with IGAC.

The meeting was brought to a close on Friday afternoon. The 25th SPARC SSG meeting in conjunction with a regional science workshop will be held in Seoul, Korea, in late 2017.

WCRP/SPARC Workshop: "Challenges for Climate Science – Synergies between SPARC and the WCRP Grand Challenges" Berlin, 31 October-1 November 2016

Hauke Schmidt[1], Neil Harris[2], Katja Matthes[3], Judith Perlwitz[4], and Fiona Tummon[5]

[1]Max Planck Institute for Meteorology, Hamburg, Germany, **hauke.schmidt@mpimet.mpg.de**, [2]Centre for Atmospheric Informatics and Emissions Technology, Cranfield University, UK, [3]GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany, [4]Physical Sciences Division, NOAA Earth System Research Laboratory, USA, [5]SPARC Office, ETH Zurich, Switzerland

64 scientists from 15 nations met in Berlin to discuss science related to SPARC and the WCRP Grand Challenges (GCs). WCRP has identified seven GCs (**www.wcrp-climate.org/grand-challenges**) representing areas for specific focus in scientific research for WCRP in the coming years. Progress in these areas will lead to actionable information for decision makers. Organized back-to-back with the annual meeting of the SPARC scientific steering group, this workshop brought together scientists active in GC research, in SPARC activities, and scientists that thus far have had fewer links to WCRP, with the goal of exploring synergies and fostering scientific exchange. The discussions concentrated on four of the GCs where links to SPARC seem most obvious. For each of these four research areas, one scientist involved in the GC presented ideas and ongoing work, followed by a few invited presentations covering specific related topics, and a lively poster session.

Guy Brasseur, Chair of the WCRP Joint Scientific Committee, opened the workshop with an overview of the programme, including its organisation into thematic working groups, the four core projects (CLIC, CLIVAR, GEWEX, and SPARC), and the seven GCs covering topics cutting across the core projects (see **Figure 2**). He emphasized that it is timely "to start developing a new perspective for WCRP that responds to the societal challenges of the next decades, and puts more emphasis on regional aspects, on natural variability, and on possible surprises." Regional approaches for WCRP are based on three legs: foundational climate science, application-oriented climate science, and trans-disciplinary engagement.

Clouds, Circulation and Climate Sensitivity

Ted Shepherd introduced the GC on "Clouds, Circulation and Climate Sensitivity". He pointed out that the growing emphasis on regional climate, as presented by Guy Brasseur, and on Near-Term Climate Prediction (see below), is exposing the limitations in our understanding of atmospheric circulation and its response to climate change. As examples, he mentioned the uncertainty of climate projections for Europe (including the Mediterranean) being largely related to the way different models simulate large-scale circulation, and even in the tropics, where models disagree most, circulation has a profound influence.

Ice formation in clouds and the relevance of small-scale uncertainties in cloud microphysical processes for large scales were the topic of **Corinna Hoose**. She emphasized the relevance of a changing cloud-phase distribution in a warming world and that this distribution, being dependent on the frequency, season, and location of occurrence of different cloud types, will also be impacted by circulation changes.

Hella Garny gave an overview of changes in the large-scale circulation of the middle atmosphere and its impact on chemistry and climate. She identified key open questions that concern past middle atmosphere circulation changes (*e.g.,* how to reconcile them and what role transport, mixing, and gravity waves play), and the quantification of the influence of the middle atmosphere on the troposphere.

Gabi Stiller reviewed the role of stratospheric water vapour in climate change. Obviously, stratospheric water vapour has a large impact on radiative forcing and hence for climate change. However, she highlighted that the puzzle of water vapour entry into the stratosphere is not yet solved. Trends in water vapour itself and in cold-point temperatures are not in agreement, in observations, models, or reanalyses.

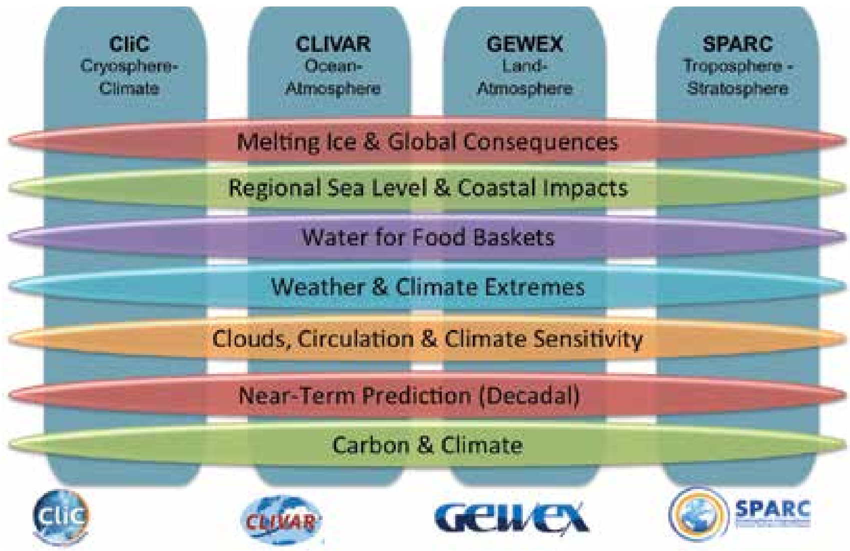

Figure 2: The four WCRP core projects (CliC, CLIVAR, GEWEX, and SPARC) and the seven Grand Challenges covering topics cutting across the core projects (figure adapted from the workshop presentation by Guy Brasseur).

Near-Term Climate Prediction

The GC on "Near-Term Climate Prediction" was introduced by **Judith Perlwitz**. Such predictions are intended to fill the gap between long-term centennial projections and seasonal forecasts. The three objectives of the GC are a) research and development to improve predictions on the interannual to decadal timescale, b) to collate and synthesize existing projections, and c) to develop structures for future routine decadal predictions.

The German MiKlip project, that aims to develop an operational decadal climate prediction system, was presented by **Wolfgang Müller**. Among the lessons learned so far in this project are: initialisation is crucial but still a challenge (model-consistent assimilation would be nice to have for this); key processes for prediction skill (*e.g.* North Atlantic heat content) have been identified, but models may need improvements to benefit from this knowledge; bias-correction methods improve prediction skill but also need further improvement.

Claudia Timmreck emphasized the role of large volcanic eruptions for near-term climate predictions. Once such an event occurs the resulting forcing needs to be taken into account for the predictions. She showed that the skill of hindcasts up to a decade in length lose a large part of their skill if volcanic events are ignored.

Katja Matthes gave an overview of the effects of solar variability on climate and highlighted its role for near-term climate predictions. For instance, it has been shown that there is predictive skill for the NAO on timescales of up to one year ahead, partly resulting from knowledge about the solar forcing. She also noted that not only the solar forcing (in radiation and particles) but also a consistent representation of its effect on stratospheric ozone is crucial.

Two further presentations

concentrated on timescales shorter than one year. **Daniela Domeisen** reviewed the involvement of the stratosphere in seasonal predictions, showing that it is clear that seasonal prediction skill is much higher for the tropics than for the extra-tropics. In particular, Europe is a region for which the skill is currently low. However, there are predictors that can provide skill, most of which are relevant for the winter season, in particular those acting via the stratosphere (*e.g.*, QBO, ENSO, or solar forcing).

The even shorter sub-seasonal timescale was covered by **Andrew Charlton-Perez**, who presented the Stratosphere Network for the Assessment of Predictability (SNAP) and its relevance to the WCRP GCs. As for the other time-scales, one fundamental interest of SNAP is to understand the dynamics of coupling between the stratosphere and troposphere. Andrew emphasized the importance of the state of the polar vortex, the MJO, and the QBO for predictive skill.

Climate Extremes

Olivia Martius introduced the GC on "Climate Extremes" which has two perspectives: service and science. While there is a huge public demand for information on extremes, we still have to improve our understanding of causes and mechanisms of variability and change in extremes, as well as their predictability. The GC focusses on four types of extremes: heavy precipitation, storms, heatwaves, and droughts. A link to SPARC is in particular provided by the relevance of circulation, because extreme events are often related to specific circulation patterns as blocking events.

In his presentation **Kai Kornhuber** concentrated on dynamical changes relevant to summer extremes. He argued that the mid-latitude summer circulation is less thoroughly studied than the winter circulation, even though it is possibly more sensitive to relatively subtle changes. There is some evidence for zonal flow and storm tracks weakening under climate change and possible drivers of this were discussed.

A complementary view on extremes was provided by **George Craig** who presented the HIWeather project of the World Weather Research Programme (WWRP). The project aims to achieve a dramatic increase in resilience to high impact weather through improving forecasts on timescales from minutes to two weeks. To achieve this, the project is working to improve the links between forecasters (*i.e.,* meteorologists) and decision makers. With respect to WCRPs regional activities (see above), it would certainly be useful to benefit from the WWRP's experience.

Carbon feedbacks in the Climate System

Finally, the workshop covered the GC on "Carbon feedbacks in the Climate System" and other trace gases relevant to SPARC. **Tatiana Ilyina** presented this GC, which aims to understand how biogeochemical cycles and feedbacks control CO_2 concentrations and thus impact the climate system. Guiding questions of this GC concern a) the drivers of land and ocean carbon sinks, b) the potential for amplification of climate change via carbon cycle feedback, and c) greenhouse gas fluxes from highly vulnerable carbon reservoirs.

Atmosphere-ocean coupling via trace gases was the topic of **Susann Tegtmeier**, who pointed out that oceanic trace gases are important for atmospheric chemistry and climate, and that it is necessary to better understand the processes involved. Improved observations will be necessary to accomplish this. An example of an open question on this topic is the "missing source" of atmospheric sulphur, which is necessary to reconcile atmospheric observations of trace gases concentrations and various emission source estimates.

Bill Collins provided an overview of short-lived climate forcers (SLCFs) and made the point that quantifying the climate impacts of SLCFs is crucial a) for deducing historical climate sensitivity to CO_2, b) to make near-term climate predictions, and c) to quantify the climate impacts of air quality policies. He proposed a new SPARC activity to coordinate research focusing on understanding the climate effects of SLCFs, particularly on the regional scale.

The Harnack House, the conference venue of the Max Planck Society in Berlin, provided a stimulating environment for discussion among researchers from different backgrounds and rooted in different research fields. We hope that fruitful collaborations will result from this meeting. Although the topics presented were very diverse, it became clear that there are strong links from SPARC to all the four GCs covered in this workshop. Such links include the relevance of large-scale circulation in understanding regional climate change and extremes, as well as the importance of factors such as solar forcing QBO, volcanoes in advancing the skill of predictions on annual to decadal time scale.

CMIP6 and Involvement of SPARC Activities

Veronika Eyring[1] and David Carlson[2]

[1]Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany, **Veronika.Eyring@dlr.de**, [2]World Climate Research Programme, Geneva, Switzerland

The WCRP Coupled Model Intercomparison Project (CMIP) serves as a fundamental basis for international climate research. Approximately 45% of climate research papers published during 2016 in the Journal of Climate (designated by Thomson Reuters as one of the prestigious journals in the field of climate research) explicitly cite CMIP5. A sequence of CMIP phases (*e.g.,* CMIP3 (Meehl *et al.*, 2007), CMIP5 (Taylor *et al.*, 2012)) have underpinned and enabled a parallel sequence of IPCC Assessment Reports (*e.g.,* AR4 and AR5, respectively) resulting in specific IPCC acknowledgement: "The IPCC's Fifth Assessment Report (AR5) relies heavily on the Coupled Model Intercomparison Project, Phase 5 (CMIP5), a collaborative climate modelling process coordinated by the World Climate Research Programme (WCRP)." The CMIP process represents a remarkable technical and scientific coordination effort across dozens of climate modelling centres involving perhaps 1000 or more researchers. Here we provide a brief overview of the design, intended capabilities and progress of the current 6th Phase of CMIP (CMIP6) and highlight SPARC activities that are part of CMIP6. Interested readers should access the full and definitive CMIP6 description in Eyring *et al.* (2016a), lead paper of a GMD special issue on the CMIP6 experiment design (**http://www.geosci-model-dev.net/special_issue590.html**).

Although model intercomparison projects now seem standard, the fundamental motivation for CMIP arose as a few atmospheric modelling centres around the world first started running coupled ocean and atmosphere models for climate - hence the 'coupled' identifier in the CMIP acronym - and quickly recognised a need and opportunity to share and intercompare outputs of those models. As the tasks of sharing and intercomparing proved easier said than done, a strong motivation arose for a persistent organised set of protocols and mechanisms to be established and for a process through which to develop and support the coordination itself and the necessary intercomparison tools. In response, WCRP's Working Group on Coupled Modelling (WGCM) initiated CMIP. Early and consistent support from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) allowed CMIP to develop useful formats and standards and to establish effective mechanisms for model output availability.

The need for and challenges facing CMIP, in particular CMIP6, have grown. More centres run more versions of more models. The models themselves have grown in complexity to meet demand; a modern Earth system model might now have full atmospheric chemistry, active land processes including vegetation growth and decay, as well as an interactive carbon cycle on land and in the ocean. These model amendments compete with resolution - one still can't achieve all desired features at high resolution over climate time scales - and the list of necessary and desired model outputs has grown enormously while basic resolution has improved. Some CMIP6 models in some configurations will run at global resolutions of 25km, better than regional resolutions of only a few years ago. Running these models requires enormous computational resources while archiving, documenting, sub-setting, supporting, and distributing the Terabytes and increasingly Petabytes of model output - 20 to 40 Petabytes for CMIP6 - challenges the capacity and creativity of the biggest data centres and fastest data networks.

Box 1

CMIP Panel

Veronika Eyring (Chair, DLR, Germany)
Sandrine Bony (CNRS, France)
Jerry Meehl (NCAR, USA)
Cath Senior (MetOffice, UK)
Bjorn Stevens (MPI, Germany)
Ron Stouffer (GFDL, USA)
Karl Taylor (PCMDI, USA)

In designing CMIP6, the CMIP Panel (see **Box 1**) undertook a rigorous assessment of past performance and future needs. They listened carefully to customers, in this case modelling centres and research users. Based on prior CMIP phases, particularly the increment from CMIP3 to CMIP5 (CMIP4 involved only a small addition to CMIP3 protocols), they assessed which strategies and practices aided or limited substantial progress in model skill and scientific understanding. From this consultation the CMIP Panel set five design goals for CMIP6:

- To facilitate relationships between and intercomparisons among various MIPs within CMIP6 and to ensure consistency across CMIP phases (to allow, for example, model or ensemble means assembled from CMIP5, CMIP6, and CMIP7 components);
- In view of the enthusiastic proliferation of MIPs, to enable the research community to provide modelling centres with a science-based priority outline of CMIP6 preferred activities;
- To allow modelling groups to implement self-determined development schedules and research experiments uncoupled from but still relevant to a singular IPCC deadline;
- To strengthen overall MIP activities for CMIP by embedding them within a coherent scientific framework leading to an enhanced collective outcome; and
- To achieve all of the above through an open and inclusive process.

The CMIP6 design as it evolved and as implemented to date achieves these goals through three fundamental changes in process and procedure and by adopting the WCRP Grand Challenges as an encompassing scientific framework.

Continuous and flexible operations

To avoid alternating haste and delay in the lead-up to a fixed deadline, CMIP6: a) allows modelling centres to implement improved model versions and to run various CMIP experiments as ready and as convenient so long as they also b) complete and submit Diagnosis, Evaluation, and Characterization of Klima experiments (DECK) and the CMIP6 historical simulation according to the CMIP guidelines as certification of their CMIP capabilities and as 'entry cards' to CMIP6. For CMIP6, historical forcing datasets, including emissions and concentrations of greenhouse gases, land use changes, solar and stratospheric (volcanic aerosol and ozone) forcing are now available, allowing modelling centres to start running CMIP6 entry card experiments. Forcing datasets for future climate projections will become available by May 2017 from the Integrated Assessment Modelling (IAM) community allowing climate projection experiments to start at that point. The majority of the CMIP6-Endorsed MIP experiments will be run during the 2017-2018 period. Research based on analysis of the CMIP6 output will start to emerge in 2018-2020, in time to contribute to IPCC AR6.

