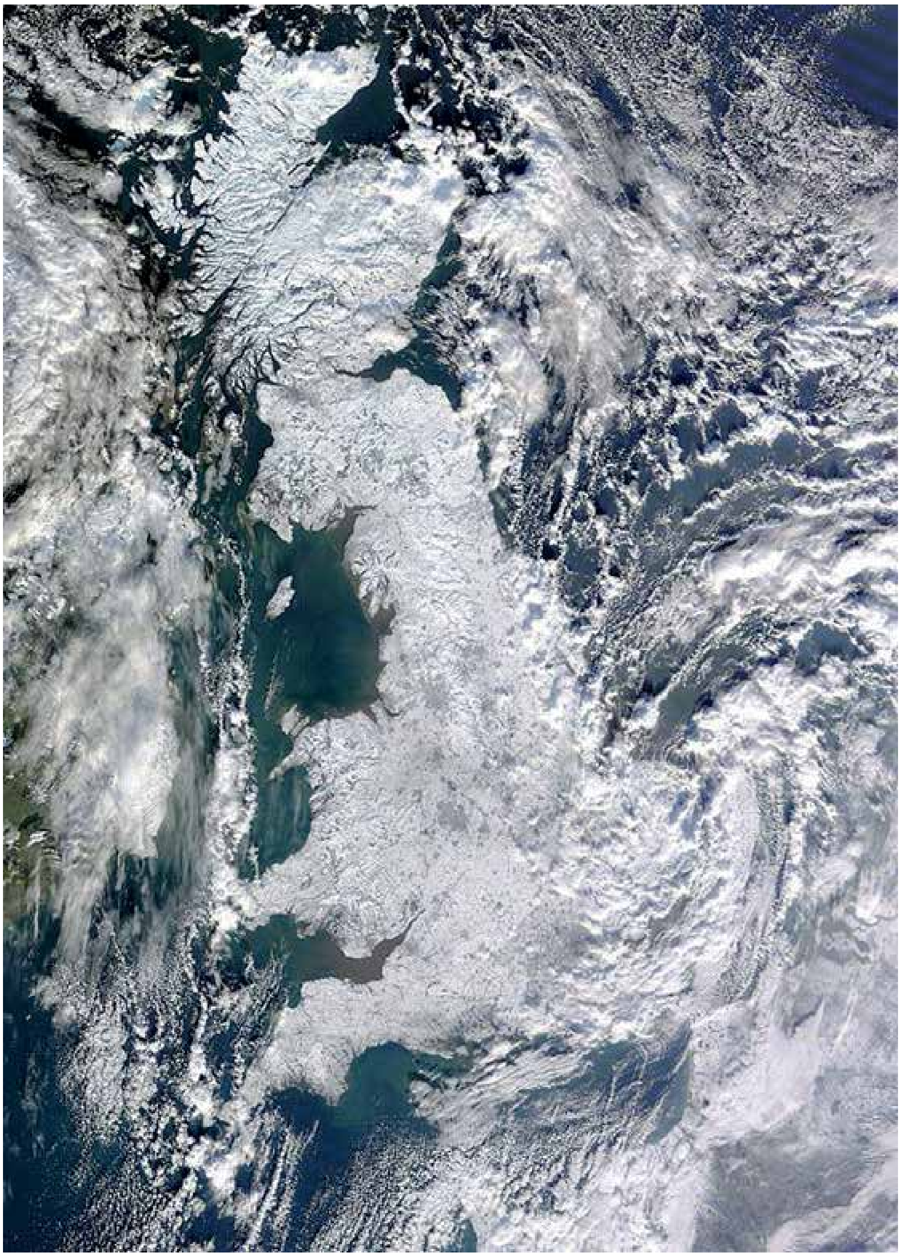
www.sparc-climate.org

SPARC

Stratosphere-troposphere Processes And their Role in Climate

newsletter n° 47
July 2016



Atmospheric blocking events are large-scale patterns in the atmospheric pressure field that are effectively stationary. They can remain in place for several days at a time, causing the areas affected by them to have the same kind of weather for an extended period of time. In the Northern Hemisphere mid-latitudes, areas on the eastern side of blocking anticyclones or under the influence of anomalous flows from colder continental interiors related to blocks can experience severe winters. A SPARC-supported workshop was held in April to discuss recent advances in our understanding of blocking, its impacts and its representation in numerical models. Image courtesy of the NASA MODIS Rapid Response Team.

Contents

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

The 37th Session of the WCRP Joint Steering Committee April 2016, Geneva, Switzerland

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

[1]SPARC Office, ETH Zurich, **fiona.tummon@env.ethz.ch**, [2]Physical Sciences Division, NOAA Earth System Research Laboratory, [3] Cranfield University

The 37th session of the WCRP Joint Steering Committee (JSC) was held in Geneva, Switzerland, from 25-27 April 2016. Representatives from all three of WCRP's sponsors, the World Meteorological Organisation (WMO), Intergovernmental Oceanographic Commission (IOC), and International Council for Science (ICSU), were present, particularly since WCRP will be undergoing an ICSU review in the next year or so. **Petteri Taalas,** secretary-general of the WMO since January 2016, warmly welcomed all meeting participants, emphasising the importance of climate research to WMO. Attending on behalf of SPARC were the co-chairs, **Judith Perlwitz** and **Neil Harris**, and the project office director, **Fiona Tummon**.

JSC meetings are an occasion to discuss the broad range of WCRP activities, highlighting or encouraging links between them, as well as WCRP's strategic directions and links with other international research programmes. For the sake of brevity, this report will just focus on those aspects of relevance to SPARC.

WCRP overview

Over the past year **Guy Brasseur**, JSC Chair, felt that WCRP had been quite successful in supporting frontier research, its core projects, the grand challenges, and introducing new research themes. More focus was still required to develop an active communication interface to better present WCRP science (*e.g.*, to climate services), as well as on developing WCRP's regional presence and capacity development programme, particularly through enhancing the role of the JSC members. A further issue was that of sustained long-term funding, which remains a matter of concern for WCRP and as a consequence for SPARC. Finally, all projects and working groups were encouraged to make open calls for nominations of steering groups/panels if not already doing so. SPARC has set up an online nomination form in this regard and nominations for scientific steering group (SSG) members are open until 30 September 2016.

The JSC was asked to give their support to YESS, the Young Earth System Scientists community (presented by **Vera Schemann**), with which SPARC has been working over the past year. The YESS community provides an excellent resource and voice for early career researchers across all disciplines within the Earth system sciences and the JSC endorsed the community in principle, encouraging the core projects and working groups to find ways to include YESS members in their activities.

WCRP Core Projects

Amongst many activities, **Annalisa Braco** (CLIVAR co-chair) highlighted the CLIVAR climate dynamics panel, which focuses specifically on climate processes such as storm tracks, jet streams, tropical-extra-tropical interactions, the El Niño-Southern Oscillation, and coupled atmosphere-ocean feedbacks. The JSC encouraged more interaction between the panel and other WCRP activities related to atmospheric dynamics; SPARC is represented on the panel by Elisa Manzini. One of CLIVAR's main foci of 2016 is the Open Science Conference being held in Qingdao, China, from 18-25 September (more information about the event can be found on: **http://clivar2016.org**).

Neil Harris presented the SPARC report, focusing on recent activity results, the new implementation plan, as well as possible new areas of interest. One such topic may be tropical processes, particularly how convection influences atmospheric composition. This would have obvious links with SPARC's ACAM activity as well as CLIVAR and GEWEX's Monsoon activities. He also noted SPARC's capacity development activities from the past year and that the planning for the 2018 SPARC General Assembly is underway. The JSC recognised that SPARC is well structured and continuing to produce good science. It was suggested that WCRP adopt reports similar to SPARC so as to provide distinct products in support of the IPCC.

GEWEX (presented by **Graeme Stephens**) is spinning up several new activities this year, including one on aerosol-cloud-precipitation interactions, which is being led by Sue van der Heever and Philip Stier. This initiative as well as one of the five GEWEX Process Evaluation Studies (PROES) on upper tropospheric clouds and convection may be of interest to the SPARC community. Also of relevance is a convection-permitting climate modelling workshop being organised in Boulder, Colorado, from 6-8 September 2016.

CliC functions very similarly to SPARC, with a range of limited-lifetime activities as well as various research fora on specific topics (**Gerhard Krinner**). SPARC-CliC links have been mostly focused around the Polar Climate Predictability Initiative (PCPI), which has obvious links to the Melting Ice and Near-term Climate Prediction grand challenges.

WCRP Grand Challenges

Overviews of all five grand challenges were made: Regional Sea Level Rise and Coastal Impacts (**Detlef Stammer**); Water for the Food Baskets of the World (**Peter van Oevelen**); Extremes (**Sonia Seneviratne**); Clouds, Circulation, and Climate Sensitivity (**Sandrine Bony**); and Melting Ice – Global Consequences (**Greg Flato**). Both the challenges on Extremes and Clouds, Circulation, and Climate Sensitivity have focus on atmospheric dynamics, the former aiming to dissect the large-scale circulation impacts on extremes from regional processes. The latter has most obvious links with SPARC, and both the DynVar and VolMIP CMIP-6 activities will contribute to some of the modelling work of this group. This grand challenge is aiming to write a brief assessment report on climate sensitivity, which will be coordinated by Steve Sherwood and Mark Webb to be finalised in 2018.

Two potential new grand challenges on Near-term Climate Prediction and Biogeochemical Cycles and Climate Change were also presented. **Adam Scaife** presented the proposed grand challenge on Near-term Climate Prediction, which aims to produce routine annual to decadal predictions. This grand challenge will thus fill an important gap in terms of seamlessness between seasonal and centennial scales, providing vital information to policy makers and society at large. Major questions include: What are the sources of predictability? Can models simulate this predictability accurately? They will attempt to improve model initialisation methods as well as the specification of external forcing (*e.g.*, aerosols and solar variability). It is hoped that the grand challenge will be completed in 2020 when such near-term predictions become a routine product from the main global forecasting centres.

The second proposed grand challenge on Biogeochemical Cycles and Climate Change was presented by **Tatiana Ilyina** and **Pierre Friedlingstein**. This grand challenge will largely focus on the carbon cycle since it is related to the largest feedbacks on the climate system. Enormous uncertainty remains in terms of the CO_2 emissions compatible with a given climate target and in terms of a total global carbon budget, both issues which are of significance in terms of the Paris agreement on climate change. Major questions that aim to be addressed include: What are the drivers of land and ocean carbon sinks? What is the potential for amplification of climate change over the 21st century via climate-biogeochemical feedbacks? How do greenhouse gas fluxes from highly vulnerable carbon reservoirs respond to a changing climate? The JSC endorsed both proposed grand challenges, with some minor revisions to the implementation plans put forward.