Consistent and persistent entry cards

The DECK (atmosphere only, forced with fixed sea surface temperature and sea ice concentrations, pre-industrial control run, abrupt and gradual CO_2 perturbations) and the CMIP6 historical simulation (1850-2014) extend a sound pedigree from prior CMIP phases. Note that for the purpose of CMIP6, future climate begins in 2015. The DECK simulations also very likely represent the experiments that most modelling groups use or will use to test and evaluate their newest model versions in any case. We expect that the protocols for the DECK and CMIP historical simulation will remain quite consistent for future CMIP phases. In this way, rather than imposing performance or computational barriers, the DECK and historical simulations encourage consistency among models and across phases. Eyring *et al.* (2016a) provide additional details, clear explanation and ample justification for the DECK and the CMIP historical simulation as the set of experiments used to characterize the ensemble. They describe a plausible implementation scheme whereby various perturbation experiments branch off various control experiments to subsequent CMIP6-Endorsed MIP experiments and extend over consistent and appropriate time periods. They also suggest and justify ensemble members of a few components in a manner that anticipates maximal scientific impact but minimises computational requirements.

Improved standards and documentation

The push for improved standards and documentation arises internally due to the growing complexity of the models and externally in recognition that more and more users outside the climate modelling community want access to CMIP data. The CMIP Panel works closely with the WGCM Infrastructure Panel (WIP) to establish and promulgate requirements, formats, and specifications for output products, model and simulation documentation, and archival and access systems. These guidelines and standards, coupled with the long-term viability of the overall CMIP process, have allowed and encouraged the parallel evolution of data and evaluation infrastructure.

One new effort in CMIP6 will be the execution of community-based evaluation packages whenever an archive site registers a new CMIP entry card simulation (Eyring *et al.,* 2016b). Our initial goal is that two capabilities will be coupled to the Earth System Grid Federation (ESGF) to produce a broad characterization of CMIP6 DECK and historical simulations as soon as new model experiments are published on the CMIP6 archive: the Earth System Model Evaluation Tool (ESMValTool, Eyring *et al.,* 2016c), which itself includes other well-known packages such as the NCAR Climate Variability Diagnostic Package (CVDP, Phillips *et al.,* 2014), and the PCMDI Metrics Package (PMP, Gleckler *et al.,* 2016). Starting with available data in existing CMIP5 replica caches, the evaluation package developments are currently being tested at dedicated sites (some of the super-nodes) and prepared for CMIP6. In parallel, developments with respect to the supporting infrastructure (replication, cache maintenance, provenance recor-ding, parallel processing) are starting. We expect this initial effort to spur developments toward a uniform approach to analytic package deployment. Eventually we aspire to put in place a robust and agile framework whereby new diagnostics developed by individual scientists can quickly and routinely be deployed on a large scale. Routine use of these tools will greatly facilitate systematic model evaluations as part of subsequent assessments, for example the Evaluation of Climate Models chapter (Chapter 9) in the IPCC AR5 Working Group I Report (Flato *et al.,* 2013). The CMIP standards and guidelines have also enabled a substantial data assembly effort, focused on gathering and converting observations (observations for MIPs, obs4mips (Ferraro *et al.,* 2015; Teixeira *et al.,* 2014) and reanalysis products (reanalyses for MIPs, ana4mips) into accessible and CMIP-like formats for use in model evaluation. All of these model evaluation efforts will broaden and accelerate during CMIP6. Fundamentally, these community-based CMIP evaluation tools and data sources encourage progress on model development and on scientific exploration.

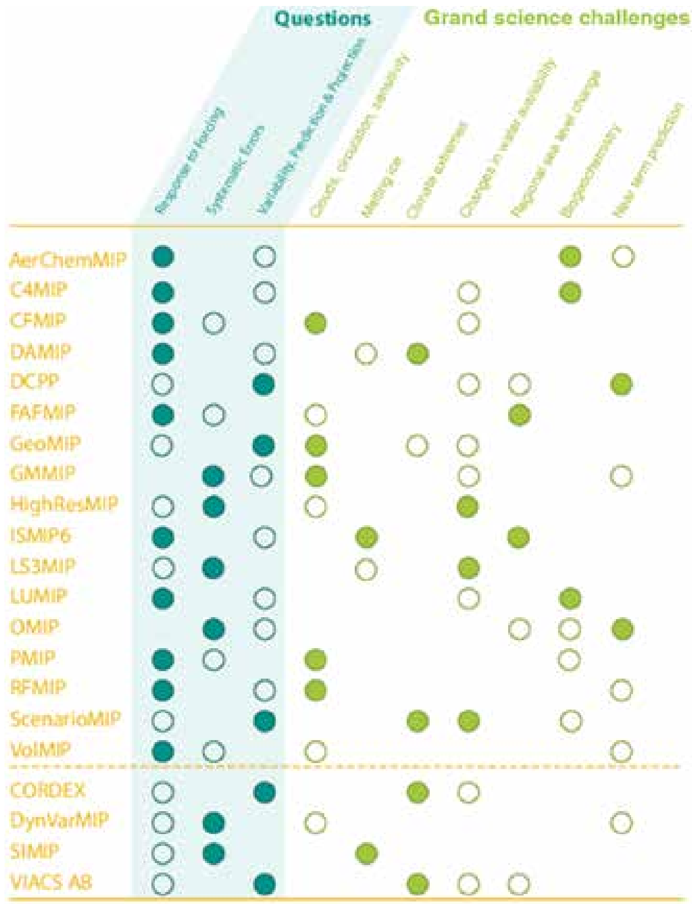

Figure 3: Contributions of CMIP6-Endorsed MIPs to the three CMIP6 science questions and the WCRP Grand Challenges. A filled circle indicates highest and an open circle second highest priority. Some of the MIPs additionally contribute with lower priority to other CMIP6 science questions or WCRP Grand Challenges (Figure from Eyring *et al.*, 2016a).

Deliberate science focus

In the face of increasing complexity of individual models, more versions running at more modelling centres and the increase in the number of MIPs within and outside of CMIP, the CMIP Panel wanted to ensure the dual roles of CMIP: to advance model development and to facilitate and advance climate research. In evaluating more than 30 MIPs proposed for CMIP6, the Panel considered relevance of each MIP to the three fundamental science questions of CMIP6:

1. How does the Earth system respond to forcing?
2. What are the origins and consequences of systematic model biases?
3. How can we assess future climate changes given climate variability, predictability and uncertainties in scenarios?

The CMIP6 questions serve as the model improvement basis for the seven WCRP Grand Challenges. From more than 30 initial MIP proposals, the Panel merged, adjusted, and revised the list to 21 CMIP6-Endorsed MIPs. **Figure 3** demonstrates that each CMIP6-Endorsed MIP contributes to one or more CMIP6 science question and WCRP Grand Challenge. Likewise, each topic draws attention from at least two and as many as five to 10 CMIP6-Endorsed MIPs. All of the CMIP6-Endorsed MIPs earned a commitment from 10 or more modelling centres: the centres committed to running all the top priority (Tier 1) experiments specified by the MIP and to produce all requested diagnostic outputs and information. This convergence of MIP goals with modelling centre commitments did not occur automatically or spontaneously. It represents a clear signal that the CMIP process does and will focus on highly relevant science questions extracted from and contributing to the WCRP Grand Challenges. Obviously the MIPs tailored their goals and requests to expected model capabilities and capacities, but through this process modelling centres also participated directly in designing the scientific focus and size of CMIP6.

To gain endorsement, and to help CMIP6 and the modelling centres set priorities and monitor progress, all of the MIPs specify top priority Tier 1 activities. Most also contain longer lists of optional and encouraged experiments. ScenarioMIP (O'Neill *et al.*, 2016) will run a new set of future long-term integrations engaging input from both the climate science and integrated assessment modelling communities. The new scenarios are based on a matrix that uses the shared socioeconomic pathways (SSPs) and forcing levels of the Representative Concentration Pathways (RCP) as axes (Riahi *et al.,* 2016). They span the same range as the CMIP5 RCPs, but fill critical gaps for intermediate forcing levels and questions, for example, on short-lived species and land-use. CMIP6 also takes a deliberate step towards improved communication through the establishment of a vulnerability, impacts and adaptation and climate services advisory board (VIACS AB, Ruane *et al.,* 2016). The GMD special issue presents full descriptions of the full range of CMIP6-Endorsed MIPs.

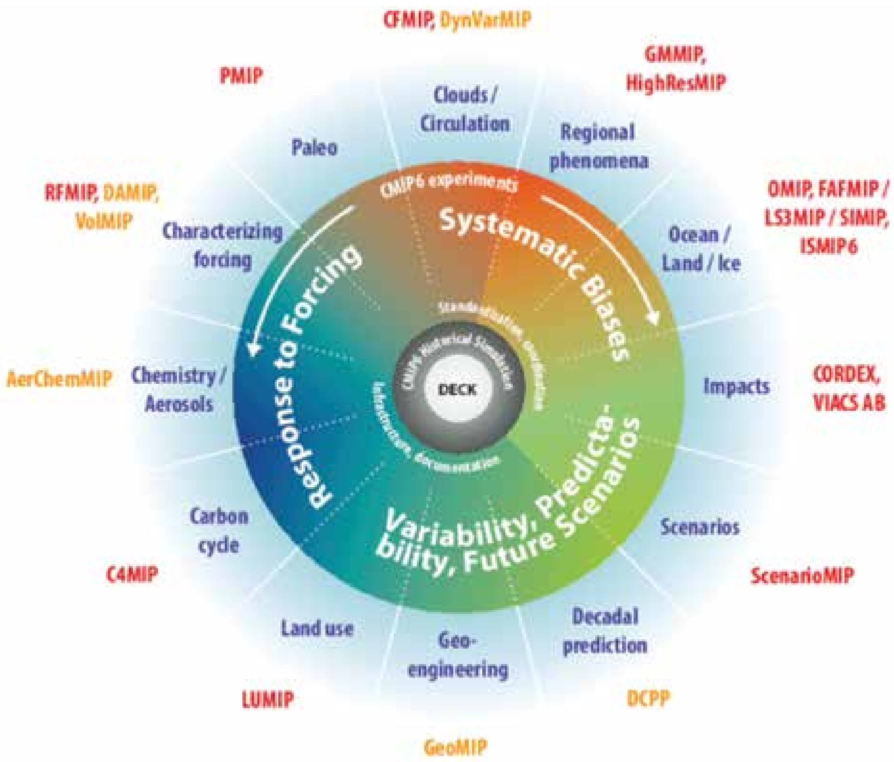

Figure 4: Schematic of the CMIP/CMIP6 experiment design. The inner ring and surrounding white text involve standardized functions of all CMIP DECK experiments and the CMIP6 historical simulation. The middle ring shows science topics related specifically to CMIP6 that are addressed by the CMIP6-Endorsed MIPs, with MIP topics and the names of the CMIP6-Endorsed MIPs shown in the outer ring. CMIP6-Endorsed MIPs with SPARC involvement are highlighted in orange (modified from Figure 2 of Eyring *et al.,* 2016a).

SPARC involvement in CMIP6

SPARC initiatives contribute to CMIP6 in various ways. First, SPARC activities have provided important CMIP6 forcing datasets. To avoid conflating uncertainty in the response of models to a given forcing, models are integrated with the same forcing in the DECK and CMIP6 historical simulations. Forcing uncertainty is then sampled in supplementary simulations that are proposed, for example, as part of the Detection and Attribution MIP (DAMIP, Gillett *et al.,* 2016) or the MIP on climatic responses to volcanic forcing (VolMIP, Zanchettin *et al.,* 2016). The final forcing datasets for the DECK, CMIP historical simulations, and CMIP6-Endorsed MIPs have been published in the ESGF (see **https://pcmdi.llnl.gov/projects/input4mips**) and documented in separate contributions to the CMIP6 Special Issue.

- For models without interactive ozone chemistry, time-varying gridded ozone concentrations and nitrogen deposition fields are provided by the IGAC/ SPARC Chemistry-Climate Model Initiative (CCMI, **http://blogs.reading.ac.uk/ccmi/**). The ozone database developed for CMIP5 (Cionni *et al.,* 2011) for the first time allowed time-varying ozone to be included in the CMIP simulations that did not have interactive chemistry. However, the underestimation of the Antarctic ozone hole in the past and the restriction to a single greenhouse gas scenario for stratospheric ozone in the future were known weaknesses of the CMIP5 ozone database. There was hence a need to provide an updated version of this dataset for CMIP6. The new IGAC/SPARC CCMI ozone database and nitrogen-deposition fields cover the period from the pre-industrial era to the future (1850-2100).

- The solar forcing dataset for CMIP6 is provided by the SPARC SOLARIS-HEPPA activity and includes both radiative properties and particle forcing at daily and monthly resolution for the CMIP6 historical simulation (1850–2014), the future (2015–2300), and the preindustrial control simulation (Matthes *et al.,* 2016). Radiative properties include total solar irradiance (TSI), solar spectral irradiance (SSI; from extreme ultra violet to infrared), and F10.7 cm radio flux, while particle forcing, which is provided for the first time in a CMIP exercise, includes geomagnetic indices and ionization rates to account for the effects of solar protons, electrons, and galactic cosmic rays. Differences to CMIP5 include a new, lower reference TSI value: 1361.0 ± 0.5 W/m^2 as well as future solar forcing that does not stay constant at the solar cycle 23 level but decreases to a Gleissberg-type solar minimum at the end of the 21st century. An additional extreme Maunder minimum-like sensitivity scenario, as well as time-varying forcing for the preindustrial control simulation are also provided but are not officially part of CMIP6. CMIP6 models with a well-resolved shortwave radiation scheme are encouraged to use SSI, and CMIP6 models without interactive chemistry are encouraged to use solar-induced ozone signals, which are embedded in the CMIP6 ozone database. This will improve the representation of solar climate variability compared to models that only prescribe TSI and/or exclude the solar-ozone response.
- The stratospheric aerosol dataset for CMIP6 models includes monthly and zonal means averaged in latitude bands of five degrees for the 1850-2014. Three dimensional data are provided (time, altitude, and latitude) between 90°S and 90°N and from altitudes from 5-39.5km at 0.5km resolution (see **ftp://iacftp.ethz.ch/pub_read/luo/CMIP6**). The data products include surface area density (sad in µm^2/cm^3), mean radius (r_{mean} in µm), aerosol volume density (volume_density in µm^3/cm^3), and H_2SO_4 density given as the number of H_2SO_4 molecules in the aerosol phase per cm^3 of air (H_2SO_4_mass). The data are reliable strictly only above and at the tropopause. The tropospheric values are less reliable due to the cloud-clearing process introducing noise. Furthermore, in the polar winter stratosphere, data may be contaminated by polar stratospheric clouds. It is strongly recommended that the data are used below the instantaneous local model tropopause only to establish a smooth transition between the stratospheric aerosol and tropospheric aerosol used by the models. In addition, corresponding radiative properties (extinction coefficients, single scattering factors, and asymmetric factor for solar radiation) are provided for all modelling groups participating in CMIP6.

Second, SPARC activities lead or are involved in several of the CMIP6-Endorsed MIPs that are highlighted in orange in **Figure 4**. These include the aerosols and atmospheric chemistry MIP (AerChemMIP, Collins *et al.,* 2016). This is one of the MIPs that have newly emerged since CMIP5 as the modelling community has developed more complex Earth system models (ESMs) with interactive components beyond the carbon cycle. AerChemMIP aims at a consistent quantification of forcings and feedbacks and was formed based on lessons learned from the Aerosol Comparison (AeroCom) initiative (Schulz e*t al.,* 2006), the CMIP5 Atmospheric Chemistry and Climate MIP (ACCMIP, Lamarque *et al.,* 2013), and the CCMI activity (Eyring *et al.,* 2013). Other CMIP6-endorsed MIPs specifically target systematic biases, among these the SPARC Dynamics and Variability MIP (DynVarMIP, Gerber and Manzini, 2016) that aims to improve understanding of circulation and variability with a focus on stratosphere-troposphere coupling. Other CMIP6-endorsed MIPs with SPARC involvement are the Decadal Climate Prediction Project (DCPP, Boer *et al.,* 2016), DAMIP (Gillett *et al.,* 2016), the Geoengineering Model Intercomparison Project Phase 6 (GeoMIP6, Kravitz *et al.,* 2015), and VolMIP (Zanchettin *et al.,* 2016). The DCPP protocol, for example, includes experiments that are proposed jointly with VolMIP to examine the effects of volcanoes on past and potentially on future decadal predictions. Key novel features of DAMIP include new single forcing historical simulations with aerosols-only, stratospheric ozone-only, CO_2-only, solar-only, and volcanic-only forcings, facilitating an improved estimation of the climate response to individual forcing elements. New topics in GeoMIP6 that will be addressed include research on key uncertainties in extreme events and cirrus cloud thinning to allow more longwave radiation to escape to space. VolMIP studies model uncertainties regarding the climatic response to strong volcanic forcing by defining a coordinated set of idealized volcanic perturbation experiments based on historical eruptions with well-constrained volcanic forcing. Overall, we expect that model output from CMIP6 simulations will provide a very valuable resource for SPARC research.

Third, SPARC activities are also contributing to the CMIP evaluation tool capability by providing additional diagnostic codes to the ESMValTool to enhance routine evaluation of chemistry, aerosol, and stratosphere-troposphere coupling aspects in the CMIP simulations. The broader SPARC community is encouraged to contribute to the community developed evaluation tools that, as this capability matures, is expected to produce an increasingly systematic characterization of models that will more quickly and openly identify the strengths and weaknesses of the simulations (Eyring *et al.,* 2016b).

Summary

In summary, CMIP6 envisions and encourages a more consistent and persistent set of core activities, enhanced tools and mechanisms for access and analysis, and a simultaneously broad but focused scientific impact. It sets a notable example for inclusivity, transparency, and open access of its information and products. It functions almost entirely through coordination, collaboration, and cooperation. Although the meteorological community understands global (atmospheric) models and rapid exchange of high-quality data and model outputs, the CMIP endeavour almost certainly exceeds numerical weather prediction in complexity and data volumes. Now, the growing dependency on CMIP products by a broad research community and by national and international climate assessments means that basic CMIP activities, such as the creation of forcing datasets, the provision and archiving of CMIP products, and model development, require substantial efforts. CMIP continues to rely heavily on volunteer efforts by enthusiastic climate researchers. It represents one of society's most robust and reliable sources for climate information – a source that deserves international acclaim and substantial ongoing support.

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Report on the International Workshop on Stratosphere-Troposphere Dynamical Coupling in the Tropics 22-24 October 2015, Kyoto, Japan

Marvin Geller[1], Peter Haynes[2], Seok-Woo Son[3], and Shigeo Yoden[4]

[1]Stony Brook University, New York, USA, **marvin.geller@stonybrook.edu**, [2]University of Cambridge, Cambridge, UK, [3]Seoul National University, Seoul, Korea, [4]Kyoto University, Kyoto, Japan

From 22-24 October 2015, a group of 18 researchers from seven different countries met at the Graduate School of Science Seminar House of Kyoto University (**Figure 5**). The organiser of the workshop was Professor Shigeo Yoden of Kyoto University. One of the SPARC science themes for almost a decade was "Stratosphere-troposphere dynamical coupling", but to date this was concentrated almost exclusively on coupling in mid- and high-latitudes, where the standard paradigms for interpreting and explaining troposphere-stratosphere coupling have been based on balanced dynamics, the distribution of potential vorticity (PV) on isentropic surfaces (or quasi-geostrophic PV on pressure surfaces), the material conservation of PV under adiabatic conditions, and the inversion of the PV field to recover all other dynamic and thermodynamic quantities. Great advances in understanding have occurred using these paradigms directly or paradigms related to the dynamics that arises from them, including Rossby wave propagation, baroclinic instability, wave mean-flow interaction, and so on.

On the other hand, the dynamic regime in the tropics is very different from that at higher latitudes; weather systems in the tropics involve multi-scale interactions with moist convection, for which no comparable interpretive paradigm exists. Mesoscale moist convection is the predominant source driving atmospheric motion in the tropics, whereas it is synoptic-scale baroclinic instability in the extra-tropics. Nonetheless, there is observational evidence that stratospheric variations do influence tropospheric variability in the form of moist convection or its large-scale organisation into meso- to planetary-scale systems. Furthermore, there have been some modelling studies, with both global general circulation models and regional cloud-resolving models, which show similarities to these observations, but such modelling studies have not yet reached a mature state.

This workshop was organised to discuss recent observational and modelling research in the area of stratospheric influences on tropical weather and climate, with a goal of proposing SPARC activities in this area. Topics covered during the workshop included the Quasi-Biennial Oscillation (QBO) influence on seasonal-mean tropical deep convection; QBO influence on tropical cyclones; QBO influence on the Madden-Julian Oscillation (MJO) and monsoon circulation; the influence of stratospheric sudden warmings (SSWs) on the tropical troposphere; influence of the 11-year solar cycle and stratospheric cooling trends on convection and its organisation; moist convection and multi-scale interactions in the tropics; wave-mean flow interactions and induced circulation in the tropics; and how our proposed activity might link with WCRP and other international activities.

Figure 5: Workshop attendees. Standing left to right: Harry Hendon, Tieh-Yong Koh, Marvin Geller, Kunihiko Kodera, Ji-Eun Kim, Toshitaka Tsuda, Kaoru Sato, Matthew Hitchman, Peter Haynes. Kneeling left to right: Keiichi Ishioka, Shigeo Yoden, Satoshi Noda, Eriko Nishimoto, Kohei Yoshida, Tri Wahyu Hadi, Seok-Woo Son, Masakazu Taguchi. Absent on this occasion: Masato Shiotani.

Discussions

Discussions took place on published results such as works on the QBO influence on tropical convection (Collimore *et al.*, 2003; Liess and Geller, 2012). These were observational studies that found statistically significant, but rather small, QBO influences on tropical deep convection using Outgoing Long-wave Radiation (OLR) data, Highly Reflecting Clouds (HRC) data, and International Satellite Cloud Climatology Project (ISCCP) data. They found that QBO easterly conditions favoured tropical deep convection, especially in regions where deep convection frequently occurs, but that the regions of enhanced convection were also accompanied by regions of suppressed convection. These papers suggested possible mechanisms to account for their results through vertical coupling (shown as Route 1 in **Figure 6**), such as QBO influences on Upper Troposphere/Lower Stratosphere (UTLS) temperatures and stability as well as QBO influences on the vertical shear of mean zonal wind in the UTLS. Another mechanism discussed at the workshop was QBO modulation of the tropics via the subtropical jets (Route 2 in **Figure 6**), which are possibly directly affected by the QBO (*e.g.*, Inoue *et al.*, 2011; Garfinkel and Hartmann, 2011a,b) perhaps through the Plumb-Bell meridional circulation (Plumb and Bell, 1982) or some generalization thereof.

Little progress has been made on modelling these effects, although the work by Giorgetta *et al.* (1999) did find a QBO effect on convective systems in a full general circulation model, where QBO nudging was applied. Of course, since most climate models can now self-consistently simulate the QBO, this could be re-examined. There have also been two very recent studies using cloud-resolving models to examine QBO influences on convection. One is the recent paper by Nie and Sobel (2015), which used the weak temperature gradient approximation as a simplified representation of the effect of large-scale circulation, and the other is the recent PhD dissertation by Yuan (2015). While both of these investigations point to the importance of convection interacting with the large-scale circulation, this was most apparent in the latter work that compared results with and without such interactions.

Published results have also indicated significant influence of the QBO on the number of Atlantic Hurricanes (*e.g.*, Gray, 1984) and on typhoon tracks in the Western Pacific (Ho *et al.*, 2009). It is interesting that early Atlantic Hurricane forecasts included the influence of the QBO but later ones did not. This is consistent with a recent paper by Camargo and Sobel (2010), which noted a significant correlation between the QBO and Atlantic Hurricanes before the 1980s, which seemed to disappear after that. Interestingly, Garfinkel and Hartmann (2007) pointed out that the correlations between the ENSO and QBO indices changed sign from negative to positive in the 1980s. It was pointed out that the Ho *et al.* (2009) paper is consistent with a QBO modulation of tropical rainfall in the western tropical Pacific, as suggested by Collimore *et al.* (2003), and Liess and Geller (2012), leading to a changed wave train in the tropospheric circulation, and in turn to a change in the steering circulation for typhoons.

A very exciting new result presented at the workshop was the data analysis by Yoo and Son (2016) which showed that the QBO has a significant influence on the MJO in the Northern Hemisphere (NH) winter. Their work shows that the MJO amplitude is substantially greater under QBO-easterly (E-QBO) conditions. **Figure 7** illustrates the standard deviation of MJO-filtered OLR for all NH winters (top), and the anomalies of this standard deviation for QBO westerly (W-QBO) phase (middle), and those for E-QBO phase (bottom). Note that the E-QBO anomalies are positive and the W-QBO anomalies are negative, and the QBO-related MJO anomalies range roughly ±10% of the climatology. Correlations between the OLR MJO Index (OMI) and mean zonal winds in the lower stratosphere are largest during NH winter months (-0.56 at 70hPa, and -0.59 at 50hPa), which are much larger than the ENSO/OMI correlations. Perhaps these new results are consistent with the QBO enhancing organised convection systems, as is suggested by Liess and Geller (2012), and recent cloud-resolving modelling results. However, more work is needed in this latter area.

Marshall *et al.* (2016) showed that the predictability of the MJO is enhanced under E-QBO phase, not only because forecasts initialised with stronger MJO events have greater skill, but also because the MJO events during E-QBO phases are more persistent compared to those of similar initial amplitude during W-QBO phases. This result has implications for global sub-seasonal to seasonal predictions. Multi-week forecast outputs from the Sub-seasonal to Seasonal (S2S) Prediction Project (**www.s2sprediction.net**) could be used for the application of extended-range predictability studies of the stratosphere-troposphere coupled system in the tropics regulated by the QBO.

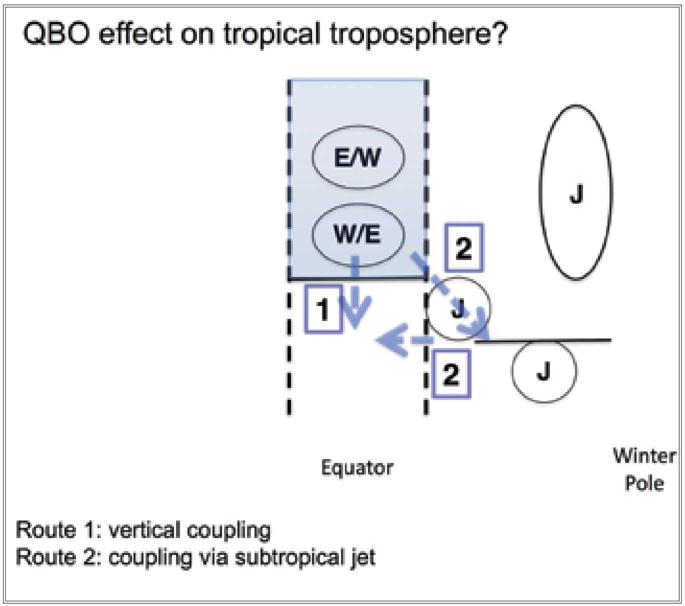

Figure 6: Illustration of two routes through which the equatorial QBO could influence the tropical troposphere. (Figure courtesy Haynes, 2016; *unpublished*).

There are other stratospheric influences on the tropics for which these QBO results have implications. One is the influence of stratospheric cooling trends on Atlantic hurricane activity (Emanuel *et al.*, 2013). Another is the influence of SSWs, since decreasing stratospheric temperatures in the tropical lower stratosphere have been shown to accompany warming at higher latitudes. Thus, as far as the tropical UTLS is concerned, its response to an SSW is similar to its response during the E-QBO phase (*e.g.*, Eguchi and Kodera, 2010; Kodera *et al.*, 2015).

Other topics presented at the workshop included new SMILES (Superconducting Submillimeter-Wave Limb Emission Sounder) observations (Sakazaki *et al.*, 2013), modulation of gravity wave characteristics as observed by the AIRS (Atmospheric Infrared Sounder) instrument (Sato *et al.*, 2016; Tsuchiya *et al.*, 2016); high vertical resolution temperature profiles from COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) full-spectrum inversion (Noersomadi and Tsuda, 2016); and vertical profiles of moisture, cirrus clouds, and chemical composition (Jensen *et al.*, 2015) from the NASA ATTREX (Airborne Tropical Tropopause Experiment) campaign.

There were discussions of the theoretical background of the results discussed (*e.g.*, Haynes *et al.*, 1991; Holton *et al.*, 1995), as well as some studies using a new formulation of 3-D diagnostics for wave-mean flow interactions

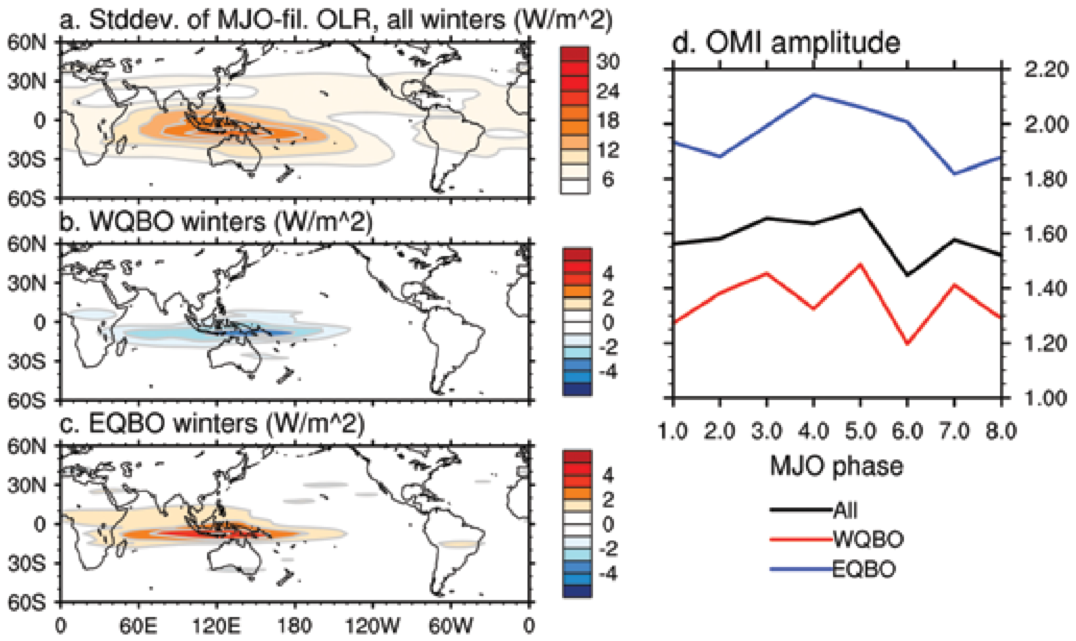

Figure 7: (a) The standard deviation of wintertime MJO-filtered OLR for all NH winters, where the MJO filtering retrieves eastward propagating wave numbers 1–5 and periods of 20–100 days. (b, c) As in (a) but for anomalies of the W-, and E-QBO winters, respectively. (d) OMI amplitude composites taken for eight MJO phases of all (black), W-QBO (red), and E-QBO (blue) winters with active MJOs. (Figure from Yoo and Son, 2016).

(*e.g.*, Kinoshita and Sato, 2014). There was also discussion about using a simplified model of the stratosphere-troposphere coupled system in the tropics (Nishimoto *et al.*, 2016), in which a QBO-like oscillation exists throughout the stratosphere and troposphere as a result of convective and gravity-wave momentum transports.

Finally, there was discussion about how the new activity might fit together with the FISAPS (Fine Scale Atmospheric Processes and Structures) activity (**www.sparc-climate.org/activities/fine-scale-processes**), as well as with the proposed new Equatorial MU Radar (**www.rish.kyoto-u.ac.jp/ear/index-e.html**) and the Years of the Maritime Continent for 2017-19 (**YMC; www.bmkg.go.id/ymc**).