WDAC and WMAC

The WCRP advisory councils for data (WDAC) and modelling (WMAC) were presented by **Otis Brown** and **Christian Jakob**, respectively. WDAC has recently focused particularly on reanalyses, with a dedicated task team on the intercomparison of these products. Two platforms currently exist that aim to aid reanalysis intercomparisons: ana4MIPS and CREATE-IP; in this context the SPARC S-RIP activity, and the extensive intercomparison they are carrying out, was mentioned. WDAC are also involved in the organisation of the 5th international reanalysis conference which is likely to take place in Europe in 2017. WDAC noted the looming gap in several satellite and *in situ* observations (*e.g.,* ozonesondes, lower tropospheric water vapour, limb sounders for atmospheric composition) that SPARC and other groups have been highlighting over the past 2-3 years.

A highlight on the WMAC 2015 calendar was a training school on atmospheric moist processes, which was organised in Hamburg, Germany. The training school was a great success and heavily over-subscribed so WMAC are planning a 2nd training school to be held in Sao Paulo, Brazil, in 2017 on parameterisation of the grey zone. The lectures from the Hamburg school are all available online for further training purposes (see **https://lecture2go.uni-hamburg.de/veranstaltungen/-/v/18136**). WMAC will have their next meeting in Princeton, USA, in combination with a workshop on model hierarchies. They are also involved in the organisation of a workshop on systematic model errors that will be held in Montreal, Canada, in June 2017.

Links with other programmes

Gilbert Brunet provided an overview of the World Weather Research Programme's (WWRP) activities and links with WCRP. A common challenge for both programmes is providing seamless predictions in time, space, and complexity (*i.e.* covering different aspects of the weather/climate system). There are already three joint projects: S2S (sub-seasonal to seasonal predictions), PPP (Polar Prediction Project), and HiWeather (High-Impact Weather); the SPARC SNAP activity is contributing to the S2S project. There are also links between WWRP's Data Assimilation project and WCRP's reanalysis intercomparison efforts, as well as WWRP's Predictability, Dynamics, and Ensemble Forecasting (PDEF) group and the WCRP grand challenges on Extremes and Near-term Climate Prediction.

WCRP is further working with WWRP and the Global Atmosphere Watch (GAW) programme on a joint urban climate initiative. Although there are numerous urban climate activities on-going around the globe, WCRP/WWRP/GAW want to become a well-known source of research and knowledge for weather and climate information at the urban scale.

WCRP continues to engage with Future Earth, with **Thorsten Kiefer** of the Paris Hub giving a presentation about current Future Earth activities. They have eight focal challenges, similar to WCRP's grand challenge, as well as Knowledge Action Networks (KANs), where research is to happen within various core projects. Of interest to SPARC is of course IGAC, with whom SPARC is jointly carrying out the ACAM and CCMI activities, and possibly their project on Monsoon Asia (MAIRS).

The presentations from the meeting and further information are available at: www.wcrp-climate.org/jsc-37-documents.

The SI2N Initiative: A Better Understanding of Ozone Profile Trends

Neil Harris[1], Birgit Hassler[2,3], Daan Hubert[4], Fiona Tummon[5], and Johannes Staehelin[5]

[1]Cranfield University, Cambridge, UK, **Neil.Harris@cranfield.ac.uk**, [2]CIRES, University of Colorado, Boulder, USA, [3]NOAA/ESRL CSD, Boulder, USA, [4]BIRA-IASB, Brussels, Belgium, [5]ETH Zurich, Zurich, Switzerland

The stratospheric ozone layer is expected to recover slowly following the successful implementation of the Montreal Protocol and consequent reduction in ozone-depleting substances. Detection of the first signs of this recovery have been anticipated in the vertical distribution of ozone since the majority of ozone lies in the stratosphere and tropospheric ozone changes may confound what occurs over the total column. However, robustly estimating vertically resolved ozone trends remains challenging for several reasons: (1) no long-term, global, homogeneous dataset exists that covers the entire period over which ozone changes have been occurring; (2) interpreting the datasets that do exist is complex in itself because of the interannual variability of ozone compounded by changes in ozone due to climate change; and (3) the expected changes to date are small (on the order of 2-5%/decade) and a variety of small factors used in different statistical analyses may have a large influence on trend estimates. In 2011 SPARC, the ozone focus area of the Integrated Global Atmospheric Chemistry Observations (IGACO-O3), the international ozone commission (IO3C), and the Network for the Detection of Atmospheric Composition Change (NDACC) supported the SPARC/IO3C/IGACO-O3/NDACC (SI2N) initiative with the aim of updating knowledge of vertical ozone profile trends. In total 54 papers, including three synthesis papers, were prepared for a special issue joint among Atmospheric Chemistry and Physics, Atmospheric Measurement Techniques, and Earth System Science Data (see the full list on: **www.atmos-chem-phys.net/special_issue284.html**). The first overview paper, Hassler *et al.,* 2014, summarises the wide range of available ozone profile measurements, highlights how they contribute to our general understanding of its long-term evolution, and provides a "bottom-up" view of the potential data quality and state of the retrieval algorithms. The second, Hubert *et al.,* (in preparation), contains a thorough comparison of the various datasets and assesses the consistency between them, building on the work of Hubert *et al*., 2016. The third synthesis paper, Harris *et al.,* 2015, discusses the long-term changes calculated from several merged datasets and compares these changes with those found in other studies. This report provides a brief overview of the main SI2N results, particularly highlighting findings of the three synthesis papers.

Ozone Profile Measurements

Routine ground-based observations of the ozone profile, mostly using the Umkehr technique and ozonesondes, started in the early 1960s in the Northern Hemisphere mid-latitudes. For most of the 1960s and 1970s, few or no observations were made elsewhere, and it is only during the 1990s that the ground-based measurement network was extended to include stations in poorly sampled regions such as the tropics and the Southern Hemisphere. In the late 1970s quasi-continuous ozone profile observations from satellites complemented the sparse ground-based observations, providing a more global picture. However, especially in the early years there were temporal gaps between satellite instruments. From the beginning, dealing with these gaps has been a challenge in stratospheric ozone trend analyses (McPeters *et al*., 1994; Randel *et al*., 1999; Cunnold *et al*., 2000). An additional period of sparse global measurements was caused by the eruption of Mt. Pinatubo in June 1991. The resulting increase in stratospheric aerosol loading caused retrieval problems for several satellite instruments as well as some ground-based instruments (Yu and She, 1995; Bhartia *et al*., 2013). From the early 2000s until the early 2010s many instruments on several different satellites provided stratospheric ozone profiles with different vertical resolutions and geographical coverage (Hassler *et al*., 2014). In April 2012 contact with the Envisat satellite was lost on which many of the high-resolution ozone profile instruments were located. Since then ozone profiles with a high vertical resolution and an almost global coverage are mainly be provided by the Aura Microwave Limb Sounder (MLS), an instrument that is nearing the end of its lifetime. So far, concrete plans to replace the ceased instruments have not yet been established.

Observation Intercomparisons

Rigorous assessment of measurement uncertainties and stability are key to both robust trend calculations and the development of long-term merged datasets. In principle, a reference standard is required to test datasets for stability, however, in reality this is complicated by the fact that available ozone profile records have uncertainties on the same order of magnitude and can exhibit temporal signatures of the instrument and processing history. This limits their accuracy and stability over time. Hubert *et al*., 2016, showed that ozonesonde and lidar observations can be used to detect satellite instrument drifts at the level of 2-3%/decade and 3-4%/decade in the middle stratosphere and lower/upper stratosphere, respectively. But, these stability levels do not meet the stringent requirements specified by the Global Climate Observing System (GCOS), namely 0.6%/decade in the stratosphere. In contrast, it is generally possible to provide uncertainty estimates within the 5% accuracy limits set out by GCOS. Exceptions are for regions, for example the upper troposphere/lower stratosphere, where increased atmospheric variability leads to large contributions to the intercomparison error budget (Hubert *et al*., 2016).

Numerous teams contributed to the SI2N validation and intercomparison efforts. Using a variety of methods for instruments covering different spatial and temporal resolutions a reasonably consistent picture emerged. In general, the different data records agree quite well throughout most of the stratosphere (between 20-40km), with biases less than ~5%, precision better than ~5-12%, and decadal drift less than ~5%/decade. Towards the stratopause and especially the tropopause, differences between records become larger. Intercomparisons of level-2 profiles revealed that a few satellite records exhibit a significant drift of at least 5%/decade in parts of the atmosphere (Hubert *et al*., 2016), which also showed up as differences in the intercomparison of trend results from (merged) level-3 data

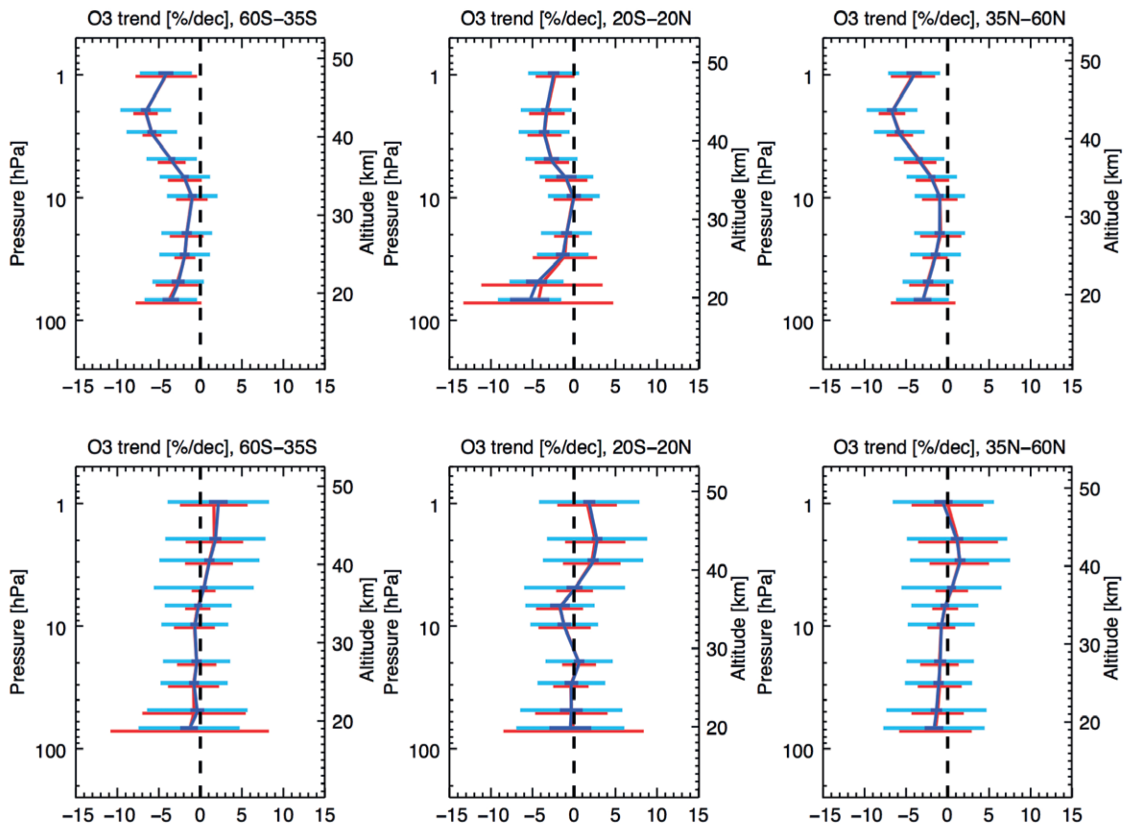


Figure 1: Ozone trends derived from combining satellite trend estimates for the periods before 1998 (top row) and after 1998 (bottom row). The error bars show the 95 % confidence level calculated in three ways: The thick blue lines show the central estimates and their associated most likely range found by propagating the individual trend errors assuming the individual datasets are independent. The light blue line, based on the same analyses, additionally includes a term for the possible drift of the overall observing system (Hubert *et al.*, 2016). The thick red lines show the possible range for the ozone trends calculated assuming the individual datasets are not independent. See Harris *et al.,* 2015, for further details.