Deliverables

The group envisioned that the new SPARC activity on Stratospheric and Tropospheric Influences On Tropical Convective Systems (SATIO-TCS) would have the following near-term deliverables:

1. A review paper on stratosphere-troposphere dynamical coupling in the tropics (based on this workshop) will be submitted to the Journal of the Meteorological society of Japan or the Bulletin of the American Meteorological Society;
2. Workshops and/or conferences on stratosphere-troposphere dynamical coupling in the tropics will be held in Kyoto in 2017 and 2020, with a report article or a special journal issue or section;
3. Results stemming from the collaborative research could lead to improved tropical predictions, and contribute to the WCRP Grand Challenge on near-term predictions;
4. Capacity building through the South-East Asian School on Tropical Atmospheric Science (SEASTAS) in association with the YMC project.

The proposal has been revised and approved as a SPARC emerging activity in the 24th Scientific Steering Group meeting. Anyone interested in getting involved is more than welcome to do so. Please visit the SPARC website for more details and contact the activity leaders: **www.sparc-climate.org/activities/emerging-activities/#c1880.**

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Report on the SPARC Gravity Wave Symposium
15-20 May 2016, Pennsylvania State University, United States

Fuqing Zhang[1]**, Joan Alexander**[2]**, and Kaoru Sato**[3]

[1]Pennsylvania State University, State College, USA, **fzhang@psu.edu**, [2]Northwest Research Associates, Boulder, USA, [3]Tokyo University, Tokyo, Japan

The SPARC gravity wave symposium is a continuation of a series of successful similar meetings held every five years since 1986. The 2016 SPARC symposium co-sponsored by the US National Science Foundation took place at the Pennsylvania State University, United States, from 15-20 May 2016. Approximately 100 scientists (~50 early career scientists) from more than 10 countries attended the 4.5-day symposium. Local logistic support was provided by the Pennsylvania State University's Center for Advanced Data Assimilation and Predictability Techniques coordinated through Dandan Tao. The major theme of this symposium was on the "*sources, and effects on weather and climate of atmospheric gravity waves*." Some particular emphases were the dynamics and sources of gravity waves in the troposphere including but not limited to convection, jet/fronts, and orography. More specifically, there were five thematic topics:

1. Observations and sources of gravity waves: jet, convection, and topography;
2. Theoretical advances in understanding gravity wave processes;
3. Gravity wave drag parameterization;
4. Gravity wave impacts on turbulence, energy spectra, convection and clouds;
5. Gravity wave impacts on general circulation and climate.

The plenary talk was given by **Louis Uccellini**, Director of the United States National Weather Service entitled "Historical perspective on the research and operational applications of weather-significant gravity waves". The historical overview started from the original Rossby-Cahn geostrophic adjustment theory in the late 1930s and 1940s, to the first link of surface pressure pulsations to gravity waves during severe weather (thunderstorms), followed by surface mesoscale analysis of such pressure jumps and theoretical framework in the 1950s. After decades of hiatus, there was renewed research in weather-significant gravity waves from the 1970s into the 1980s, culminating with a seminal overview by Uccellini and Koch (1987) that proposed a conceptual model of gravity wave generation by unbalanced flow from atmospheric jets. This keynote talk concluded by stressing the importance of gravity waves to weather (in particular convection), and the demand for further research in this area, the opportunities of detecting gravity waves offered by recently enabled high-resolution automatic surface mesonet stations, and the need for operational forecasters to account for gravity waves in forecasts and warnings. The significance of gravity waves on weather was further presented in invited talks that reviewed the two-way coupling of gravity waves and moist convection (**Steven Koch**), and the hazardous weather associated with the passage of large-amplitude inertia gravity waves (**Anton Seimon**).

Continuous progress has been achieved in the understanding and characterisation of gravity waves generated from mid-latitude baroclinic jet-front systems using idealized mesoscale model simulations beyond the coarse-resolution hemispheric modeling study of O'Sullivan and Dunkerton (1995) and the high-resolution multi-nested study of Zhang (2004), in particular on the impact of surface fronts on gravity wave initiation (**Hye-Yeong Chun** and **Young-Ha Kim**) and importance of moist processes in gravity wave generation and impacts in baroclinic jet-front systems (**Junhong Wei** and **Fuqing Zhang**). A theoretical framework presented by **Christoph Zülicke** showed the promise of a new non-orographic gravity-wave source parameterisation that includes the sources from convection, jets, and fronts without tuning constants.

The theme on the "significance of gravity waves to weather" was continued in the session focusing on the impact of gravity waves on atmospheric turbulence and energy spectra. The session started with two invited talks, one on using convection-permitting simulations to examine the crucial role of organised convection and multiscale gravity waves in "clear-air turbulence" spanning diverse meteorological settings (**Stan Trier**), and another on the UK Met Office's new diagnostic approach to forecasting mountain wave-induced clear air turbulence. There is renewed interest in understanding the contribution and significance of gravity waves in atmospheric energy spectra, as demonstrated by a new wave-vortex decomposition method (**Oliver Bühler**), its application to aircraft measurements (**Joern Callies**), and spectral energy budget analysis on the joined role of gravity waves and convection to the -5/3 energy spectral slope, which can also have significant implications for atmospheric predictability (**Qiang Sun**).

The significance of tropical and subtropical convection-generated gravity waves to the general circulation has long been studied and recognised. This symposium featured a few invited talks on this thematic area, one on convectively-coupled gravity waves in global models versus observations (**Stefan Tulich**), one on convectively-generated diurnal gravity waves on the offshore rainfall maximum over the maritime continent (**Todd Lane**), and another on the observational analysis of gravity and Kelvin wave activities in the tropical lower stratosphere (**Thomas Birner**). Other contributed talks discussed the characteristics, propagation and impacts of convectively-generated gravity waves over the Monsoon region (**Min-Jee Kang** and **Brentha Thurairajah**) as well as the modulation of subtropical stratospheric gravity waves by equatorial convection (**Naftali Cohen**). Also discussed were the impacts of Kelvin waves on Madden Julian Oscillation (MJO) convection and cirrus clouds (**Richard Johnson**) and the coupling between the lower and upper atmosphere via convectively-generated gravity waves (**Jia Yue**). Gravity waves also influence cirrus microphysical processes as presented in an invited talk (**Eric Jensen**) and a contributed talk (**Ji-Eun Kim**).

Significant advances in the theory and methodology of atmospheric gravity waves were reported. This included two invited talks: one on the interaction between mesoscale waves and synoptic-scale flow analysed using a new multi-scale asymptotic analysis including both the tropospheric regime of weak stratification and the stratospheric regime of moderately strong stratification (**Ulrich Achatz**), and the other on the relationship between gravity wave momentum fluxes and background wind speed which is likely due to both the colocation of the stratospheric jet with tropospheric sources and lateral propagation into regions of stronger winds (**Riwal Plougonven**). Contributed talks included a new theory for downslope windstorms and trapped mountain waves (**Francois Lott**), the relative importance of the boundary layer and the stratosphere in the dissipation of trapped lee waves (**Dale Durran**), important local and global changes to the thermosphere from the dissipation of convection-generated gravity waves (**Sharon Vadas**), a weakly non-linear theory for large-amplitude gravity waves near a breaking level facing non-uniform stratification (**Mark Schlutow**), an investigation of gravity wave transmission and reflection dynamics due to atmospheric inversion layers and instability (**Brian Laughman**), and the impact of tropopause properties on gravity waves from realistic case studies (**Vera Bense**). Other contributed talks included theoretical studies from idealised frameworks that examined gravity wave emission and propagation in differentially heated rotating annulus experiments (**Steffen Hien**), generation and impact of gravity waves from dipoles (**Norihiko Sugimoto**), direct numerical simulations of mixing and instability characteristics in the middle atmosphere (**Ling Wang**), the numerical implementation of a fully coupled gravity-wave ray tracer in atmospheric models (**Gergely Bölöni**), and the use of 4-D ray tracing to investigate the interaction between gravity waves and solar tides (**Bruno Ribstein**).

Continuous progress has been made in gravity wave characterisation through long-range super-pressure balloon flights in the tropical and polar stratosphere (**Albert Herzog**). Improvements to the retrieval of momentum fluxes for short period waves (<20 minutes) were reported by combining these data with high-precision GPS positioning information (**Robert Vincent**). The super-pressure balloon measurements have also been used to examine Lagrangian temperature and vertical wind fluctuations that impact chemistry and microphysics in polar stratospheric clouds and cirrus clouds in the tropical tropopause layer (**Aurelien Podglajen**). These data provide local and global-scale measures of gravity wave momentum fluxes that have been used to validate gravity waves appearing in ECMWF analyses (**Valerian Jewtoukoff**). Results show that while the geographical distribution of gravity waves in the analysis is consistent with the observations, the momentum fluxes are generally smaller by a factor of five.

Exciting investigations of inertia-gravity waves in the Antarctic troposphere, stratosphere, and mesosphere observed by the first full-system operation of the PANSY radar (a VHF clear-air Doppler radar) at Syowa Station was reported; with the aid of a high-resolution model, it was shown that gravity waves with a half-day period are likely generated from the polar-night jet and/or tropopause jet (**Ryosuke Shibuya**, **Kaoru Sato**). Mesospheric gravity waves are seen propagating mostly south eastward relative to the wind in summer, and long period gravity waves (3 hours-1day) contribute most of the momentum flux at these altitudes. The measurements have also revealed common occurrences of double tropopause events caused by inertia-gravity waves.

Though limited in spatial and temporal resolution, satellite measurements can provide the most holistic view with global coverage of atmospheric gravity waves that can be used to constrain gravity wave parameterisations and potential gravity wave responses to changing climate through long-term observation (**Jie Gong**). An analysis of AIRS high-resolution temperature retrievals showed that momentum flux vectors generally point opposite to the mean wind, *i.e.*, eastward in the summer subtropical region and westward in the polar night jet region, even when the jet is distorted by planetary wave meanders (**Manfred Ern**). Combining multiple types of satellite observations such as MLS on Aura and AIRS on Aqua is found to improve the estimation of momentum flux vectors associated with gravity wave events visible in both measurements (**Corwin Wright**). Better characterisation of diurnal variations of gravity waves is one benefit to be gained by combining IASI and AIRS measurements (**Lars Hoffman**). Satellite observations from HIRDLS were compared to gravity waves in the ECMWF analysis to provide insight into causes of vertical variations seen in HIRDLS data (**Peter Pressue**). Based on AIRS observations spanning eight years, gravity waves in the stratosphere were found to display significant MJO and El Niño/ Southern Oscillation (ENSO) variations (**Kaoru Sato**).

Field measurements and model studies associated with the DEEPWAVE Campaign have produced a variety of exciting new results (**David Fritts**). The campaign explored gravity waves from the surface to the mesosphere-lower-thermosphere region utilising airborne and ground-based measurements over and around New Zealand. Aircraft data from flights over the mountains showed that the Eliassen-Palm relation between energy and momentum flux is well satisfied. An interesting downshift of horizontal wavelength was noted in strong gravity wave events (**Ron Smith**). Characteristics of non-orographic gravity waves were observed over the Southern Ocean and stratospheric sources are suggested from ECMWF analysis (**Andreas Doernbrack**). Analysis of rotary spectra for radiosonde observations showed stratospheric gravity waves with near-inertial intrinsic frequencies that mainly propagate energy upward suggesting tropospheric sources (**Sonja Gisinger**). Airborne Rayleigh lidar and Na lidar measurements show interesting features of mountain wave propagation into the stratosphere and mesosphere (**Biff Williams**). Ground-based Rayleigh/ Raman lidar measurements during DEEPWAVE were interpreted in terms of mountain wave propagation and secondary generation of gravity waves associated with breaking mountain waves (**Bernd Kaifler**).

Dynamics and predictability of gravity waves observed during DEEPWAVE were examined using the COAMPS adjoint modeling system. Sensitive regions for predictability were the jet, fronts, and convection. Large uncertainties were seen in momentum fluxes of mountain waves (**Jim Doyle**). Two Advanced Mesospheric Temperature Mappers (AMTM) were deployed for DEEPWAVE: one ground-based and the other airborne, observing at the height of about 87km. High correlation in gravity wave features between AMTM results and other observations and model data was highlighted. Strong breaking MW events together with small-scale ripples were also reported (**Mike Taylor**). Water vapour and ozone transport across the tropopause was also inferred from DEEPWAVE airborne measurements. Tracer-tracer-correlation analysis provided evidence that strong mountain waves caused strong mixing (**Romy Schlage**). Rayleigh lidar measurements conducted over New Zealand suggest that intense cross mountain flow over the Southern Alps excited large amplitude mountain waves, and the co-location of the polar and subtropical jets allowed for almost unhindered propagation of the mountain waves into the stratosphere (**Benedikt Ehard**).

Other field measurements were obtained during the South Georgia Wave Experiment (SG-WEX), which included observations by two radiosonde campaigns, COSMIC, a meteor radar, and high-resolution modelling at South Georgia (54.5°S 37°W) in the South Atlantic as a gravity wave hotspot. Differences in gravity wave characteristics between two seasons were highlighted (**Nicholas Mitchell**).

As computing power has increased with time, global models that explicitly resolve gravity waves are becoming more common, however the simulations generally remain limited in one aspect or another (**Joan Alexander**, **Han-li Liu**, **Erich Becker**, **Laura Holt**, **Sebastian Borchert**, **Nedjeljka Zagar**, **Ayrton Zadra**). Analogous to issues with resolving clouds in models, these might be better called gravity-wave-permitting models since they resolve only portions of the full spectrum. Some simulations extend to deep altitudes in order to study gravity wave dissipation throughout the middle atmosphere and/or into the thermosphere, but at the expense of limited horizontal and/or vertical resolution. Many modelling centres are experimenting with high horizontal resolution but without increasing vertical resolution. These various resolution choices, as well as the model's numerical scheme, can give rise to excessive dissipation that prevents the resolved waves from driving the circulation in a realistic way. Further, the sources of the waves may not be resolved. An example is convection, which is known to be an important gravity wave source. The global gravity-wave-permitting models are generally still dependent on convection parameterisation schemes and topography may also be poorly resolved, which limits the realism of gravity wave sources. Thus many of these models remain dependent on parameterisation schemes to maintain realistic zonal mean wind and temperature structure, and scaling down the grid spacing does not necessarily allow a proportional decrease in the dependence on parameterised gravity wave drag. Despite these limitations, such gravity-wave-permitting model studies have provided many new insights, including (a) the importance of meridional wave propagation for the latitude/height dependence of drag in the middle atmosphere, (b) geographical and seasonal variations in waves from different sources, and (c) global variations in intermittency in gravity wave fluxes and (d) nonlinear interactions of gravity waves with the larger-scale circulations like the tides.

Figure 8: Participants at the SPARC gravity waves symposium held in May 2016.

Very high-resolution modelling remains impractical for long-term climate studies, and interest remains in improving methods for parameterisation of gravity wave drag aimed at reducing modelled wind and temperature biases (**Anne Smith**, **Hyun-Joo Choi**, **Stephen Eckermann**, **Thai Trinh**, **Andrew Bushell**, **Alvaro de la Camara**, **Rolando Garcia**, **Manuel Pulido/ Guillermo Sheffler**, **Christopher Kruse**). Various approaches include tuning of existing orographic and non-orographic wave schemes, inclusion of new specialised wave source schemes, and using observations of gravity waves to provide new constraints for parameter choices within these schemes. In particular, the inclusion of gravity wave amplitude intermittency through stochastic parameterisation methods shows promise for improving model biases at levels from the upper troposphere through the middle atmosphere.

Gravity wave drag not only reduces wind and temperature biases in models, but it also contributes to driving the Brewer-Dobson circulation that controls the transport of trace gases like ozone and water vapour in the stratosphere (**Claudia Stephan**, **Ed Gerber**). Climate models predict that this circulation will increase with climate change in the future, however inter-comparisons show the models do not agree on the relative importance of gravity waves to the total wave drag, nor do they agree on what is driving the trend in the circulation. The differences among models are likely due to the simple nature and different tunings of the parameterisation schemes rather than any fundamental gap in understanding.

The symposium concluded with a dedicated special session led by **Joan Alexander** and **Kaoru Sato** on the SPARC Gravity Wave Activity through open discussions that involved all symposium participants. Specific attentions was given to topics that may particularly benefit from the sort of international coordination SPARC promotes, which included (1) a new focus on the resolvability of gravity waves for global high-resolution modelling, and (2) a renewed focus on gaining a quantitative understanding of gravity waves emitted from various sources. Also discussed was a potential future gravity wave field campaign that seeks to understand the detailed source mechanisms and impacts of gravity waves over a large continent. This future field campaign would help to better understand the impacts of gravity waves on both weather and climate, as well as their modelling and predictability in various resolution regional and global models.

The Large-Scale Atmospheric Circulation: Confronting Model Biases and Uncovering Mechanisms SPARC/DynVar and S-RIP Workshop

Edwin Gerber[1], Alexey Karpechko[2], Elisa Manzini[3], Daniela Domeisen[4], Chaim Garfinkel[5], Kevin Grise[6], Maddalen Iza[7], Alison Ming[8], Michael Sigmond[9], Isla Simpson[10], Jacob Smith[8], and Nicholas Tyrrell[2]

[1]New York University, New York, USA, **gerber@cims.nyu.edu**, [2]Finnish Meteorological Institute, Helsinki, Finland, [3]Max-Planck Institut für Meteorologie, Hamburg, Germany, [4]GEOMAR, Kiel, Germany, [5]Hebrew University of Jerusalem, Jerusalem, Israel, [6]University of Virginia, Charlottesville, USA, [7]Universidad Complutense de Madrid, Madrid, Spain, [8]University of Cambridge, Cambridge, UK, [9]Canadian Centre for Climate Modelling and Analysis, Victoria, Canada, [10]National Center for Atmospheric Research, Boulder, USA.

Persistent biases in forecast and climate prediction systems hinder our ability to model circulation changes, both in operational forecasts and in climate projections. To foster the advancement of modelling the stratosphere-troposphere system, a workshop on "The Large-Scale Atmospheric Circulation: Confronting Model Biases and Uncovering Mechanisms" was held in Helsinki, Finland, from 6-10 June 2016. The workshop, jointly organized by the SPARC DynVar and S-RIP activities, was kindly hosted by the Finnish Meteorological Institute (FMI). We would first and foremost like to acknowledge the great hospitality of FMI and express special thanks to the many people at FMI who made the workshop possible. In addition, funding from WCRP/SPARC and the US NSF allowed the participation of a number of early career scientists. The workshop attracted 74 participants from 16 countries (**Figure 9**) and consisted of 60 oral presentation and 17 posters, with additional time dedicated to discussion.

A key goal of the workshop was to connect the wider climate research community with The Dynamics and Variability Model Intercomparison Project (DynVarMIP; Gerber and Manzini 2016), which will enable a more rigorous investigation of atmospheric circulation in the Coupled Model Intercomparison Project Phase 6 (CMIP6). The workshop was also instrumental in the revision of the DynVarMIP data request for CMIP6. Briefly, the DynVarMIP primarily addresses questions on the origin and consequences of systematic model biases in the context of atmospheric dynamics and asks for diagnostics to (1) characterize daily variability in the troposphere and lower stratosphere and (2) quantify transport of momentum and heat by resolved and unresolved (*i.e.* parameterized) processes in the atmosphere. For the specific variables, model levels, and diagnostics requested please see Gerber and Manzini (2016).

The DynVar meeting was held in conjunction with a sub-set of the SPARC Reanalysis Intercomparison Project (S-RIP), as two themes from this project are highly relevant to the DynVarMIP: the Brewer-Dobson Circulation and Stratosphere-Troposphere Coupling. It is hoped that the DynVarMIP diagnostics will allow us to more carefully compare CMIP6 models against atmospheric reanalyses. An important element of the discussion concerned the classification of Sudden Stratospheric Warmings (SSW) across reanalyses and models.

Thanks to the action of **Alison Ming**, the workshop was tweeted

Figure 9: Participants at the joint SPARC/DynVar and S-RIP Workshop held on 6-10 June 2016 in Helsinki, Finland.

live by @wcrp_sparc. All the original posts are accessible at: **https://twitter.com/WCRP_SPARC**, and combined into an illustrated narrative with "storify" at **https://storify.com/alisonming/sparc-dynvar-2016-conference**. (For those of us less in the know, "storify" provides a means of grouping and archiving the social media activity relating to a conference or event!) The twitter activity was a dissemination success, with ~9000 users seeing the tweets during the 5 day period of the workshop. Each tweet received about 100 views, and the invited speakers were more popular with over 200 views. About a dozen people attending the workshop were on twitter and interacted with @wcrp_sparc. Given the availability of the workshop storify – which provides a nice summary of the presentations – in the remainder of this newsletter report we highlight the key points of discussions and plans for the future.

Discussion time was structured into four breakout groups: (1) Basic research and model development: A hierarchy of models (Rapporteurs: **Chaim Garfinkel** and **Maddalen Iza**), (2) Process oriented approaches to evaluating and reducing model biases (Rapporteurs: **Isla Simpson** and **Jacob Smith**), (3) The circulation response to external forcing (Rapporteurs: **Kevin Grise** and **Michael Sigmond**), and (4) Predictability across timescales: Subseasonal to decadal (**Daniela Domeisen** and **Nicholas Tyrrell**).

Basic research and model development: a hierarchy of models

The breakout group on connecting basic research and model development discussed the various uses of a hierarchy of idealized models. Historically, idealized models have been used for two previously disconnected purposes: (1) to verify model components and (2) to answer open scientific questions in a simplified framework. Whether these two purposes can occasionally be combined synergistically was discussed, and in particular whether the research community using idealized models can assist the development of comprehensive models. Several possible and inter-related ways forward were considered.

First, while cloud parameterizations generally receive most attention, many other parameterizations in climate models are also poorly constrained, *e.g.* gravity waves and surface drag parameterizations. These parameterizations are generally undocumented in multi-model ensemble exercises such as CMIP, in spite of a large body of literature demonstrating substantial sensitivity of atmospheric circulation to the parameterizations of dynamical processes. This state of affairs motivates a more systematic exploration of the atmospheric response to changes in these parameterizations of atmospheric momentum transfer in idealized models, the rationale being that the responses in idealized models could be connected to those of the comprehensive models which use a similar scheme. It may also help elucidate the anticipated results on the atmospheric momentum budget in reality and in CMIP6 models, where for the first time diagnostic output of the momentum budget will be made available through DynVarMIP.

Second, models from different modelling centres simulate qualitatively divergent climates on an aquaplanet (*e.g.*, double *vs.* single ITCZ, or circulation response to doubled CO_2). It is possible that a model configuration simpler than a full aquaplanet, but more complex than the workhorse "Held-Suarez dry dynamical core" model (Held and Suarez, 1994) could be very helpful in sorting out the differences related to parameterizations of atmospheric momentum transfer. The idealized modelling community could help to identify where the additional rung(s) on the model hierarchy should be placed, and DynVar could provide a platform to discuss and coordinate joint efforts across modelling centres and the idealized modelling community.

Finally, on a related note, it may be easier to understand the circulation response to climate in idealized models than in comprehensive models. It is recommended to perform CMIP6 DECK (Eyring *et al.*, 2016) experiments (or the equivalent, for models with simplified radiative transfer capability) with a wide range of idealized models in order to understand the origins of diverse responses in comprehensive models.

Process oriented approaches to evaluating and reducing model biases

A continuing challenge in global climate modelling and atmospheric dynamics is to ensure that our models represent the real atmosphere with fidelity. As with the first discussion group, the topic of parameterization came to the fore: we still rely on sub-grid scale parameterization schemes to represent many important physical processes, and the behaviour of these schemes is often governed by parameters that are not well constrained by observations. It is thus possible that a realistic climate could be obtained for the wrong reasons. A detailed process based understanding of the behaviour of our models - and how they compare with the real world - could help us identify compensating errors.

In this respect, our efforts to assess model fidelity are hampered by the short observational record that is available for comparison. The prevalence of internal atmospheric variability can lead to difficulty in assessing the real world climatology, let alone long-term trends. Certainly, continued and improved observations of physical processes of our atmosphere are vital. But in the mean time, we can continue to focus our attention on aspects that are observationally constrained, as well as exploit this internal atmospheric variability to explore the relative roles of our physical parameterizations and resolved atmospheric dynamics in producing it. The high time-frequency fields as well as tendencies from parameterized processes that are requested from CMIP6 within DynVarMIP will be key to this effort and will allow, for the first time, a multi-model comparison of processes that contribute to internal variability, throughout the troposphere and stratosphere, on short timescales. Even for aspects that are not well constrained by observations, there is still much to be gained by detailed process-oriented understanding of a model's behaviour.

There are still many climatological aspects of the circulation that need improving in models, such as the tilt of the North Atlantic jet, the location of the Southern Hemisphere westerlies or the representation of the inter-tropical convergence zone. Not only will the forthcoming DynVarMIP project aid in the interpretation of these long-standing model biases, but it will also allow us to assess to what extent models agree on the processes that contribute to important aspects of atmospheric variability, such as blocking events, the quasi-biennial oscillation (QBO), and sudden stratospheric warmings (SSWs). The lack of high time-frequency and vertical resolution data has precluded a multi-model intercomparison of these aspects of the circulation until now, and this will surely open up new research focus areas when it comes to model evaluation.

The circulation response to external forcing

The breakout group on the circulation response to external forcing generally agreed that, while in many cases a consensus has been reached on the sign of the atmospheric circulation's response to external forcing (such as stratospheric ozone depletion or increasing greenhouse gases), the responsible mechanisms remain poorly understood. Progress is often inhibited by the lack of available model output, especially that relevant for stratospheric circulation. To isolate the mechanisms responsible for the circulation response, it was recommended that CMIP6 models contributing to DynVarMIP include output of additional dynamical variables from idealized simulations, such as those that impose external forcings abruptly (abrupt4xCO_2) or linearly (1pctCO_2), impose external forcings individually (DAMIP and VolMIP runs), or fix sea surface temperatures uniformly in all models (amip4xCO_2, amip4K, amipFuture). These recommendations were communicated to the DynVarMIP leadership, who made the suggested diagnostics a part of the DynVarMIP formal request (Gerber and Manzini, 2016).

One topic of conversation in the breakout group was centred on why models have different circulation responses to the same amount of external forcing. Discussion focused on whether or not it is feasible to define a "circulation sensitivity" metric for global climate models, as a dynamical equivalent of climate sensitivity. It was concluded that, unlike climate sensitivity, circulation sensitivity cannot be quantified by one or two metrics, but that a whole range of metrics should be considered. It was recommended that DynVar coordinate a circulation assessment paper that catagorises the sensitivity of global climate models to a variety of external forcings, focusing on future changes and those in the stratospheric circulation (such as the Brewer-Dobson circulation) to avoid overlap with other community efforts. Additionally, such a paper could define a timescale of emergence for these circulation changes, identifying a timeframe when the forced signal would exceed some threshold of natural variability.

Predictability across timescales: sub-seasonal to decadal

The discussion first clarified the different predictability timescales and the associated phenomena: sub-seasonal to seasonal (S2S, 2 weeks - 3 months), intra-annual (6 - 12 months) and inter-annual to decadal (2 - 10 years). On S2S timescales, the focus lies on the prediction and impacts of SSW events. On intra-annual to inter-annual timescales, processes such as ENSO, the QBO, the solar cycle, sea ice, or continental snow cover, have been found to provide predictability. The key open questions for the stratosphere-troposphere coupling community are to assess (and understand) the impact of these processes on the stratosphere and the degree to which they couple to the surface.

The second part of the discussion brought together existing collaborative activities related to the stratosphere and predictability, and recognized the role of DynVar in linking them. Represented at the workshop were, for instance, SNAP, the "Stratospheric Network for the Assessment of Predictability", which coordinates projects for predictability involving stratospheric processes and analysis of the S2S database of sub-seasonal to seasonal model ensemble forecasts (**Andrew Charlton-Perez**) and SHFP, the Stratospheric Historical Forecast Project, a WCRP database of model hindcasts from seasonal prediction models for both high and low top models (**Amy Butler**), and QBOi, a SPARC modelling initiative on the representation of the quasi-biennial oscillation in climate models (**Scott Osprey**).

The main outcome of the discussion was an increased focus on the predictability of tropospheric anomalies related to stratospheric forcing, as well as the applications of S2S and longer-term forecasts related to the stratosphere in collaboration with the stakeholder community. The goal lies in answering the question of which mechanisms have been identified to potentially contribute to predictability relating to stratospheric processes, and if predictability can indeed be shown on the above-mentioned timescales. A separate outcome of the predictability focus within the SPARC community is a forthcoming book chapter on stratosphere-troposphere coupling led by Andrew Charlton-Perez as part of the SNAP and S2S projects.

Summary and Plans for the future

The presentations and discussions in Helsinki demonstrate a growing research community interested in the role of atmospheric dynamics in the predictability of the climate system and the circulation response to anthropogenic forcing. And the topic is not merely academic: local manifestations of climate change are strongly controlled by the large-scale circulation response, making "regional climate a global problem," in the words of **Geoff Vallis** – the opening speaker of the meeting.

Presentations and discussion at the workshop greatly influenced the final plan for DynVarMIP. As an endorsed model intercomparison project within the CMIP6, this effort will be moving forward over the next four years. To ensure that these diagnostics are fully investigated and exploited, another workshop is tentatively set for 2019 (potentially jointly with another SPARC activity), at a point where we should have access to the bulk of the data.

The future of the DynVar Activity remains more open. The activity has reached its original goals: to ensure a more realistic representation of the stratosphere in climate prediction models and to get the stratospheric dynamics community actively involved in the development and assessment of climate projections. Is it thus time to move into new territory – for example, a greater emphasis on the troposphere – with renewed focus and new leadership. This change is indeed already happening. At the Helsinki workshop, the activity brought together a community of atmospheric modellers and theoreticians, a "research forum" held together by a common interest in atmospheric dynamics and their role in climate. To foster this growth and momentum, another option could be to reconsider the activity as a more long-standing working group on dynamics and variability within SPARC.

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Update on SOLARIS-HEPPA Activities: New Working Groups

Katja Matthes[1,2], Bernd Funke[3], Cora Randall[4], and Pekka Verronen[5]

[1]GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany, **kmatthes@geomar.de**, [2]Christian-Albrechts Universität zu Kiel, Kiel, Germany, [3]Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain, [4]University of Colorado, Boulder, CO, USA, [5]Finnish Meteorological Institute, Helsinki, Finland

The SOLARIS-HEPPA (SOLAR Influences for SPARC) activity met twice during the last year. A SOLARIS-HEPPA working group meeting with approximately 31 (+4 remote) participants took place at the Laboratory for Atmospheric and Space Physics (LASP) in Boulder, Colorado, USA, in November 2015 (**Figure 10**; **http://solarisheppa.geomar.de/boulder2015**). A special focus was on the discussion of the solar forcing dataset for CMIP6, which is now published in the CMIP6 special issue (Matthes *et al.*, 2016). The 6th HEPPA-SOLARIS workshop with 57 participants took place at the Finish Meteorological Institute (FMI) in Helsinki, Finland, from 13-17 June 2016 (**http://heppa-solaris-2016.fmi.fi/**) (**Figure 11**). The workshop lasted for a whole week and included ample discussion time after talks and posters. Several splinter meetings took place, of which the most important decisions and guidelines for future activities will be summarized here.

Based on the experience gained during the coordinated analysis of solar (irradiance) signals in the Coupled Model Intercomparison Project – 5 (CMIP5) assessment, where three joint publications resulted (Mitchell *et al.*, 2015; Hood *et al.*, 2015; Misios *et al.*, 2016), the planning of new working groups to systematically analyse the CCMI experiments with respect to solar (irradiance and particle) forcing was started in Boulder and further discussed in Helsinki. This analysis will be carried out before the coordinated analysis of the CMIP6 runs, which will not start before 2018. Besides for the comprehensive solar forcing recommendation for CMIP6, this activity will be the first joint analysis carried out by SOLARIS-HEPPA. So far, the impact of solar irradiance signals and energetic particles was analysed separately in observations and (chemistry) climate models (CCMs). However, the newly available experiments from the SPARC Chemistry Climate Model Initiative (CCMI) (Eyring *et al.*, 2013) will allow a joint evaluation of solar cycle signals with a special focus on their respective relevance for surface climate. Several outstanding questions remain, *e.g.* whether the two-year lagged signal in the North Atlantic is due to atmosphere-ocean interaction (Scaife *et al.*, 2013, Gray *et al.* 2013, Thiéblemont *et al.*, 2015) or whether energetic particles could also play a role (*e.g.*, Seppälä *et al.*, 2009, Calisto *et al.*, 2011, Rozanov *et al.*, 2012).