records (*e.g.,*, Harris *et al.*, 2015; Tummon *et al.*, 2015). Estimates of drift in level-2 satellite data relative to ground-based instruments were used to produce a conservative estimate of the stability of merged limb and occultation data records (level-3), for the pre-1997 and post-1998 periods and for three layers in the stratosphere (Hubert *et al.*, 2016). These values were then used in the trend estimates presented in the third SI2N overview paper (Harris *et al.*, 2015), where three possible methods for combining trend estimates were explored (see **Figure 1**).

Ozone Profile Trends

Harris *et al.*, 2015, reported trends for a number of long-term datasets from both ground-based and merged satellite records. Trends were calculated for periods before and after the peak in Equivalent Effective Stratospheric Chlorine (EESC) in 1997. The findings for the period prior to 1997 were broadly similar to those reported elsewhere, with decreases in the upper stratosphere at all latitudes and in the mid-latitude lower stratosphere. The trend estimates calculated at 45km for the combined SAGE-I/II dataset, covering 1979-97, were slightly larger than those found elsewhere for just the SAGE-II dataset (Remsberg, 2014; Damadeo *et al.*, 2014) and those for the merged datasets that rely primarily on SAGE-II for this period (Kyrölä *et al.*, 2013; Bourassa *et al.*, 2014; Tummon *et al.*, 2015). Reasonably good agreement was found in the lower stratosphere where the trends using just the SAGE-II measurements, *i.e.* from 1984 onwards, are smaller than the ones starting in 1979. Considerable benefits would be gained if the SAGE-I record could be revised to be consistent with the SAGE-II record without having to use the altitude correction from Wang *et al.*, 1996, as it would lead to better knowledge of the lower stratospheric ozone changes in this early period.

For the second half of the record, from 1998 onwards, it is clear that the downward trend seen in the pre-1997 period in upper stratospheric ozone has not continued and it is likely that there has been an increase since 1998. However there is disagreement about both the magnitude and statistical significance of the observed increase. In particular, the trends are sensitive to the choice of start/end point of the period analysed and the statistical significance is very sensitive to any assumptions made about the independence of the datasets considered as well as any estimates of drifts in the observation system (**Figure 1**). Furthermore, the problem is compounded by the fact that the change in ozone to be detected is relatively small, as consistent with model calculations (*e.g.*, Fleming *et al.*, 2011; WMO, 2014).

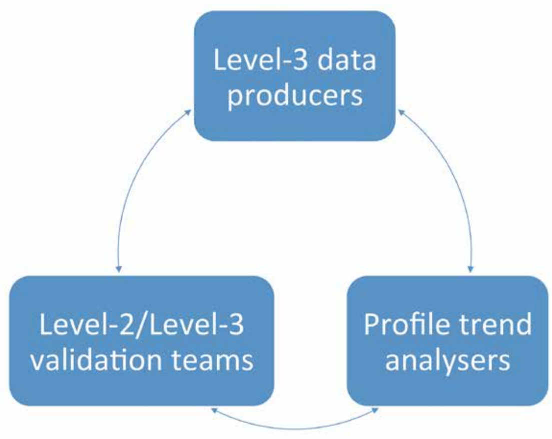


Figure 2: Communication between data producers and data users is essential.

Future questions and lessons learned

One goal of the SI2N Initiative was to raise awareness about the increased demand for high-quality and consistent datasets that have well-defined uncertainty estimates. These are required so that advanced statistical methods can be applied to detect and attribute small changes in stratospheric ozone due to decreasing ODS levels. Only with highly stable and accurate profile ozone measurements will this be possible.

As such, no single measurement system with proven superior accuracy and/or stability exists, that, at the same time, also provides sufficient spatial and temporal sampling and coverage to act as a reference standard. Hence, multi-instrument validation and intercomparison exercises will remain key in identifying issues in single data records. In this respect, it will be crucial to maintain as much independence between data records as possible. Here, the ground-based networks along with the homogenisation of existing data records will play a key role. Maintenance of these networks will be central to ensuring the continued success of the future space-based ozone measurements by providing a ground truth as well as providing a means of filling any gaps in the record.

A thorough investigation of the impact of sampling as well as the intercomparison methods themselves is also needed. For example, at present, it is unclear how level-2 dataset characteristics propagate through to the more derived level-3 (*e.g.,* long-term merged) datasets that are often used to estimate ozone profile trends. Furthermore, best practices for merging several different datasets need to be established, as does the independence of these datasets need to be better understood. This very issue led to different interpretations of ozone trend results between SI2N and WMO (2014), and remains a critical open question. Its resolution will require concerted action between all involved parties (see **Figure 2**).

Improvements in the underlying measurements, in the techniques used to combine them, and a few additional years of measurements will all increase our confidence in the derived trends. Improved estimates of the uncertainties will require considerably enhanced rigour in how they are propagated from individual measurements through to a decadal trend derived from multiple datasets. This issue, which is equally important for other long-term geophysical time series, is a major, under-recognised challenge.

References

Bhartia *et al.*, 2013: Solar Backscatter UV (SBUV) total ozone and profile algorithm, *Atmos. Meas. Tech.*, **6**, 2533–2548.

Bourassa *et al.*, 2014: Trends in stratospheric ozone derived from merged SAGE II and Odin-OSIRIS satellite observations, *Atmos. Chem. Phys.*, **14**, 6983–6994.

Cunnold *et al.*, 2000: SAGE (version 5.96) ozone trends in the lower stratosphere, *J. Geophys. Res.*, **105**, 4445–4457.

Damadeo, R.P., J.M., Zawodny, and L.W. Thomason, 2014: Reevaluation of stratospheric ozone trends from SAGE II data using a simultaneous temporal and spatial analysis, *Atmos. Chem. Phys.*, **14**, 13455–13470.

Fleming *et al.*, 2011: Forecasts and assimilation experiments of the Antarctic ozone hole 2008, *Atmos. Chem. Phys.*, **11**, 1961–1977.

Harris *et al.*, 2015: Past changes in the vertical distribution of ozone – Part 3: Analysis and interpretation of trends, *Atmos. Chem. Phys.*, **15**, 1-19.

Hassler *et al.*, 2015: Past changes in the vertical distribution of ozone – Part 1: Measurement techniques, uncertainties and availability, *Atmos. Meas. Tech.*, **7**, 1395–1427.

Hubert *et al.*, 2016: Ground-based assessment of the bias and long-term stability of 14 limb and occultation ozone profile data records, *Atmos. Meas. Tech.*, **9**, 2497-2534.

Kyrölä *et al.*, 2013: Combined SAGE II–GOMOS ozone profile data set for 1984–2011 and trend analysis of the vertical distribution of ozone, *Atmos. Chem. Phys.*, **13**, 10645–10658.

McPeters *et al.*, 1994: Comparison of SBUV and SAGE II profiles: implications for ozone trends, *J. Geophys. Res.*, **99**, 20513–20524.

Randel *et al.*, 1999: Space- time patterns of trends in stratospheric constituents derived from UARS measurements, *J. Geophys. Res.*, **104**, 3711–3727.

Remsberg, E.E., 2014: Decadal-scale responses in middle and upper stratospheric ozone from SAGE II version 7 data, *Atmos. Chem. Phys.*, **14**, 1039-1053.

Tummon *et al.*, 2015: Intercomparison of vertically resolved merged satellite ozone data sets: interannual variability and long-term trends, *Atmos. Chem. Phys.*, **15**, 3021–3043.

Wang, H.J., D.M., Cunnold, and X. Bao, 1996: A critical analysis of Stratospheric Aerosol and Gas Experiment ozone trends, *J. Geophys. Res.*, **101**, 12495–12514.

WMO, 2014: Scientific Assessment of Ozone Depletion: 2014, Global Ozone Research and Monitoring Project – Report No. 55, World Meteorological Organization, Geneva, Switzerland

Yu, J.R. and C.Y. She, 1995: Climatology of a midlatitude mesopause region observed by a lidar at Fort Collins, Colorado (40.6°N, 105°W), *J. Geophys. Res.*, **100**, 7441–7452.

FISAPS – An Emerging SPARC Activity

Marv Geller[1], Hye-Yeoung Chun[2], and Peter Love[3]

[1]Stonybrook University, New York, USA, **marvin.geller@stonybrook.edu**, [2]Yonsei University, Seoul, Korea, [3]Australian Antarctic Division, Hobart, Australia

At the 23rd meeting of the SPARC Scientific Steering Group, FISAPS (FIne-Scale Atmospheric ProcesseS and Structures) was endorsed as an emerging SPARC activity. In the following, we will briefly describe the scientific rationale for FISAPS along with what we expect FISAPS to accomplish.

Many atmospheric phenomena that influence large-scale dynamics occur on vertical scales less than one kilometre. This activity will utilise operational high vertical resolution radiosonde data (HVRRD) and other sounding data to study several of these phenomena. Studies that have already utilised these data include SPARC's gravity wave activity, which focuses on spatial and temporal variations of gravity waves in the troposphere and lower stratosphere (*e.g.,* Wang *et al.*, 2005). The data have also been used to investigate various other important phenomena such as the fine structure of the extra-tropical tropopause (*e.g.,* Birner, 2006) and to characterise the planetary boundary layer for comparison with climate models (*e.g.,* Seidel *et al.*, 2012). HVRRD have also been used as a transfer standard to justify the use of IGRA (Integrated Radiosonde Archive; see **www.ncdc.noaa.gov/data-access/weather-balloon/integrated-global-radiosonde-archive**) data over longer periods than those for which HVRRD are available, such as was done for evaluating El Niño Southern Oscillation – Quasi-Biennial Oscillation relations (*e.g.,* Yuan *et al.,* 2013). With the advent of even higher resolution data made possible by the transition of radiolocation sondes to GPS sondes, studies of turbulence are now conceptually possible (*e.g.*, Clayson and Kantha, 2007). Numerous other applications have been explored and continue to emerge. Modelling has evolved to the point where realistic modelling of wave transitions to turbulence is now being carried out (*e.g.*, Fritts, *et al.*, 2015). It is important to note that while such HVRRD are available at hundreds of stations around the world only a small fraction are conveniently available to the research community. One of the prime goals of this activity is to improve the archiving of these data so that more is available to the worldwide research community.