The following working groups (WGs) were defined and are described in more detail on the SOLARIS-HEPPA website (**http://solarisheppa.geomar.de/workinggroups**):

- WG1 (leads: **Ulrike Langematz** and **Gabriel Chiodo**) Stratospheric Signal: This WG will analyse the solar irradiance and particle effects on the stratosphere in both historical (1960-2010) and future (2010-2100) simulations, *i.e.* REF-C1 and REF-C2 simulations.
- WG2 (leads: **Klairie Tourpali** and **Stergios Misios**) Surface Signal: This WG will analyse the solar irradiance and particle effects on surface climate taking atmosphere-ocean coupling processes into account in both historical (1960-2010) and future (2010-2100) simulations, *i.e.* REF-C1 and REF-C2.
- WG3 (lead: **Eugene Rozanov**, **Amanda Maycock**, and **Alessandro Damiani**) Comparison with (satellite) observations: This WG will compare the observed solar signal resulting from solar irradiance and particle forcing in the specified dynamics experiments covering the satellite era from 1980-2010 (REF-C1SD).
- WG4 (leads: **Rémi Thiéblemont** and **William Ball**) Methodological Analysis: This WG will do a thorough comparison of existing statistical approaches to analyse solar signals in model and observational data. In a first step a multiple linear regression (MLR) code will be made available on the SOLARIS-HEPPA website. In a second step, the limitations of the MLR will be discussed and other (non-linear) statistical

methods will be tested for their applicability to solar signals in the atmosphere.

- WG5 (leads: **Miriam Sinnhuber** and **Hilde Nesse Tyssøy**) Medium Energy Electrons (MEE) Model-Measurement intercomparison: This WG will compare observed chemical responses to MEEs in the mesosphere with available model simulations that account for MEE ionization (*e.g.*, by including the newly available MEE parameterization for CMIP6 (Matthes *et al.*, 2016)).

The WG leaders will coordinate the analyses within their WG. If you are interested in participating in one of the WGs, please get in touch with the respective WG leaders or contact Bernd and Katja! For the internal communication of the WGs and the data and result exchange, an internal communication platform will be established (*e.g.* slack, wiki). The first results of this joint analysis will be discussed at the next SOLARIS-HEPPA working group meeting in late 2017 in Paris, France. The next joint HEPPA-SOLARIS workshop will be held in summer 2018.

Acknowledgements

We would like to thank WCRP/SPARC for its support, as well as LASP in Boulder, Colorado, the Finnish Meteorological Institute in Helsinki, SCOSTEP/VarSITI, and IAMAS/IUGG. We especially thank the local organizing committees headed by C. E. Randall in Boulder and P. T. Verronen in Helsinki for the excellent venues and organisation of the meetings.

Figure 10: Group picture of the SOLARIS-HEPPA Working Group Meeting held in Boulder, CO, USA, November 2015 (photo: LASP Boulder).

Figure 11: Group picture of the HEPPA-SOLARIS Workshop held in Helsinki, Finland, May 2016 (photo: Erkki Kyrölä).

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Workshop on Drag Processes and their Links to the Large-Scale Circulation
Reading, UK, 12-15 September 2016

[1]Irina Sandu and [2]Ayrton Zadra

[1]ECMWF, Reading, UK, **Irina.Sandu@ecmwf.int**, [2]Environement and Climate Change Canada, Toronto Canada.

The workshop on 'Drag processes and their links to the large-scale circulation', organised jointly by ECMWF, the World Climate Research Programme (WCRP) and the World Weather Research Programme (WWRP), with the support of SPARC, WMO's Working Group on Numerical Experimentation (WGNE) and the GEWEX Global Atmospheric System Studies (GASS) project, was held at ECMWF from 12-15 September 2016. Despite their importance for the large-scale circulation, to date the representation of drag processes remains a major source of uncertainty in global models. 'Drag' refers to the effects of friction on atmospheric flow caused by elements of the land surface, ocean waves, orography and the breaking of mountain-induced gravity waves.

The workshop aimed to assess the current state of our understanding of drag processes and their impact on large-scale circulation on timescales from synoptic to climate. The workshop also aimed to review how these processes are represented in global models, discuss and sharpen the research challenges to be overcome in order to achieve substantial advances in this area, foster collaborations, and stimulate further research. The idea of organizing this workshop partially stemmed from the WGNE 'Drag project', which demonstrated that the main NWP and climate models differ significantly both in the representation of total surface stress (or friction), particularly in regions with orography, and in the partitioning of surface stress among various physical processes.

The workshop attracted about 50 participants (**Figure 12**) from the main numerical weather prediction (NWP) and climate centres in Canada, France, Germany, Japan, the Netherlands, the UK, and the US, as well as from several universities. The participants included well-established scientists and early-career researchers, six of whom were funded by the WMO.

Outcomes

A broad range of scientific questions were discussed through invited talks, a poster session, and working group discussions. Three main themes were covered:

(1) theoretical aspects of drag processes and impacts of uncertainty associated with drag processes in NWP and climate models,

(2) the representation of drag in global models (parameterizations, ancillary fields such as mean and sub-grid orography *etc.*), and

(3) constraining drag processes through observations, reanalysis, and fine-scale modelling. The working groups made numerous recommendations for further research in these areas. A few examples include:

- Consolidate knowledge regarding the impacts of drag processes on large-scale circulation, *e.g.*, by reproducing results in different models, and develop a more quantitative understanding of effects of drag on aspects of circulation, such as the mean state, stationary waves, and synoptic systems. Understand what level of parameterization is required to reproduce given phenomena and whether there are processes that are currently not represented in global models.
- Strive to further understand the inter-model differences in surface stress, *e.g.*, through the following activities: a survey regarding the ancillary files, in which all centres would provide details on corresponding databases and methods as well as samples of ancillary fields; numerical experiments aiming to better define the appropriate sub-grid scales for orographic fields as a function of the model's (effective) resolution; extending the WGNE Drag project by comparing the tendencies given by the various parameterizations in regions of maximum uncertainty, and by using relevant single-column model experiments.
- Explore the use of high-resolution simulations, which can now be performed

Figure 12: Participants at the Drag Processes-workshop held in Reading, UK, in September 2016.

at resolutions of a few hundreds meters over large regions, to help understand the underlying processes contributing to orographic drag and to constrain current parameterization schemes. As surface drag cannot be observed on large scales, this type of simulation could provide a reference estimate of surface drag that would be extremely valuable for improving the parameterizations used in global models.

- Explore new methods to identify the parameterizations responsible for model errors and devise ways of optimising poorly constrained parameters that go beyond empirical tuning. These can include initial tendency diagnostics, nudging techniques, data assimilation methods, but also a more process level-based evaluation of the phenomena represented by the parameterizations (*e.g.*, waves *vs.* turbulence) or the evaluation of theoretically understood far-field responses to changes in drag.
- Make more extensive use of existing direct or indirect observations to evaluate the representation of drag processes in models. Here, examples include emerging observations of momentum fluxes, gathered either in observational campaigns or at permanent supersites, and scatterometer wind data or bulk measures of drag impacts on the circulation, such as the change in wind direction throughout the boundary layer.

The presentations from the workshop are available at: **www.ecmwf.int/en/learning/workshops-and-seminars/drag-processes-and-their-links-large-scale-circulation.**

Annotation

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Report on the SPARC QBO Workshop: The QBO and its Global Influence - Past, Present and Future
26-30 September 2016, Oxford, UK

James Anstey[1], Scott Osprey[2], Neal Butchart[3], Kevin Hamilton[4], Lesley Gray[2], Mark Baldwin[5]

[1]Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, Canada, **james.anstey@canada.ca**, [2]National Centre for Atmospheric Science, University of Oxford, UK, [3]Met Office Hadley Centre, UK, [4]International Pacific Research Center, University of Hawaii, USA, [5]Exeter University, Exeter, UK

There is no known atmospheric phenomenon with a longer horizon of predictability than the quasi-biennial oscillation (QBO) of tropical stratospheric circulation. With a mean period of about 28 months, the QBO phase can routinely be predicted at least a year in advance. This predictability arises from internal atmospheric dynamics, rather than from external forcings with long timescales, and it offers the tantalizing prospect of improved predictions for any phenomena influenced by the QBO. Observed QBO teleconnections include an apparent QBO influence on the stratospheric winter polar vortices in both hemispheres, the Madden-Julian Oscillation (MJO), and the North-Atlantic Oscillation

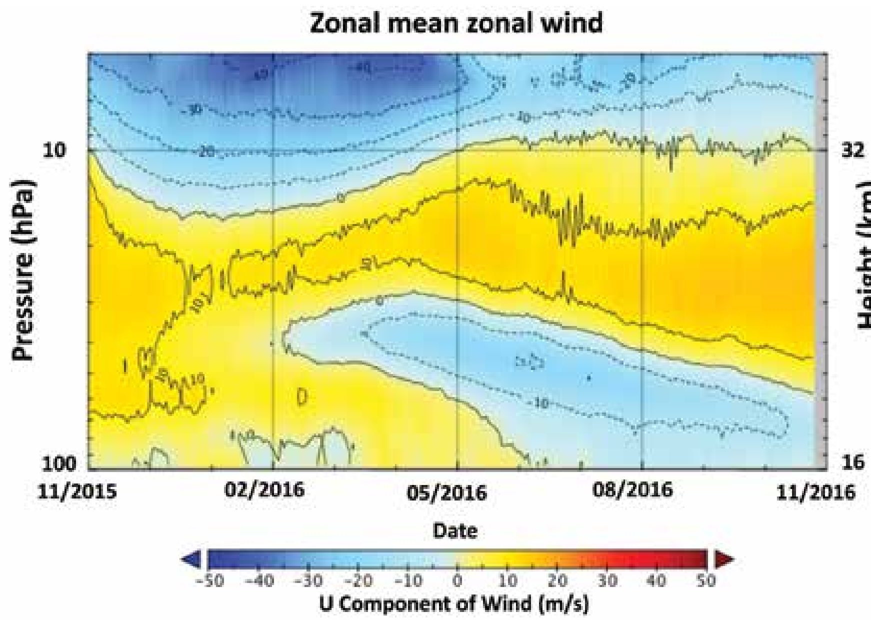

Figure 13: Vertical profile timeseries of 6-hourly zonal-mean zonal wind from the ECMWF Operational Analysis showing the recent disruption of the QBO and its recovery. Units are m/s.

(NAO). Yet the degree to which such teleconnections are real, robust, and sufficiently strong to provide useful predictive skill remains an important topic of research. Utilizing and understanding these linkages will require atmospheric models that adequately represent both the QBO and the mechanisms by which it influences other aspects of the general circulation, such as tropical deep convection.

The 2016 QBO workshop in Oxford aimed to explore these themes, and to build on the outcomes of the first QBO workshop, held in March 2015 in Victoria, BC, Canada (as reported in SPARC Newsletter No. 45). This earlier workshop was the kick-off meeting of the SPARC QBOi (QBO Initiative) activity, and its key outcome was to plan a series of coordinated Atmosphere General Circulation Model (AGCM) experiments (the “phase-one” QBOi experiments). These experiments provide a multi-model dataset that can be used to investigate the aforementioned themes. While the focus of the Victoria meeting was primarily on the QBO itself, the Oxford workshop has broadened the scope of the QBOi activity to encompass QBO impacts. Its primary outcome is a planned set of core papers analysing the phase-one QBOi experiments, which will be described in more detail below.

The phase-one experiments address the ability of AGCMs to capture the QBO in the present climate, to predict its behaviour under climate-change forcings, and to predict its evolution when initialized with observations (*i.e.* hindcasts). A goal of QBOi is to provide guidance to the wider climate community about the importance of representing the QBO and its teleconnections in global model climate projections. The phase-one experiments should also help expose and diagnose differences in the response among models that may have been tuned to produce similar present day QBO simulations. Because the QBO is well known to be sensitive to many aspects of model formulation (as will be described in more detail below), it is expected that trade-offs between compensating errors will differ among models.

The apparent fragility of the QBO in models – *i.e.* its sensitivity to many aspects of model formulation – seems to stand in stark contrast to the robust predictability of the real QBO as observed since the early 1950s. Yet midway between the Victoria and Oxford workshops, the real QBO produced a surprise. A shallow layer of equatorial easterlies appeared near 40hPa in February, in the middle of a prevailing QBO westerly phase, which subsequently deepened and descended (**Figure 13**). A casual perusal of the observed record of QBO winds shows that this event is unprecedented (**http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/**). In sharp contrast to previous experience, the 2016 disruption was completely missed by current seasonal forecasting systems. This failure indicates that the models have great difficulty capturing the full range of QBO variability, suggesting that they may be over-tuned to represent the typical behaviour of the present-day QBO. The disruption also raises the possibility that the real QBO is less robust than previously thought.

The early 2016 QBO disruption provided a unique impetus to the Oxford workshop. It was the subject of a special session on the Monday afternoon, and discussion returned to it throughout the week. Other sessions focused on teleconnections, observations and reanalyses, constituents and transport, and idealized simulations. Approximately fifty people attended (**Figure 14**), and over the five days ample time was allowed for discussion, including three breakout sessions on outstanding science questions, new experiments, and teleconnections. The teleconnections theme was further bolstered by the Oxford workshop doubling as the inaugural meeting of the new Belmont Forum JPI-Climate GOTHAM project (Globally Observed Teleconnections in Hierarchies of Atmospheric Models), which involves a number of the QBOi modelling groups (Belmont Forum: **http://www.igfagcr.org/**, Joint Programming Initiative "Connecting Climate Knowledge for Europe" (JPI Climate): **http://www.jpi-climate.eu/home**).

Teleconnections

The workshop began with a keynote talk by **Peter Haynes** reviewing current understanding of the QBO and its role in climate variability. The most well known QBO teleconnection is the coupling between the QBO and the Northern Hemisphere (NH) winter stratospheric polar vortex, often referred to as the Holton-Tan effect. This terminology has been the source of some confusion, since Holton and Tan (1980) presented both a statistical correlation and a hypothesized mechanism. While the statistical link has persisted so far, its mechanism is still not clearly established. Less studied is the similar effect on the Southern Hemisphere (SH) winter stratospheric polar vortex, which manifests as a modulation in the timing of the late-winter vortex breakdown. At lower latitudes, the QBO affects tropical deep convection (Nie and Sobel 2015) and may also impact the tropics via changes in the subtropical jet. There is no reason to confine attention only to the "stratospheric path" for QBO influence, as the keynote talk by **Adam Scaife** emphasized. Rossby wave trains extending from the tropics to high latitudes, forced by QBO-modulated deep convective heating anomalies, could provide one "tropospheric path" for high-latitude impacts. Improved understanding of stratosphere-troposphere coupling within the tropics seems necessary to better characterize how the QBO influences the tropical troposphere (**Shigeo Yoden**), such as the apparent QBO modulation of the MJO (Yoo and Son 2016; Eriko Nishimoto).

The robustness of the extra-tropical surface teleconnection, which resembles the NAO in NH winter, remains an important topic. The fact that models tend to underestimate the signal in comparison to observations, which could reflect model error or internal variability – *i.e.*, how well the observed signal can be defined from the short observational record – is a recurring issue (**Adam Scaife**, **Martin Andrews**). There seems a clear need for large sample sizes of model data, which is being addressed by extending the phase-one QBOi experiments, since multiple samples that are of similar size to the observed record can exhibit large variations in the extra-tropical response (**Figure 15**). A step change in sample size may result from the incipient Drivers Of Change In mid-Latitude weather Events (DOCILE) project, which will use distributed computing to generate "super-ensembles" of stratosphere-resolving model simulations to search for statistically robust stratospheric influence on the troposphere (**Dann Mitchell**, **David Wallom**). A novel diagnostic approach to potentially address the robustness of teleconnections is the "complex networks" approach discussed in a keynote talk by **Jürgen Kurths**. Application of these methods to climate problems has shown many promising recent results (Donges *et al.*, 2015); **Verena Schenzenger** showed a first application to the QBO-NAO relationship, and there will be more coming soon from the GOTHAM project.