The objective of this activity is to realise the full potential of HVRRD archived worldwide. Providing coordination for the growing community of HVRRD users will promote the development of innovative applications of HVRRD by facilitating the sharing of expertise on analysis techniques, data handling, and technical capabilities and limitations. This sharing of expertise will similarly be of benefit for the refinement and improvement of existing fields of research using HVRRD. Due to restrictions on access to HVRRD, previous studies have been limited to relatively small geographic coverage. This activity aims to address this limitation by two means, first, by coordinating broader regional intercomparisons and global studies that bring together researchers from the global HVRRD community. And second, by providing improved access of existing HVRRD to the research community.

An initial focus will be on the preparation of a review article on research uses of HVRRD. Finalisation of this review will probably require a small meeting of principal authors, who will likely form the core of the activity steering group. It is hoped that this review paper can be submitted to either the Bulletin of the American Meteorological Society or Eos within about a year. It is also envisaged that the activity might produce a journal special issue documenting current research on fine-scale processes and structures, emerging applications of HVRRD, and new findings emerging from studies with broad geographic coverage facilitated by improved access to HVRRD; but this is likely some years away. As part of this process, a follow up meeting to the Workshop on Research Applications of High Resolution Radiosonde Data held at Stony Brook University in May 2013 will be organised within the first two years of the activity.

The research community using HVRRD has proposed a global High Vertical Resolution Sounding Data Archive to facilitate research on the topics including those mentioned above and future unforeseen areas. An important function of this activity will be to advocate for this archive among meteorological services worldwide and to liaise with archive users regarding data usage and applications. This role will be key to realising studies with broader regional or global coverage. Studies conducted under the auspices of the activity will produce secondary HVRRD products, which themselves will be useful for further research, model development and other purposes, for example, turbulence and gravity wave statistics, and climatologies.

The initial FISAPS activity leads will be **Marvin Geller** (USA), **Hye-Yeong Chun** (Korea), and **Peter Love** (Australia). With this article, we solicit interested individuals who wish to participate in FISAPS and the preparation of the FISAPS review article. A FISAPS steering group will be organized from those expressing interest in active participation in FISAPS. The composition of the steering group will reflect a broad basis of both scientific activity and regional representation to maximise the scope of both observation-based and modelling research activities and also the advocacy efforts for improved access to HVRRD. It is envisaged that the project will be of benefit to other WCRP core projects, particularly GEWEX, whose leadership has expressed interest in applying HVRRD to their research. The GCOS Reference Upper Air Network is now an important member of the HVRRD community with which this project can work on sharing complementary resources to achieve a mutual objective of promoting process studies using HVRRD. Furthermore, we will invite liaison members from several of the global forecasting/analysis centres to participate in this steering group, since their involvement will be crucial to the success of this activity.

While the initial focus of FISAPS will be on fine-scale dynamical structures, it is anticipated that FISAPS may expand its scope into fine-scale constituent structures and processes. It is clear that troposphere and stratosphere observations of atmospheric constituents show fine structures, yet chemistry-transport models display relatively smooth structures. Quantifying how the absence of fine-scale structures in modelled chemical constituents affects computed chemical reaction rates would be a focus of this expanded activity.

References

Birner, T., 2006: Fine-scale structure of the extratropical tropopause region, *J. Geophys. Res.*, **111**(D4), doi:1029/2005JD006301.

Clayson, C.A., and L. Kantha, 2008: On turbulence and mixing in the free atmosphere inferred from high–resolution soundings, *J. Atmos. Ocean. Tech.*, **25**, 833–852, doi:10.1175/2007JTECHA992.1.

Fritts, D.C., *et al.*, 2015: Numerical Modeling of Multi-Scale Dynamics at a High Reynolds Number: Instabilities, Turbulence, and an Assessment of Ozmidov and Thorpe Scales, *J. Atmos. Sci.*, **73**, 555-578, doi: 10.1175/JAS-D-14-0343.1.

Seidel, D.J., *et al.*, 2012: Climatology of the planetary boundary layer over the continental United States and Europe, *J. Geophys. Res.*, **117**, D17106, doi:10.1029/2012JD018143.

Wang, L., M.A. Geller, and M.J. Alexander, 2005: Spatial and temporal variations of gravity wave parameters. Part I: Intrinsic frequency, wave-length, and vertical propagation direction, *J. Atmos. Sci.*, **62**, 125–142, doi: 10.1175/JAS-3364.1.

Yuan, W., M.A. Geller, and P.T. Love, 2013: ENSO influence on QBO modulations of the tropical tropopause, *Q.J.R. Meteorol. Soc.*, **140**, 1670-1676, doi:10.1002/qj.2247.

Chemical Kinetics and Photochemical Data for Use in Atmospheric Studies

A New Release by the NASA Panel for Data Evaluation

Stanley P. Sander[1], James B. Burkholder[2], Jonathan P.D. Abbatt[3], John R. Barker[4], Robert E. Huie[5], Charles E. Kolb[6], Michael J. Kurylo[7], Vladimir L. Orkin[5], David M. Wilmouth[8], and Paul H. Wine[9]

[1]NASA Jet Propulsion Laboratory, Pasadena, CA, USA, **Stanley.Sander@jpl.nasa.gov**, [2]NOAA Earth System Research Laboratory, Boulder, CO, USA, **James.B.Burkholder@noaa.gov**, [3]University of Toronto, Toronto, Canada, [4]University of Michigan, Ann Arbor, MI, USA, [5] National Institute of Standards and Technology, Gaithersburg, MD, USA, [6]Aerodyne Research, Inc., Billerica, MA, USA, [7]Goddard Earth Sciences, Technology and Research Program, Baltimore, MD, USA, [8]Harvard University, Cambridge, MA, USA, [9]Georgia Institute of Technology, Atlanta, GA, USA.

The 2015 Jet Propulsion Laboratory (JPL) compilation (JPL 15-10) is the 18th in a series of critically-evaluated atmospheric kinetic and photochemical datasets prepared by the National Aeronautics and Space Administration (NASA) Panel for Data Evaluation. The primary objective of the evaluation is to provide an up-to-date database for use in experimental and modelling investigations of stratospheric and upper tropospheric chemical processes. The evaluation includes comprehensive coverage of approximately 670 bimolecular reactions, 85 three-body reactions, more than 30 equilibrium constants, 225 photochemical species, 575 aqueous and heterogeneous processes, thermodynamic parameters for almost 800 species, and approximately 4500 literature citations. Each item includes recommended values (*e.g.*, rate coefficients, absorption cross-sections, uptake coefficients, *etc.*) with estimated uncertainty factors and a note describing the available experimental and theoretical data together with an explanation for the recommendation. These notes contain important information that could not be conveniently tabulated.

The NASA JPL tabulations of evaluated data have become recognized as international assets for atmospheric research aimed at understanding the interplay between changes in atmospheric composition and climate. The evaluations now include O_x, $O(^1D)$, singlet O_2, HO_x, NO_x, Organic, FO_x, ClO_x, BrO_x, IO_x, SO_x, and Na reactions, three-body reactions, equilibrium constants, photochemistry, aqueous chemistry, heterogeneous chemistry and processes, and thermodynamic parameters. In preparing JPL 15-10, particular emphasis was placed on critically evaluating data for the following:

- Reactions of $O(^1D)$
- Reactions of OH with halocarbons
- Reactions of sulfur compounds
- Initial steps in isoprene oxidation
- Photochemistry of ozone, organic compounds, and halogen oxides
- Heterogeneous processes on liquid water, water ice, alumina and solid alkali halide salts
- Gas-liquid solubility (Henry's Law Constants)

- Thermodynamic parameters (entropy and enthalpy of formation)

When important new laboratory data are published on topics that are not scheduled for immediate reevaluation in the cycle, the Panel may add a "special topics" category to the evaluation. Feedback from the atmospheric modelling community has often identified important reactions for this category.

Atmospheric chemistry models are needed to accurately describe the composition and the temporal/spatial behaviour of the Earth's atmosphere. Such models have been used for studying Earth's stratospheric ozone layer and its response to anthropogenic and natural forcings and for estimating atmospheric lifetimes of ozone- and climate-related trace gases. Accurate chemical models require accurate data for many hundreds of chemical reactions and photochemical processes. Thus, critically-evaluated data like those provided by the NASA Panel are essential for the continued development of these models and their application in environmental assessment activities.

History of the NASA Panel for Data Evaluation

The formalization of photochemical and kinetic data evaluation activities within the US dates back to 1972 when the Department of Transportation established the Climatic Impact Assessment Program (CIAP) to study the possible effects of nitrogen oxides (released as engine exhaust from a projected fleet of supersonic aircraft) on Earth's protective ozone layer. In addition to its support of laboratory studies of atmospheric reactions, the CIAP, together with the US Department of Commerce's National Bureau of Standards (NBS) Chemical Kinetics Information Center, recognized the need to develop a uniform input database for atmospheric models being used to investigate this issue. Thus, in response to a national priority having significant industrial and economic impact, an evaluation activity for stratospheric kinetic and photochemical data was initiated under joint CIAP and NBS support.

Subsequent concerns about halogen-catalysed destruction of ozone initiated further international focus on stratospheric photochemistry and kinetics. In June 1975, the US Congress directed NASA "to conduct a comprehensive program of research, technology and monitoring of the phenomena of the upper atmosphere." NASA's FY1976 authorization bill provided a clear mandate to perform research concerned with depletion of the ozone layer and gave birth to NASA's Upper Atmosphere Research Program (UARP). In 1977, recognizing the importance of continuing atmospheric data evaluation activities on an even broader scale than initially fostered by the CIAP, NASA's UARP established the NASA Panel for Data Evaluation. Present Panel membership maintains the original participation of scientists from US government institutions, and from the academic and private sectors and now includes members from NASA JPL, the National Oceanic and Atmospheric Administration Earth System Research Laboratory, the National Institute of Standards and Technology (formerly the NBS), the Georgia Institute of Technology, Harvard University, the University of Michigan, the University of Toronto (Canada), Aerodyne Research Inc., and the Universities Space Research Association.

Just as the original data evaluation activity played an important role in the first US assessment of the environmental effects of stratospheric aircraft, the NASA Data Panel has provided and continues to provide critical input to national and international assessment activities. These include a 2008 US Climate Change Science Program Synthesis and Assessment Product and more than two decades of climate assessments under the Intergovernmental Panel on Climate Change and of scientific assessments of ozone depletion under the auspices of the World Meteorological Organization and the United Nations Environmental Programme.

Current Panel Evaluation Approach

For the first 12 evaluations it was the practice of the Panel to re-evaluate the entire set of reactions with individual Panel members taking responsibility for specific chemical families or processes. In more recent years, the upper troposphere and lower stratosphere (UTLS) have become the primary areas of focus for model calculations and atmospheric measurements related to studies of ozone depletion and climate change. The high chemical and dynamical complexity of the UTLS has required that a different approach be adopted for more recent evaluations. Because it is no longer practical to completely re-evaluate the entire database for each release, particular subsets are chosen for re-evaluation, with several Panel members working in a given area. This approach makes it possible to treat each subset in greater depth, to examine the consistency of the recommended parameters within a given chemical family, and to expand the scope of the evaluation to new areas. It is the aim of the Panel to consider the entire set of kinetics, photochemical, and thermodynamic parameters every three review cycles. Nevertheless, each release of the evaluation contains not only the new evaluations, but also recommendations for every process that has been considered in the past. In this way, the tables for each release constitute a complete set of recommendations.

JPL 15-10 Details

In so far as possible, all recommendations are based on the results from published laboratory studies and are not adjusted to specifically fit observations of atmospheric chemical composition. In order to provide recommendations that are as up-to-date as possible, preprints and written private communications are accepted, but only when the Panel is convinced that they will soon appear in the peer-reviewed literature. For each chemical reaction, the Panel considers whether the data are consistent with reaction rate theory and discrepancies are noted. A major use of theory is to interpolate and extrapolate data for three-body reactions when the laboratory measurements do not cover the entire range of atmospheric temperatures and pressures. In some cases where no experimental data are available, the Panel may provide estimates of rate constant parameters based on thermochemical information, published theoretical studies, or on analogous reactions for which data are available. The thermodynamics section makes an even more extensive use of theory, reflecting the developing maturity of theoretical methods for computing thermochemical parameters such as enthalpies.

The layout of JPL 15-10 has been revised and improved from that of previous evaluations to include with each note the full citations for the references cited within that note. In addition, complete bibliographies appear at the end of each major section of the evaluation, as does a Master Bibliography for the entire document. Hyperlinks have been added to the master tables in the Photochemistry, Henry's Law, and Thermochemistry sections to facilitate improved document navigation.

Availability

The evaluation can be downloaded from **http://jpldataeval.jpl.nasa.gov** in pdf format. A sign-up for email notifications of news and updates is also available from this website. For more information, please contact this article's authors.

The 2015 S-RIP workshop and 11th SPARC data assimilation workshop

Quentin Errera[1], Masatomo Fujiwara[2], and Bernard Legras[3]

[1]Belgian Institute for Space Aeronomy, Belgium, **quentin@oma.be**, [2]Hokkaido University, Japan, [3]Laboratoire de Météorologie Dynamique, France

The 2015 SPARC Reanalysis Intercomparison Project (S-RIP) workshop and the 11th SPARC Data Assimilation (SPARC DA) workshop were held together at the Université Pierre et Marie Curie in Paris, France, from 12-16 October 2015. Days one and two were dedicated to discussion on the progress of S-RIP, days four and five were dedicated to scientific presentations and discussion related to SPARC DA activities, and on day three a joint session between both activities was held. The 2015 S-RIP workshop was the second one since the 2013 S-RIP planning meeting, while the 11th SPARC-DA workshop was one of a regular series (see **www.sparc-climate.org/activities/data-assimilation**) that started in 2002. As in 2014, the two activities shared the same location and week for workshops because of their close scientific link. Thirty-seven participants attended either both or one of the workshops.

The S-RIP workshop

The main goal of S-RIP is to produce a SPARC report on the intercomparison of reanalyses (with

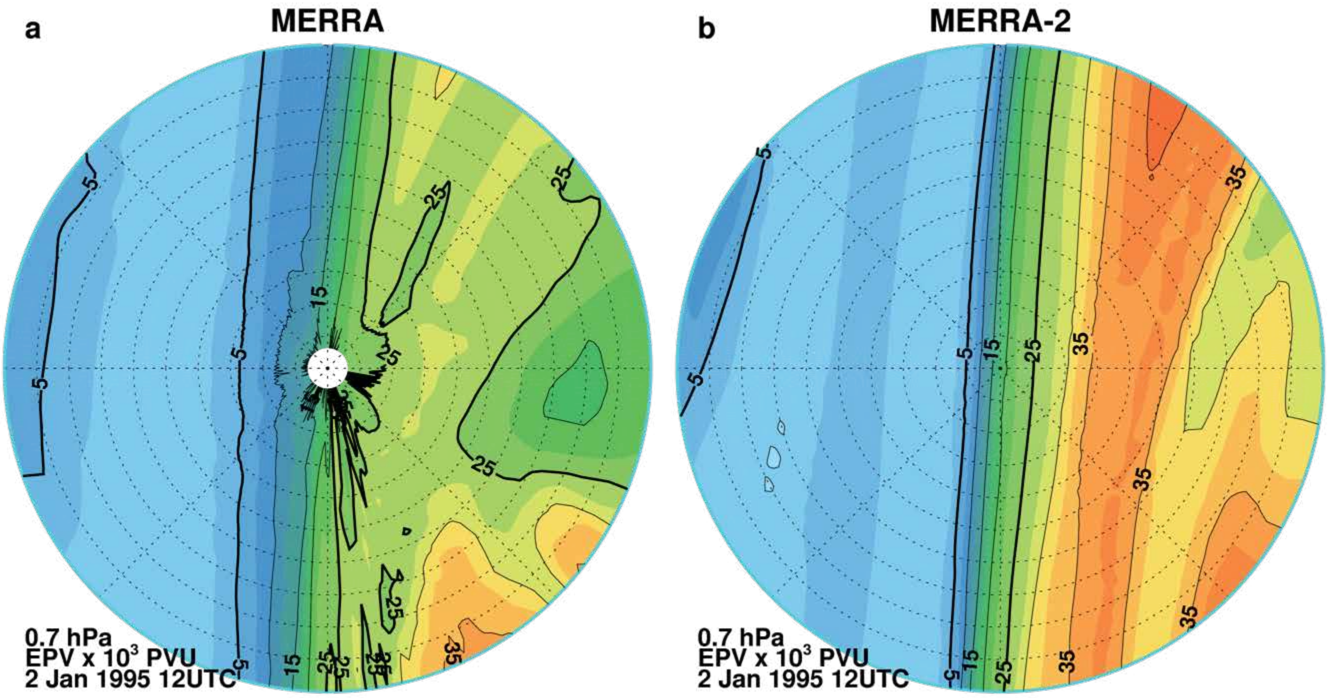


Figure 3: EPV at 0.7hPa on 2 January 1995 at 12UTC from (a) MERRA and (b) MERRA-2.

an interim report being produced in 2016 and the final full report in 2018), holding workshops annually between 2013 and 2018. As at the 2014 workshop, we discussed progress and current issues facing each chapter of the report, with one of the chapter leads (see **http://s-rip.ees.hokudai.ac.jp/report/structure.html**) reporting on the current status of each chapter. Rapporteurs were assigned for each chapter and they made brief summary presentations at the end of the workshop.

During the workshop, three major points were discussed. The first was the replacement of **David Tan**, who stepped down as S-RIP co-lead in July 2015 upon his departure from ECMWF. The workshop participants agreed that the collaborative link between reanalysis centres and SPARC data users has been successfully established during the past two years and that it is currently not critical to have a co-lead from one of the reanalysis centres; instead, it is more important to strengthen the scientific coordination of the project toward the goal of completing the 2018 report. After the workshop, two new co-leads, **Gloria Manney** and **Lesley Gray**, were confirmed with concurrence from the S-RIP working group members and chapter co-leads. **Masatomo Fujiwara** remains as co-lead. The second discussion point was the S-RIP interim report, consisting of Chapters 1-4, which will be published in 2016. **Jonathon Wright** agreed to be one of the editors of the interim report along with the S-RIP co-leads. The third discussion point focused on the consideration of an S-RIP special issue. Jonathon also agreed to take the lead on researching and organizing a special issue and we have subsequently negotiated with Atmospheric Chemistry and Physics to have a special issue on "The SPARC Reanalysis Intercomparison Project (S-RIP)" **www.atmos-chem-phys.net/special_issue829.html**), which was launched in January 2016. **Peter Haynes**, **Gabriele Stiller**, and **William Lahoz** kindly agreed to be the editors of this special issue.

S-RIP/SPARC-DA joint session on reanalyses

The joint session day started with four presentations about recent updates from reanalysis centres. **Larry Coy** discussed the NASA MERRA-2 reanalysis released in 2015. MERRA-2 has improved ozone as compared to MERRA thanks to the use of the latest SBUV/2 Version 8.6, Aura Microwave Limb Sounder (MLS), and Aura Ozone Monitoring Instrument (OMI). Model upgrades also improved the representation of the Quasi-Biennial Oscillation (QBO). A new cube-sphere grid led to a better representation of cross-polar flow (see **Figure 3**). From 2004 onwards, MLS temperature profiles have been assimilated improving the representation of the