Teleconnections in general – not only those related to the QBO – suggest the prospect of improved predictability at regional scales (*e.g.* of the NAO) achieved through better understanding of the large-scale, low-frequency variability of the atmosphere. Yet many challenges in characterizing teleconnections remain, as outlined in a keynote talk by **Ted Shepherd**: small signal-to-noise ratios, separation of correlation and causality (*e.g.*, Runge *et al.*, 2014), the fact that responses could manifest non-linearly as changes in residence frequency of regimes (*e.g.*, Palmer 1999), the possible

Figure 14: Participants of the SPARC QBO Workshop: The QBO and its Global Influence - Past, Present and Future, 26-30 September 2016, Oxford, UK.

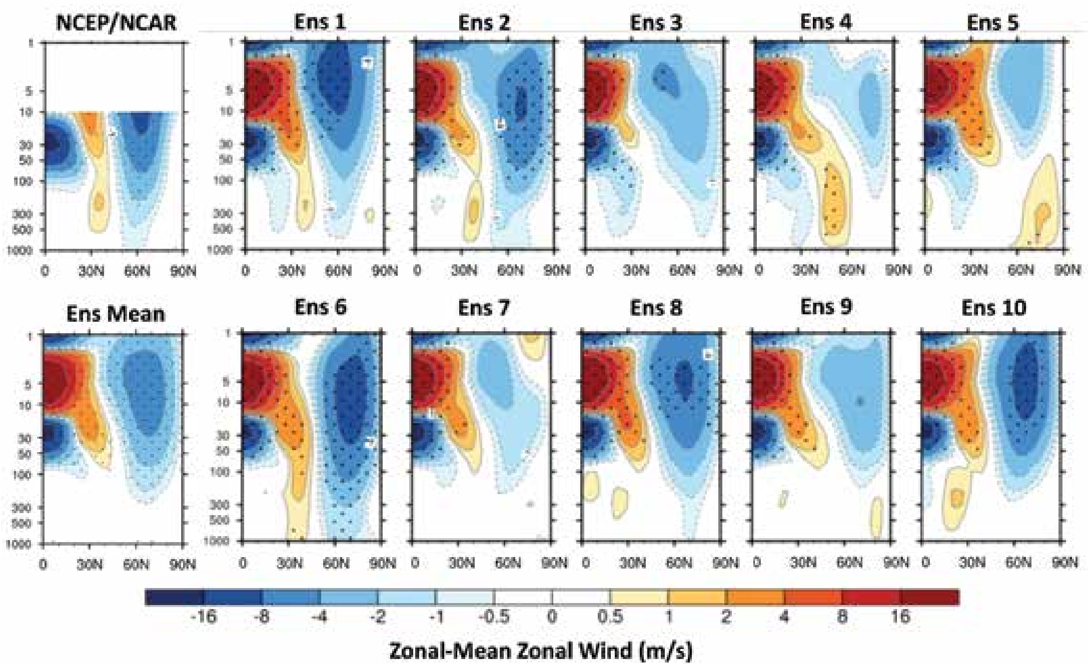

Figure 15: QBO easterly minus westerly composite differences of zonal-mean zonal wind (December-January-February average) for an ensemble of ten 50-year AMIP runs (1952-2001 SSTs) of the NCAR 46LCAM5 model. At left, the corresponding signal in NCEP/NCAR reanalysis is compared with the ensemble-mean model response (figure courtesy Jadwiga Richter).

state dependence of responses, and time lags in responses (such as the seasonal development of a response). The pitfalls and misuse of tools and terminology were also discussed: the use of significance testing is common but can be inappropriate, and there are many examples in meteorology of causal-sounding language being used to describe phenomena that are related but not necessarily in a cause-effect sense.

Dynamics of the QBO

Uncertainties in the spectrum of upward propagating tropical waves that force the QBO remain a key issue. Observational estimates of the zonal forcing by different types of equatorial waves can vary significantly among state-of-the-art reanalyses (**Young-Ha Kim**), and even the basic zonal flow can vary between reanalyses in regions of the tropical belt where there are few radiosonde observations (**Yoshio Kawatani**). High-resolution free-running AGCMs need not agree either: a model with 7 km horizontal resolution still relied on parameterized non-orographic gravity wave drag (GWD) for most of the QBO forcing (**Laura Holt**), but a recent version of the European Centre for Medium-range Weather Forecasts (ECMWF) seasonal forecast model needed to reduce its non-orographic GWD in the tropics to avoid a too-short QBO period (**Tim Stockdale**). Presumably some of these discrepancies arise due to the different deep convective parameterizations used by the models (including the reanalysis models). Several models participating in QBOi use GWD that is coupled to deep convection or is otherwise stochastic (**Andrew Bushell**, **Francois Lott**, **John McCormack**, **Jadwiga Richter**), which should increase the variability of gravity waves driving the QBO, and recent progress in the overall capabilities of gravity wave source parameterizations was reviewed (**Francois Lott**). A lack of variability in resolved or parameterized wave sources, including the seasonal variation (**Young-Ha Kim**), may cause modelled QBOs to be too regular, *i.e.*, to show less inter-cycle variation than is observed. While proper representation of wave sources is desirable, resolving the stratospheric damping of waves can be crucial: high vertical resolution (~ 1km or finer) can strongly affect the damping of resolved waves in the sharp QBO shear zones, and its benefits for the QBO outweigh those of horizontal resolution for equivalent computational cost (**Laura Holt**). It may also affect the QBO modulation of tropical tropopause height and temperature, as can be observed in Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) data (**Vinay Kumar**), that may influence tropical deep convection.

The tropical stratosphere evolves according to a slow interaction between "weak" processes – the large-scale wind is less constrained by thermal damping than in the extra-tropics, and communication by momentum fluxes with the rest of the atmosphere is relatively slow – leading to long timescales, and making the QBO a challenge for modellers (**Peter Haynes**). It is presumably because of this delicate balance that the QBO can be sensitive to many aspects of model formulation, including: vertical resolution, parameterized non-orographic gravity wave drag, dissipative processes (including radiative damping of waves), parameterized deep convection, and the background upwelling of the Brewer-Dobson circulation. The multi-year memory of the tropical lower stratosphere, without which the high predictability of the QBO would not exist, can also give rise to persistently unusual behaviour in models, such as that shown in (Hamilton *et al.*, 2001; Yao and Jablonowski 2015), and at the workshop in slides from **Peter Hitchcock**. Bearing little resemblance to the usual observations, it is tempting to disregard such behaviour as being well outside the regime in which the Earth's stratosphere apparently resides.

Early 2016 disruption

Yet the early 2016 disruption presents a striking challenge: models with seemingly realistic QBOs failed to predict this event, and it bears little resemblance to the QBO's usual regularity. The workshop special session on the disruption was kicked off by **Larry Coy**, who gave an overview of the event; this was then followed by a vigorous group discussion, briefly summarized here. The abrupt occurrence of the 40hPa easterlies (**Figure 13**) was clearly without precedent in the 63-year observational record spanning 1953-2015, and has now been the subject of several published studies (*e.g.*, Newman *et al.*, 2016; Osprey *et al.*, 2016; Coy *et al.*, 2016 under review for J. Climate). Dramatic equatorial wave breaking was presented in a movie showing the November-March evolution of potential vorticity on the 530K (~23km) isentropic surface derived from MERRA-2 reanalyses (**Larry Coy**). This suggests that the usual view of the QBO as a zonally symmetric phenomenon may be questionable in this situation, and the fact that reanalyses are strongly "anchored" by the Singapore radiosonde observations, but can diverge from each other in regions where equatorial radiosonde coverage is poor, could be problematic (**Mark Baldwin**, **Yoshio Kawatani**). Nevertheless, individual radiosonde stations throughout the tropical belt do tend to show a roughly simultaneous onset of the 40hPa February easterlies, indicating a significant zonally symmetric component to the disruption (**Fabian Wunderlich**). Subsequent to the appearance of the easterly layer, downward propagation of wind regimes began to resume, more closely resembling the usual QBO evolution, prompting the disruption to be described as a "reboot" of the QBO (**Larry Coy**).

Although the origins of the disruption are not yet settled, a prevailing view is that strong momentum fluxes from the NH due to equatorward-propagating planetary waves were important. A strong peak appeared at the equator in zonal wavenumber 1-3 Eliassen-Palm flux divergence (**Shingo Watanabe**, **Larry Coy**, **Scott Osprey**) and occurred during a QBO westerly phase when Rossby waves can propagate to the equator. If the proximate cause of the disruption is of extra-tropical origin, this may be consistent with its apparent lack of predictability: the extra-tropics are in general less predictable than the tropics, with sudden stratospheric warmings (SSWs) not being predictable more than ~12 days in advance (**Neal Butchart**). Yet the fact that forecast errors do not correct as the forecast lead-time shrinks suggests that problems with the model, not just random error, are implicated (**Tim Stockdale**). Possible problems could include the fact that non-orographic GWD schemes with fixed wave sources that are tuned to match the observed QBO period give very regular QBOs, or that model resolution limits the fidelity with which tropical wave breaking is represented (**Larry Coy**). The occurrence of a very strong El Niño event during the 2015/16 winter may have led to increased wave activity entering the extra-tropical stratosphere (**Adam Scaife**), and a precursor equatorial wave forcing event involving zonal wavenumbers 4-6 may have been important (**Shingo Watanabe**). Yet if extra-tropical planetary waves are responsible, it is unclear how to reconcile the deep vertical scale of these waves with the shallow vertical scale of the disruption (**Lesley Gray**).

Future projections

Although no seasonal forecasts predicted the disruption, analogous events have appeared – albeit rarely – in free-running models, and they appear more frequently in future projections (**Jadwiga Richter**, **Verena Schenzenger**). This suggest that QBO disruptions may become more common in future, but given model uncertainties such projections should be viewed with caution; preliminary intercomparison of some of the phase-one QBOi future projections shows that the QBO response to climate forcings might vary among models, and this non-robustness could indicate that tuning models to capture the present-day QBO is a case of over-fitting (**John Scinocca**). Using the NCAR model, **Jack Chen** also showed a different QBO response depending on whether future sea surface temperature (SST) or CO_2 changes were specified, leading to the suggestion that idealized experiments separating

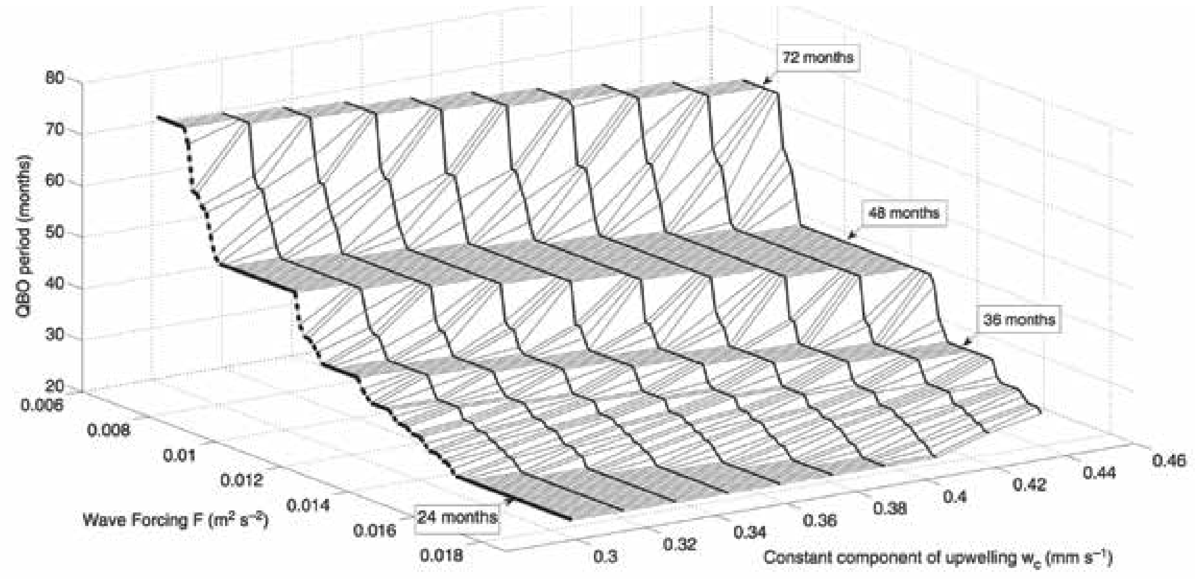

Figure 16: Variation of QBO period as a function of wave forcing strength and background upwelling in an idealized QBO model (figure from Rajendran *et al.*, 2016).

tropospheric and stratospheric climate-change effects could be useful. It is plausible that distinct effects are involved – for example, that changed CO_2 affects the thermal damping rates of waves that force the QBO, while changed SSTs could affect tropical gravity wave sources (which interact with the GWD parameterization in the NCAR model) as well as the tropospheric winds through which the waves propagate before reaching the QBO. Again, the fact that many processes contribute to the QBO creates a potential sensitivity. Apart from changes to the QBO itself, QBO teleconnections may imprint upon changes at higher latitudes: under the RCP4.5 scenario in the MPI-ESM-MR model, significantly stronger middle atmosphere trends occurred for QBO westerly than for easterly years (**Axel Gabriel**).

Idealized simulations

Given this complexity, it is appealing to consider simpler approaches than full AGCMs. In the keynote talk of the idealized simulations session, **Geoff Vallis** introduced one alternative tool, the recently developed Model of an idealized Moist Atmosphere (MiMA). The flexible configuration of this model allows it to explicitly connect from the high end (AGCMs) to the low-end theory, which is a key point: a QBO-resolving configuration of this model could offer a single framework within which to address issues surrounding model uncertainties of the QBO, including its response to climate forcing or the mechanisms underlying its teleconnections. In the same session, **Shigeo Yoden** described recent results from idealized cloud-resolving tropical simulations in which QBO-like oscillations extend from the stratosphere to the surface, modulating the organization of tropical convection; such a model provides a framework for exploring hypotheses regarding the QBO's impact on the tropical troposphere. Using an even more idealized model, a variant of the Plumb (1977) setup, **Kylash Rajendran** showed how the prevalence of QBO phase-locking with the annual cycle could occur over discrete ranges of wave forcing strength, and that this behaviour combined with increased tropical upwelling under climate change could lead to changes in the QBO's seasonal synchronization (**Figure 16**). The daunting complexity of AGCMs, approaching that of the real atmosphere, motivates further consideration of idealized simulations within the QBOi framework.

Constituents and transport

A major reason to represent the QBO in Chemistry-Climate Models (CCMs) is to capture its effects on the transport and mixing of chemical constituents such as ozone, which has historically been a strong focus of QBO research (*e.g.*, Baldwin *et al.*, 2001 and many references therein). An overview talk by **Peter Braesicke** reviewed how trace gases can affect the structure of, and be used to diagnose, aspects of the dynamical QBO. The latitudinal width of the QBO can strongly determine its effects on tracers (Hurwitz *et al.*, 2011), and **Anne Glanville** showed improved isolation of the tropical pipe when a nudged QBO was specified to be narrower. The feedback of ozone on the QBO can be significant: use of the SPARC ozone climatology in the NCAR model, as opposed to the model's usual ozone climatology, was shown to warm the lower tropical stratosphere, weakening the stratification and lengthening the QBO period (**Jack Chen**). Interactive ozone, either from full chemistry or another parameterization scheme, was shown to improve the downward penetration of the QBO easterly phase and break the annual synchronization of the oscillation in the GFDL AM4 model (**Pu Lin**). QBO influence on ozone extends to high latitudes, a behaviour that is well captured in the ESCiMo model (**Tobias Kerzenmacher**). Accurately representing the ozone QBO may be important for assessing the impact, if any, of the QBO on climate projections.

Next experiments

Following the sessions on constituents and transport and idealized simulations, a breakout session on experiments discussed how the set of QBOi experiments might be broadened beyond the current (phase-one) experiments. Because analysis of the phase-one experiments is ongoing, a consensus emerged that there is no need for a new batch of coordinated experiments at this time. However, a reasonably consistent set of suggested experiments emerged from the breakout discussions, which included:

- Extending the phase-one time-slice experiments to examine teleconnection robustness, particularly of the NAO response. (Not a new experiment, but recognition that large sample size is required.)
- Extending phase-one hindcast experiments to examine the 2016 disruption.
- Perpetual El Niño / La Niña perturbations to examine the interaction of ENSO and QBO teleconnections. These would be specified SST anomalies added to the climatological SSTs in the phase-one time-slice experiments.
- Idealized experiments separating tropospheric and stratospheric climate change effects.
- QBO *vs.* no-QBO: for models that can remove their QBOs in a straightforward way (*e.g.* by turning off tropical non-orographic GWD), what is the overall effect of the QBO on present-day climate and on projections?
- Future ozone: specified as a perturbation to prescribed climatological zonal-mean ozone, how does the QBO respond to ozone recovery?
- Interactive ozone: for models that run both with and without ozone chemistry, how does the dynamical QBO respond to ozone changes?