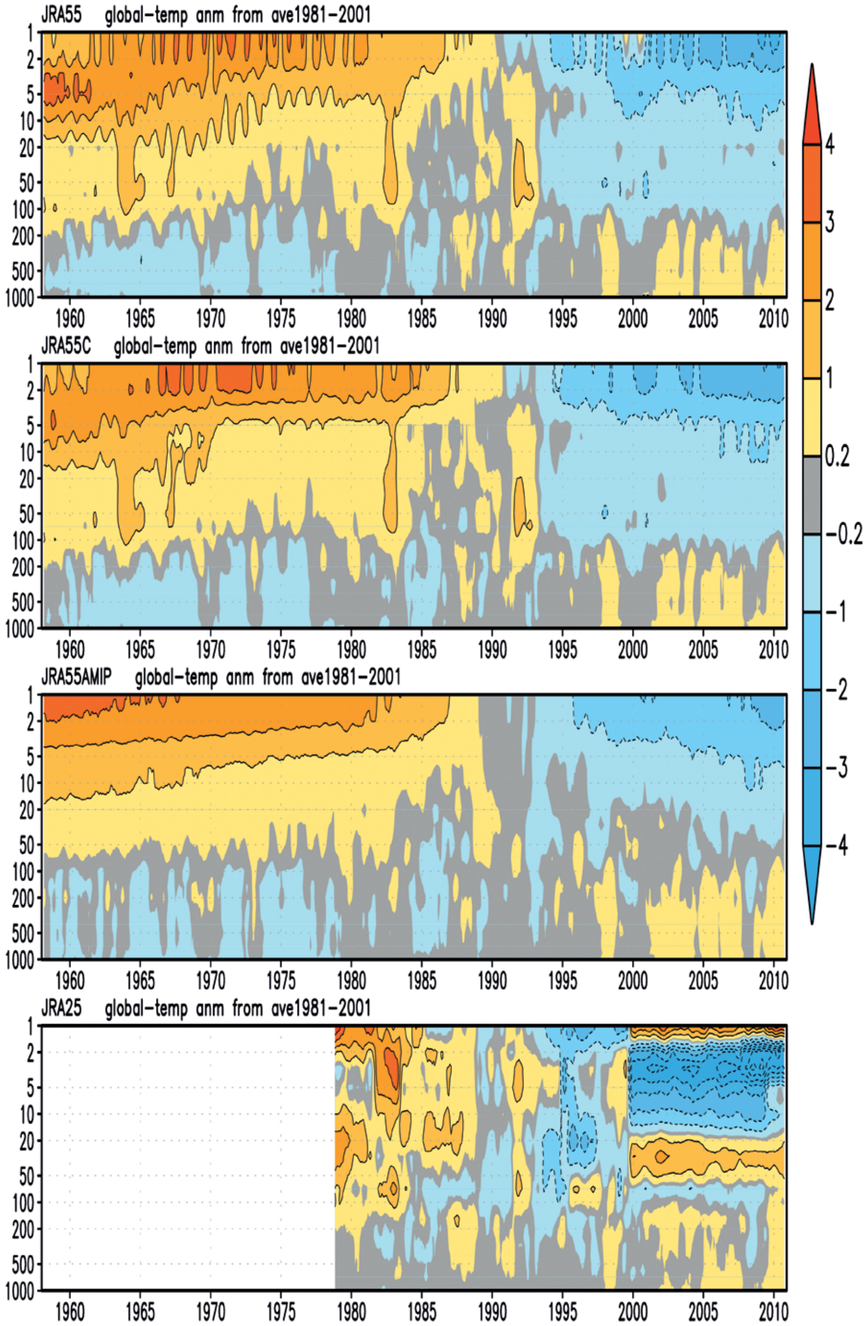


Figure 4: Global mean temperature anomalies (5-month running mean anomalies, anomalies mean climatology 1980-2001) for JRA-55 (top), JRA-55c (second from top), JRA-55AMIP (third from top) and JRA-25 (bottom).

upper stratosphere. New CRTM-based SSU assimilation also significantly impacted stratospheric temperatures, particularly in the 1980s and early 1990s. Additional information about MERRA-2 and access to the data can be found here: **http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2**.

Hans Hersbach presented the ERA5 reanalysis, successor of ERA-Interim, which ECMWF has started to produce (completion in 2016). Among the different improvements in model, observations, and data assimilation techniques, an update to the semi-Lagrangian scheme allows a significant improvement in the forecast of sudden stratospheric warming (SSW) events. The configuration of the call of the radiation scheme has been upgraded, reducing the temperature bias of 3-5°K in the upper stratosphere. ERA5 analyses will be provided hourly.

Craig Long provided updated information on NOAA reanalyses. NCEP-1 and NCEP-2 are still running, as is CFSR, but with the system having changed to CFSv2 from April 2011. Version 2c of the NOAA–CIRES 20th Century Reanalysis (20CR), covering the period 1851-2011, is now available, while at NOAA CPC a reanalysis using only conventional data (*i.e.* surface and radiosonde observations only; similar to JRA-55C) is being developed for the period from the 1940s to present. Finally, he presented the NOAA's future plans, including the Next Generation

Global Prediction System (NGGPS), which unifies the short-term weather forecast system, 2-to-6-week forecast system, and climate forecast system; and the NCEP/EMC Unified Global Coupled Modeling System (UGCMS) which will be used to make a fully coupled reanalysis (1979-present) and attendant model reforecasts.

Chiaki Kobayashi presented the JRA-55C reanalysis that assimilates only conventional surface and upper air observations, with no use of satellite observations, using the same data assimilation system as the JRA-55 (Kobayashi *et al*., 2014). The reanalysis covers the period 1972-2012 and can be downloaded at: **http://rda.ucar.edu/datasets/ds628.2**. JRA-55C aims to produce a more homogeneous dataset unaffected by changes in historical satellite observing systems. The dataset is intended for studies of climate change or multi-decadal variability. The climatological properties deduced from the early results of the JRA-55C are similar to those of the JRA-55 in the troposphere and lower stratosphere, except for high southern latitudes. On the basis of forecast skill, the quality of the JRA-55C is inferior to that of JRA-55, however JRA-55C has better temporal homogeneity. **Figure 4** provides an example of JRA-55C compared to other JRA products.

Yayoi Harada discussed the extraordinary features of planetary wave propagation during boreal winter 2013/2014, with predominance of zonal wavenumber-2. Since 1958, the starting year of JRA-55, the boreal winters of 2008/2009 and 2013/2014 have been the only winters when the ratio of the wavenumber-2 contribution to the sum of wavenumber-1 and wave number-2 were greater than 75% (Harada *et al*., 2010). She concluded that the mechanisms related to the features in winter 2013/2014 can be summarized as follows: (1) there was remarkable blocking activity over the North Pacific basin modulated by La niña-like SST conditions that excited wavenumber-2 in the upper troposphere; and (2) upward wave-packet propagations over western Russia influenced the expansion and continuation of the Aleutian

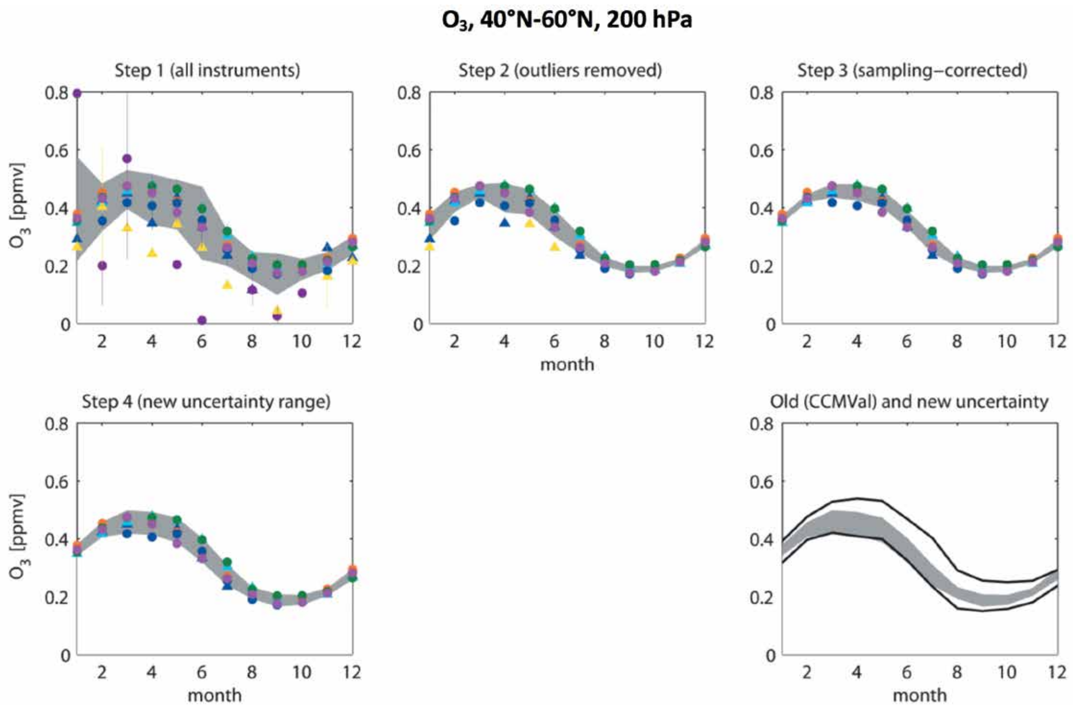


Figure 5: Ozone seasonal cycle diagnostic for 40-60°N at 200hPa. Upper left (step 1): 2005-2010 multi-annual mean values of all available instruments (each colour denotes a different instrument). The uncertainty range (grey shading) is calculated as the 1-sigma standard deviation over all instruments' multi-annual mean values. Upper centre (step 2): all data points outside the 1-sigma standard deviation from step 1 are removed and the uncertainty range recalculated. Upper right (step 3): all data points impacted by a sampling bias estimated to be larger than 10% are removed and the uncertainty range is recalculated. Lower left (step 4): as step 3, except that the uncertainty range is recalculated now taking not only the inter-instrument but also the inter-annual spread into account. This increases the uncertainty range, but is important in order to produce an uncertainty that free-running models can be compared against. Lower right: comparison between CCMVal range (black lines) and SPARC-DI multi-instruments range (grey shading).

High, which might be related to strong downward propagation over northern Canada and no occurrence of a major SSW in this winter.

Albert Hertzog (invited) presented long-duration balloon experiments in the upper troposphere/lower stratosphere (UTLS) and validation of the dynamics in various reanalyses. NCAR/NCEP and ERA-40 reanalyses had difficulties in capturing synoptic-scale variability of the poorly observed Southern Hemisphere storm track in the early 1970s. On the other hand, an excellent agreement between reanalysis fields and independent observations is found in the northern mid-latitudes. However, in the tropical tropopause region, a large and long-lasting difference is found between the balloon observations and reanalysis products. This is due to the poor resolution of equatorial waves in reanalyses as a result of missing radiosonde observations in the tropical regions, in particular over the oceans. This presentation also introduced the Strateole 2 long-duration campaign that will be carried out around the Equator from 2018-2021 (**http://tinyurl.com/strateole**).

Jingwei Liu presented an evaluation of the China Meteorological Administration (CMA) operational analysis (COA) data with two reanalysis datasets (ERA-Interim and R-2) for the period 2010-2012. For the 500hPa geopotential height field, COA data generally showed very high correlations and low root mean square errors (RMSE) compared to the other two reanalyses, however there are large inconsistencies in the tropics and over Antarctica. For relative humidity at 500hPa, COA generally showed small biases and RMSEs globally, with higher correlations with ERA-Interim compared to R-2. CMA is preparing a reanalysis dataset using their operational weather forecast model with an assimilation system in collaboration with NCAR.

Siddarth Das presented a comparison of *in situ* rocketsonde observations with different reanalyses (MERRA, ERA-40, ERA-Interim and NCEP-II). The reanalyses and observations agree well in terms of the amplitude of the annual and semi-annual oscillations, however, the reanalyses underestimate the QBO when compared to observations.

Felix Plöger compared trends of stratospheric mean age-of-air calculated with the CLaMS Lagrangian transport model driven by two different reanalyses (ERA-Interim and JRA-55). Climatologically, the age-of-air from both simulations agrees well with observations, however, in terms of decadal trends the ERA-Interim-driven simulation agrees well with observations, but not the one driven by JRA-55. By separating the contribution of residual circulation (*i.e.* slow transport) and isentropic eddy mixing (*i.e.* fast mixing), the aging by mixing in JRA-55 is negative in the Northern Hemisphere, which is not the case for ERA-Interim.

Bernard Legras compared the age-of-air among three reanalyses: MERRA, ERA-Interim, and JRA-55. The study concluded that significant discrepancies remain among reanalyses and observations. especially in long-term trends. The age spectrum diagnostic is a more robust test than the mean age-of-air for evaluating reanalyses, as the mean age is dependent on the tail distribution of ages, which tends to be badly represented in reanalyses.

Luis Millan talked about low column ozone events outside of the polar regions in winter/spring. These events are primarily the result of ozone variability due to dynamical processes rather than chemical processes. Satellite data of total column ozone from Aura OMI as well as vertical profiles from Aura MLS were used to develop a climatology of low ozone events and their relationships to stratosphere-troposphere exchange to evaluate their representation in reanalyses. The accuracy of their representation is being used as a metric to assess the reanalyses' ability to capture dynamically-driven ozone variability in the upper troposphere and stratosphere.

Thirteen posters were also displayed during the joint session. Titles and author names are available here: **http://events.oma.be/indico/event/6/page/4**.

The SPARC DA Workshop

Harmonization of long-term data records and bias correction in data assimilation

Susann Tegtmeier (invited) summarized the SPARC Data Initiative (DI), which aims to compare vertically-resolved trace gas climatologies derived from satellite measurements, identify outliers and provide merged data sets that will be used by the scientific community. The initiative is focusing on 25 trace gases and aerosols from 18 satellite instruments and results are being compiled in a SPARC report (SPARC, 2016). **Figure 5** illustrates the added value of the merged datasets provided by the SPARC DI activity.

Hans Hersbach (invited) presented the variational bias correction (VarBC) methods applied to satellite radiance measurements by forecast centres. These methods can be used to merge and filter outliers of different long-term data sets resulting in assimilated fields at each assimilation cycle and not on a monthly-zonal average basis. The implementation of a VarBC scheme requires a parametric form that represents the observation bias where parameters are optimized at the same time as the control variables (Dee and Uppala, 2009). From the ERA-Interim experience, ECMWF has learned that an adaptive bias correction system is required to correct time-varying instrument errors, handle major atmospheric forcing events (*e.g.,* Pinatubo), detect data drifts, and maintain optimal consistency among data sources. However, as long as models have systematic errors it is not possible to completely eliminate false climate signals in a reanalysis.

Quentin Errera presented a reanalysis of MIPAS stratospheric observations of N_2O and CH_4. The reanalysis generally agrees well with independent observations but suffers from time consistency due to discontinuities in the MIPAS observing system. The use of the averaging kernels of the observations, the filtering of outliers by a background quality check, and the use of a calibrated B-matrix using an ensemble method allow the reanalysis to almost eliminate the vertical oscillations in N_2O and CH_4 observations found in the tropical lower stratosphere.

On the added value of chemical data assimilation of upper tropospheric and stratospheric measurements

Richard Ménard (invited) examined the theoretical foundation of a method to estimate error covariances based on analysis residuals in observation space, also known as the Desroziers method. His analysis also included a method based on *a posteriori* diagnostics of variational analysis schemes. Using a mathematical analysis of convergence with a simplified regular observation network, he identified the conditions for convergence to the truth. In particular, he found that the estimation of variance parameters converges to the truth if the error

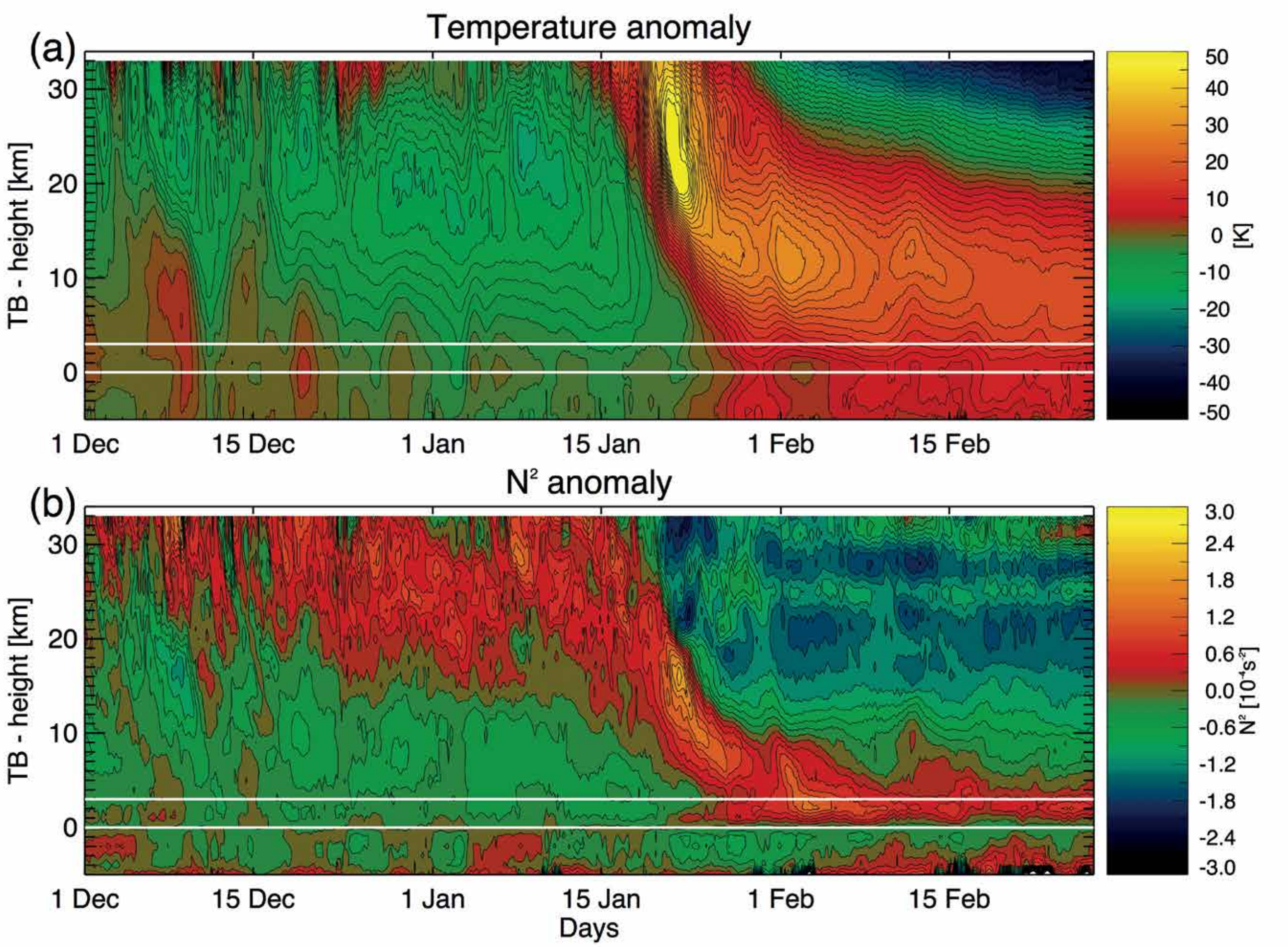


Figure 6: Temperature anomaly (top) and Brunt-Väisälä buoyancy frequency squared (N^2, bottom) zonally averaged between 75-90°N from MERRA-2 reanalysis.

correlation is specified correctly. The convergence is also much faster with the analysis increment (Desroziers) method than with the method designed for variational analysis schemes (Ménard, 2015).

Frank Baier reported on the extraction of wind information from MIPAS trace gas observations, work which is part of the European ARISE project to derive better stratospheric wind profiles. The inversion scheme is based on the SACADA assimilation model and uses adjoint advection of wind bias. MIPAS observations of HNO_3, O_3, H_2O, N_2O, and CH_4 from March 2003 were assimilated over 6-hour time windows and results were analysed with respect to species, latitude, and time. While experiments with simulated tracer and wind fields show reduced errors, comparisons with wind radio soundings over Kiruna show no bias reduction and need further investigation.

Representation of the stratosphere and mesosphere in models and analyses

Scott Osprey (invited) presented the QBO initiative (QBOi), a new SPARC activity (Anstey *et al.*, 2015; Hamilton *et al.*, 2015). The talk reviewed the performance of several CMIP5 and CCMVal-2 model simulations that reproduce observed characteristics of the QBO, showing that simulations usually do not accurately reproduce all characteristics simultaneously. To understand why models struggle to reproduce the QBO, QBOi has set up an experiment protocol that will be used to identify and distinguish the mechanisms important for accurately simulating the QBO.

François Lott (invited) presented the recent techniques used to represent non-orographic gravity waves in general circulation models, *e.g.,* the global spectral and multi-wave parameterizations. He showed how multi-wave parameterizations can be made efficient when made stochastic. He also showed how parameterized gravity waves can easily be related to their convective and frontal sources using well-understood theories. The relation with the sources render the launched wave stress very intermittent, a behaviour supported by isentropic balloon observations. He also illustrated how this intermittency is significant for the timing of the Southern Hemisphere vortex breakdown (de la Camara *et al.*, accepted).

Kris Wargan used the MERRA-2 reanalysis in combination with model simulations to study the behaviour of the polar tropopause during the 2009 major SSW. MERRA-2 shows strengthening of the polar tropopause inversion layer (TIL) during major SSW events, in agreement with previous studies (see **Figure 6**). Model simulations reveal that the primary mechanism involves an enhanced convergence of the vertical residual wind at the tropopause, but that the model underestimates the TIL's strengthening.

Yvan Orsolini examined the coupling between the stratosphere, mesosphere, and lower thermosphere (MLT) during SSWs with Elevated Stratopause (ES) events. Using the Whole Atmosphere Chemistry Climate Model (WACCM) it was shown that westward-travelling planetary waves are important to simulate the ES evolution and stratopause recovery. The impact of ES events extends well across the Equator, altering tropical wind, temperature, and ozone. After ES events, the migrating semidiurnal tides amplify due to tropical stratospheric ozone and wind anomalies (Limpasuvan *et al.*, 2016).

Valery Yudin presented an analysis of simulations from various whole atmosphere (WA) models (*i.e.* models with lids at altitudes of around 500km). WA models require further development and calibration to obtain realistic representation of wave dynamics (planetary waves, gravity waves, and tides). This presentation also highlighted two upcoming NASA thermosphere missions, ICON and GOLD, scheduled for 2017, which will provide observations of wind, temperature, and several chemical constituents at altitudes from 90-250km. These datasets will be important for space weather predictions made by NOAA and NCAR using WA models.