These experiments do not comprise a "QBOi phase two", but are adopted as "coordinated recommendations" for interested groups, so that intercomparison of results can be more easily carried out among groups that do pursue these experiments. Regarding more idealized models, no coordinated efforts are yet proposed, but interest has been building on the edges of the QBOi activity. The Victoria workshop discussed the possibility of comparing QBOs in different dynamical cores (**Christiane Jablonowski**), and the MiMA (**Geoff Vallis**) and tropical convection-resolving regional models (**Shigeo Yoden**) have emerged as useful candidates for testing hypotheses regarding the QBO and its teleconnections.

Core analyses

Rather than concentrate on new experiments, the QBOi activity is now focused on analysis of the phase-one experiments. The current plan, which is an outcome of the workshop breakout sessions and plenary discussions, is to produce the following studies:

Paper 0: Experiment design and overview of participating models, intended for the Geoscientific Model Development (GMD) journal. Provides reference material for subsequent studies.
Paper 1: Present-day (AMIP) experiments. Application of metrics to characterize the QBO and compare models with observations / reanalyses.
Paper 2: Future projections. How does the QBO respond in $2xCO_2$ / +2K SST and $4xCO_2$ / +4K SST experiments? What do the responses tell us about the robustness of modelled QBOs?
Paper 3: Hindcasts. How predictable is the QBO when models are initialized from reanalyses? How comparable are the different forcing terms in the models when initialization removes their mean-flow biases?
Paper 4: Equatorial waves. How do different types of equatorial waves compare among the models, and to reanalyses?
Paper 5: Extra-tropical teleconnections. Comparing extended time-slice runs across all models, how robust is the extra-tropical teleconnection, in both NH and SH? Does the NAO pattern consistently appear in the NH?

The set of core analyses is of course not intended to restrict the analyses that are possible with the QBOi dataset, but rather to lay groundwork for future progress; further suggestions to complement these analyses are welcome. The goal over the coming year is for the core analysis studies to be submitted by mid-2017, prior to the next QBO workshop which is anticipated for late 2017. Except for the GMD "Paper 0" (which will be submitted earlier), it is anticipated that the core analyses will contribute to a Special Collection on the QBO in the Quarterly Journal of the Royal Meteorological Society.

Links to other activities

As noted above, the scope of QBOi has broadened to include QBO teleconnections, increasing potential synergies with other activities. It should also be noted that the data request for QBOi experiment output is modelled on the Dynamical Variability (DynVar) CMIP6 data request, which may make the dataset of interest to DynVar participants. Updates on the DynVar and Stratospheric Network for the Assessment of Predictability (SNAP) activities were presented by **Andrew Charlton-Perez**. An area of SNAP's common interest with QBOi is to understand why the early 2016 QBO disruption was not predicted by current seasonal forecasting systems. **Steve Woolnough** described the S2S archive of seasonal forecast data, which lags real time by three weeks, that may be valuable for this purpose. Updates were given by **Shigeo Yoden** and **Laura Holt** on the Year of the Maritime Continent 2017-2019 (YMC) and Gravity Waves (GW) activities, respectively, which are highly relevant to QBOi given the importance of tropical observations and the important role of gravity waves in the QBO. An emerging focus of the GW activity on predictability may have strong potential for interaction with QBOi.

Summary

A synthesis presentation by **Mark Baldwin** wrapped up the workshop, encapsulating many of the points already noted above. Quoting from the Baldwin *et al.*, 2001 QBO review paper,

> "Although several GCMs have produced simulations of the QBO, there is no simple set of criteria that guarantees a successful simulation."

it was asked whether this remains equally true today. Part of the answer is that the definition of "successful" has gradually shifted: over the past 15 years the number and quality of QBO-resolving models and reanalyses has increased, placing more stringent demands on what is considered a realistic QBO. Yet key uncertainties highlighted in Baldwin *et al.*, 2001 remain relevant today, such as the partitioning of QBO forcing among different equatorial wave types, the adequacy of AGCMs in representing these waves (whether by resolving or parameterizing them), and the robustness and strength of QBO teleconnections. Current simulations are more realistic, but not necessarily for the right reasons. Improved understanding of these uncertainties is hoped to emerge from analysis of the QBOi coordinated experiments, which in turn should enable increased skill in predicting the QBO, thereby moving toward realizing any additional predictive skill that resides in QBO teleconnections.

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Online resources

Workshop agenda (includes abstracts of all oral and poster presentations): **http://users.ox.ac.uk/~astr0092/OC_Agenda.html**

Workshop Twitter hashtag: **#QBOi2016**

QBOi website: **http://users.ox.ac.uk/~astr0092/QBOi.html**

QBOi experiment and data protocol: **http://users.ox.ac.uk/~astr0092/Experiments.html**

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The 12th SPARC Data Assimilation Workshop and 2016 S-RIP Workshop

Masatomo Fujiwara[1], Quentin Errera[2], Lesley J. Gray[3,4], Gloria L. Manney[5,6], John McCormack[7], and James Anstey[8]

[1]Hokkaido University, Japan, **fuji@ees.hokudai.ac.jp**, [2]Belgian Institute for Space Aeronomy, Belgium, [3]University of Oxford, UK, [4]NERC National Centre for Atmospheric Science, UK, [5]NorthWest Research Associates, USA, [6]New Mexico Institute of Mining and Technology, USA, [7]Naval Research Laboratory, USA, [8]Environment and Climate Change Canada, Canada.

The 12th SPARC Data Assimilation (DA) workshop and the 2016 SPARC Reanalysis Intercomparison Project (S-RIP) workshop were held together in Victoria, Canada, from 17-21 October 2016. Similar to the 2014 and 2015 workshops (see Errera *et al.*, 2016), days one and two were dedicated to discussions related to DA activities, days four and five were for S-RIP, and on day three a joint session was held. Eight posters were presented during the week. For more information on each activity see **www.sparc-climate.org/activities/data-assimilation** and Fujiwara *et al.* (2016). The agenda of both meetings, the list of participants and the presentations of the SPARC DA workshop (including the joint session) can be downloaded from **https://events.oma.be/indico/event/12/overview.**

SPARC DA Workshop

The DA workshop focused on three general themes: (1) the representation of the stratosphere and mesosphere in models and analyses; (2) future directions in instruments, modelling, and DA methods; and (3) harmonization and bias correction of long-term reanalyses. The first DA session began with a series of six presentations addressing the representation of the stratosphere and mesosphere in models and analyses. The first three presentations described different aspects of the recently developed high-altitude version of the US Navy numerical weather prediction (NWP) system related to the use of ensemble-based methods to improve the background error covariance specification in the stratosphere and mesosphere (**David Kuhl**), validation with independent mesospheric wind observations (**John McCormack**), and examination of specific terms in the momentum budget from the analyzed winds to improve understanding of gravity wave effects on the mesospheric zonal winds (**Stephen Eckermann**). A presentation on the Belgian Assimilation System of Chemical Observations (BASCOE) by **Quentin Errera** then described efforts to improve analyses of constituent transport and photochemistry throughout the stratosphere and lower mesosphere using a chemical transport model and either 4-dimensional variational or ensemble-based Kalman filter DA algorithms. This was followed by a presentation from **Yvan Orsolini** on modelling the effects of energetic particle precipitation in the mesosphere and lower thermosphere using the Whole Atmospheric Community Climate Model (WACCM) with specified dynamics from stratospheric reanalyses. The final presentation in this theme was made by **Martin Charron**, who discussed recent developments in modelling the stratosphere and mesosphere with the Canadian Global Environmental Multi-Scale (GEM) NWP system.

The next session of the DA workshop consisted of three presentations focusing on the future directions theme. The first of these presentations, by **Nick Pedatella**, described the development of ensemble DA methods in WACCM. This was followed by an overview of the ALTIUS (Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere) satellite mission that described the project status and expected constituent measurements (**Emmanuel Dekemper**). The session concluded with a presentation by **Moudi Pascale Igri** describing regional applications of three-dimensional variational DA to understand variations in the location of the inter-tropical convergence zone over West and Central Africa.

The third DA session on harmonization and bias correction of long-term reanalyses consisted of four presentations, beginning with **David Plummer** discussing the use of reanalyses to constrain atmospheric dynamics in decadal chemistry-climate simulations. Next, **Gloria Manney** gave an update on the Mesospheric and Upper Stratospheric Temperature and Related Datasets (MUSTARD) project which aims to produce long-term records of temperature and geopotential height by combining observations from a variety of past and present limb-sounding radiometers and occultation instruments. This was followed by an overview of the second phase of the SPARC Water Vapour Assessment (WAVAS) activity from **Gabriele Stiller** that highlighted several recent results to be published in an ACP/AMT/ESSD inter-journal special issue. The session concluded with a presentation by **Thomas von Clarmann** on the TUNER project (Towards Unified Error Propagation).

Joint Session

The goal of the S-RIP activity is to produce two SPARC reports, one as an interim report containing the first four "basic" chapters and the other a full report in 2018 containing both "basic" (updated from the interim report) chapters and seven "advanced" chapters. **Masatomo Fujiwara**, **Jonathon Wright**, **Craig Long**, and **Sean Davis** presented overviews of Chapter 1 (Introduction), 2 (Description of the Reanalysis Systems), 3 (Climatology and Interannual Variability of Dynamical Variables), and 4 (Climatology and Interannual Variability of Ozone and Water Vapour), respectively. The review process for the S-RIP interim report was started in early December 2016. **Jonathon Wright** also described the current status of the S-RIP special issue in Atmospheric Chemistry and Physics (**www.atmos-chem-phys.net/special_issue829.html**).

Presentations from four reanalysis centres followed. **Kris Wargan** presented NASA/GMAO's evaluation of the MERRA-2 reanalysis and future reanalysis plans of GMAO. **Rossana Dragani** presented the production plans of the new ECMWF reanalysis, ERA5, whose 2010-2016 data and 1979-2009 data will be made available in the beginning of 2017 and 2018, respectively. **Craig Long** presented NOAA/NCEP's recent upgrades and future plans for the Global Forecast System, Climate Forecast System, and several other model/assimilation systems, and showed comparisons of the recently produced Conventional Observations Reanalysis (CORe) with the NCEP R-1 reanalysis over the period 1950-2009. Finally, **Yayoi Harada** gave an overview of the JRA-55 family, and presented the plans of JMA's new reanalysis, JRA-3Q, whose data will be made available in 2022.

The remainder of the talks in the joint session were science talks including several invited S-RIP talks that are described in the S-RIP section below. In addition to these: **Toshiki Iwasaki** discussed impacts of low-level polar cold air outbreaks on the Brewer-Dobson circulation using the mass-weighted isentropic zonal mean framework; **Thomas von Clarmann** discussed diagnosing the Brewer-Dobson Circulation through the direct inversion of the continuity equation; and **Tianbao Zhao** evaluated atmospheric precipitable water from several reanalyses using homogenized radiosonde humidity data over China.

Figure 17: Participants at the 12th SPARC data assimilation workshop and the 2016 S-RIP workshop held together in Canada.

S-RIP Workshop

During the two-day S-RIP workshop, the co-leads of seven "advanced" chapters provided overviews of the progress and discussion points for each chapter. Each chapter also had one to three invited scientific talks (some presented in the joint session on Wednesday), highlighting important and interesting results obtained so far.

Beatriz Monge-Sanz and **Thomas Birner** gave the overview of Chapter 5 (Brewer-Dobson Circulation). **Simon Chabrillat** presented comparisons of age-of-air in four modern reanalyses through offline modelling of SF6 transport, while **Gabi Stiller** discussed possible mechanisms for age-of-air trend patterns obtained from MIPAS SF6 measurements. In the joint session on Wednesday, **Paul Konopka** discussed trends in stratospheric water vapour and age-of-air using a chemical transport model (CLaMS) driven by different reanalyses.

Patrick Martineau gave an overview of Chapter 6 (Stratosphere-Troposphere Coupling) and also presented comparisons of the momentum budget for Sudden Stratospheric Warmings using several reanalyses. In the joint session on Wednesday, **Peter Hitchcock** discussed the importance of reanalysis data spanning the period prior to 1979 to the present (*i.e.*, much more than ~40 years) for studies of stratosphere-troposphere coupling.

Gloria Manney gave the overview of Chapter 7 (Extra-tropical Upper Troposphere and Lower Stratosphere). **Luis Millan Valle** presented reanalysis comparisons of the climatology of dynamically-induced low ozone events. **Susann Tegtmeier** gave the overview of Chapter 8 (Tropical Tropopause Layer) and **Jonathon Wright** discussed the evaluation and intercomparison of tropical high clouds in reanalyses. In the joint session on Wednesday, **Tao Wang** presented Lagrangian cold-point temperatures and transit times inferred from a forward trajectory model using four modern reanalyses. **Alex Boothe** and **Gloria Manney** gave talks encompassing material from both Chapters 7 and 8, the former on Lagrangian calculations of stratosphere-troposphere exchange, and the latter on trends and variability in the upper tropospheric jet streams; both discussed the implications of their results for trends.

The overview of Chapter 9 was given by **James Anstey**. **Young-Ha Kim** described tropical wave activity and its forcing of the QBO in the five modern reanalyses. **Kevin Hamilton** presented results from the Kawatani *et al.* (2016) study examining inter-reanalysis differences in tropical stratospheric winds and comparing them with observations from the Integrated Global Radiosonde Archive (IGRA) data set.

The overview of Chapter 10 (Polar Processes) was presented by **Michelle Santee**. Gloria Manney presented **Zachary Lawrence**'s work updating intercomparisons of the polar processing diagnostics derived from temperatures and potential vorticity originally described in Lawrence *et al.* (2015). Michelle also presented **Alyn Lambert**'s work investigating polar stratospheric cloud formation temperatures using the thermodynamics of super-cooled ternary solutions and the ice frost-point as a temperature reference to compare reanalysis data in the polar regions.

Finally, **Lynn Harvey** presented an overview of Chapter 11 (Upper Stratosphere and Lower Mesosphere). **Takatoshi Sakazaki** presented comparisons of atmospheric tides in the stratosphere and lower mesosphere from several reanalyses, and **Toshihiko Hirooka** discussed the climatology and interannual variability of the equatorial semi-annual oscillation using modern reanalyses.

Announcements

In November 2016 John McCormack was officially made co-chair of the SPARC DA activity, serving together with Quentin Errera. The SPARC DA and S-RIP activities will hold their next joint workshop from 23-27 October 2017 at ECMWF (UK).

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13 – 15 June 2017
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15 –16 June 2017
TUNER Project Meeting Saskatoon, SK, Canada

20 – 22 Juni 2017
WAVAS II, Toronto, Canada

18-20 July 2017
OCTAV-UTLS, Boulder, CO, USA

2 – 5 September 2017
Training School on Stratosphere-Troposphere Interactions, Cape Town, South Africa

9 – 14 October 2017
FISAPS, QBOi, SATIO-TCS joint workshop, Kyoto, Japan

16 – 20 October 2017
Local Workshop and SSG meeting, Seoul, Korea

SPARC-related meetings

10 – 13 April 2017
GAW 2017 Symposium, Geneva, Switzerland

2 – 3 May 2017
First ALTIUS Symposium, Brussels, Belgium

12 – 14 June 2017
9th Atmospheric Limb Workshop, Saskatoon, SK, Canada

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SPARC Office

Director
Fiona Tummon
Project Scientist
Johannes Staehelin
Communication Officer
Carolin Arndt
Office Manager
Petra Bratfisch

Contact
SPARC Office
c/o ETH Zurich
Institute for Atmospheric and Climate Science (IAC)
Universitaetstrasse 16
CH-8092 Zurich
Switzerland
office@sparc-climate.org