Sergey Skachko revisited the "model ozone deficit", the fact that many stratospheric chemistry transport models (CTM) underestimate ozone by 20-35% in the upper stratosphere/lower mesosphere (USLM). Using the CTM of the Belgian Assimilation System for Chemical ObsErvation (BASCOE), the sensitivity of the model was tested with respect to various inputs and compared to MLS ozone profiles. In particular, the ozone deficit is reduced when the photolysis rates are calculated online using ozone and temperature from the model instead of interpolating photolysis rates from a precalculated look-up table. Bias is also reduced when ERA-Interim temperature, used by the CTM, is bias-corrected in the USLM to match MLS temperature. These changes reduced the model deficit from 22 to 12%, although this deficit is still significant compared to MLS ozone observations.

Johannes Flemming studied the feedback of different representations of stratospheric ozone on temperature in the radiation scheme of the ECMWF model. The ozone representations were taken from climatologies, calculated by linearized parameterization, or calculated explicitly by solving a stratospheric chemical equation system. The different representations led to considerable differences between the temperature fields. However, temperature biases in the ECMWF model cannot be reduced just by taking into account ozone. Interestingly though, the use of prognostic ozone did not show any improvement in simulated temperature compared to the use of climatological ozone fields.

Next workshop

The next SPARC DA and S-RIP workshops will again be held jointly in 2016, this time in Victoria (BC), Canada, from 17-21 October. SPARC-DA will start the week and S-RIP will close the week with a joint session on Wednesday. More information is available on the SPARC-DA workshop page (**http://events.oma.be/indico/event/12**) and the S-RIP webpage (**http://s-rip.ees.hokudai.ac.jp/events/meeting2016**).

References

Anstey, J., *et al.*, 2015: Report on the 1st QBO Modelling and Reanalyses Workshop, *SPARC Newsletter*, **45**, 19-25.

Dee, D.P. and S. Uppala, 2009: Variational bias correction of satellite radiance data in the ERA-Interim reanalysis, *Q.J.R. Meteorol. Soc.*, **135**, 1830–1841. doi: 10.1002/qj.493.

de la Camara, A., *et al.*, 2016: On the gravity wave forcing during the southern stratospheric final warming in LMDz, *J. Atmos. Sci.*, doi: 10.1175/JAS-D-15-0377.1.

Errera, Q., M. Fujiwara, C. Long, and D. Jackson, 2015: Report from the 10th SPARC data assimilation workshop and the 2014 SPARC Reanalysis Intercomparison Project (S-RIP) workshop, *SPARC Newsletter,* **44**, 31–38.

Fujiwara, M. and D. Jackson, 2013: SPARC Reanalysis Intercomparison Project (S-RIP) Planning Meeting, *SPARC Newsletter*, **41**, 52-55.

Hamilton, K., S. Osprey, and N. Butchart, 2015: Modeling the stratosphere's "heartbeat," *EOS*, **96**, doi:10.1029/2015EO032301.

Harada, Y., *et al.*, 2010: A major stratospheric sudden warming event in January 2009, *J. Atmos. Sci.*, **67**, 2052–2069, doi:10.1175/2009JAS3320.1.

Limpasuvan, V., *et al.*, 2016: On the Composite Response of the MLT to Major Sudden Stratospheric Warming Events with Elevated Stratopause, *J. Geophys. Res.*, **121**, doi:10.1002/2015JD024401.

Ménard, M., 2015, Error covariance estimation methods based on analysis residuals: theoretical foundation and convergence properties derived from simplified observation networks, *Q.J.R. Meteorol. Soc.*, **142**, 257–273, doi: 10.1002/qj.2650.

SPARC, 2016: The SPARC Data Initiative, M. Hegglin and S. Tegtmeier (Eds.), SPARC Report No. 8, in preparation.

Wargan, K., and L. Coy, 2016 : Strengthening of the Tropopause Inversion Layer During the 2009 Sudden Stratospheric Warming: A MERRA-2 Study, *J. Atmos. Sci.*, **73**, 1871-1887, doi: 10.1175/JAS-D-15-0333.1.

Stratospheric Change and its Role for Climate Prediction (SHARP2016)

16-19 February 2016, Berlin, Germany

Ulrike Langematz[1], Blanca Ayarzagüena[2], Thomas Birner[3], Martin Budde[4], Hella Garny[5], Edwin Gerber[6], Sophie Godin-Beekmann[7], Peter Hitchcock[8], Daan Hubert[9], Stefan Lossow[10], Stefanie Meul[1], Sophie Oberländer[1], Martin Riese[11], and Andrea Stenke[12]

[1]Freie Universität Berlin, Germany, **ulrike.langematz@met.fu-berlin.de**, [2]University of Exeter, United Kingdom, [3]Colorado State University, USA, [4]Universität Bremen, Germany, [5]Deutsches Zentrum für Luft- und Raumfahrt, Germany, [6]New York University, USA, [7]CNRS, France, [8]University of Cambridge, United Kingdom, [9]Belgian Institute for Space Aeronomy, Belgium, [10]Karlsruhe Institute of Technology (KIT), [11]Forschungszentrum Jülich, Germany, [12]ETH Zürich, Switzerland.

The stratospheric response to anthropogenic changes and its feedback on tropospheric climate and weather are of growing interest in climate research and numerical weather prediction. The SHARP-2016 workshop discussed recent progress and future directions in the research on stratospheric change and its implications for climate and weather with focus on four topics:

- Brewer-Dobson circulation
- Stratospheric ozone
- Stratosphere-troposphere coupling
- Stratospheric water vapour.

In combination with the closing event of the six-year German DFG research program 'Stratospheric Change and its Role for Climate Prediction' (SHARP) (Langematz, 2011), the workshop brought together 117 scientists from 16 countries (**Figure 7**) to discuss the progress achieved since the start of the SHARP research group, to present new science in the SHARP research areas, and to discuss future research needs.

The SHARP-2016 workshop was dedicated to Professor Karin Labitzke, head of the Stratospheric Research Group at Freie Universität Berlin from 1970-2000, who passed away on 15 November 2015.

Workshop summary

The opening lecture was given by **Neil Harris**, who presented an overview of the evolving science in SPARC, from its implementation in 1992 to the recent re-orientation towards 'Stratosphere-troposphere Processes And their Role in Climate' in 2014 and new 2016-2020 SPARC Implementation Plan. The following subsections summarize the major topics addressed in the four sessions.

Day 1: Brewer-Dobson Circulation

While Brewer Dobson Circulation (BDC) research has existed since 1949, new aspects have been added or refined in the recent past, such as the separation of a lower and upper stratospheric branch of the BDC, the distinction between the residual circulation (RC) versus the BDC, or the role of mixing for the mean age-of-air (AoA), as summarized in a keynote lecture by **Thomas Birner**. Since the 1990s, modern BDC research has been fostered by climate change and stratospheric ozone depletion. A closer view of the drivers of RC (planetary, synoptic, and gravity waves) and its trends was presented by **Sophie Oberländer-Hayn**, **Felix Bunzel**, and **Peter Hitchcock**. **Hella Garny** found that the robust strengthening of the shallow branch of the BDC in free-running climate models is neither seen in simulations with specified dynamics nor in the ERA-Interim reanalysis, and suggested missing variability in the free-running models as a possible reason. Another question of interest was the relationship between RC and the transport circulation, including two-way mixing. The effects of RC and mixing on stratospheric AoA were discussed (**Felix Plöger**, **Simone Dietmüller**). Interannual variability of AoA due to past volcanic eruptions was addressed in a talk by **Mohamadou Diallo**, while **Paul Konopka** showed that the ENSO anomaly in the mean AoA is of the order ±4 months, mainly due to differences in the RC than eddy mixing. Another focus was on new measurement and analysis methods, such as the AIRCORE technique to measure AoA (**Andreas Engel**), the use of tracer measurements to derive the BDC via the continuity equation (**Thomas von Clarmann**), the use of AoA data in a new theoretical approach to derive RC (**Marianna Linz**), or the application of a 3D BDC analysis to climate model output to show future increased downwelling (~50%) over Northern Europe/West-Siberia (**Axel Gabriel)**. The application of an idealized model was suggested for better validating stratospheric transport in climate models and to help explain discrepancies between models and observations (**Eric Ray**). **Ted Shepherd** addressed the climate impact of past changes in halocarbons in the tropical upper troposphere/lower stratosphere (UTLS) region compared to the effects of CO_2. Halocarbons are an important greenhouse gas at the tropical tropopause, however chemistry-climate model (CCM) simulations showed that the expected radiative warming resulting from an increase in halocarbons is nullified by feedbacks from water vapour and ozone. While the stratospheric column ozone increases with increasing CO_2, it decreases with increasing halocarbons.

Day 2: Stratosphere–Troposphere Coupling

In a keynote lecture **Mark Baldwin** highlighted the role of the stratospheric "wave-driven pump" for stratosphere-troposphere coupling (STC), as it creates potential vorticity anomalies corresponding to weak and strong vortex conditions and moves mass into and out of the polar cap. The North Atlantic Oscillation signal from the stratosphere is self-reinforcing through modifying baroclinic eddies, thus amplifying the stratospheric signal. The use of a simple polar cap pressure diagnostic was suggested to evaluate STC in models. The downward propagation of anomalies after sudden stratospheric warmings (SSWs) was found to be independent of the strength of the SSW, suggesting an active role of the troposphere in the downward propagation (**Theresa Runde**, presented by **Martin Dameris**). **Amanda Maycock** (presented by **Peter Hitchcock**) showed that differences in the Northern Annular Mode signature between displacement and split SSWs are uncertain and dependent on the SSW definition, arguing that knowledge of the magnitude and persistence of stratospheric anomalies is likely to be more useful for predictability than knowledge of the event type. A classification of SSWs according to whether or not wave reflection occurs during the recovery phase of the SSW was introduced, with absorbing SSW types leading to an Arctic Oscillation signal (**Kunihiko Kodera**). Mechanisms for the downward influence of the stratosphere on the tropospheric jet and surface climate were discussed and the roles of interactive chemistry and feedbacks in tropospheric synoptic wave activity emphasized (**Peter Hitchcock**, **Aditi Sheshadri**, **Sabine Haase**). It was also shown in a number of talks that stratospheric ozone is clearly a leading order forcing of the climate system. Using ensemble CCM simulations **Natalia Calvo** found that stratospheric ozone minima have a significant impact on surface climate, and March Arctic ozone could be useful for tropospheric prediction of April and May surface climate in certain regions (**Diane Ivy**). The relevance of ozone in STC was also documented in presentations of stratospheric intrusions in multiple tropopauses (**Irina Petropavlovskikh**), a projected change of stratospheric-tropospheric ozone exchange with increasing greenhouse gases (**Stefanie Meul**), changes in European tropospheric ozone (**Fiona Tummon**), radiative ozone feedback (**Catrin Gellhorn**, **Michael Ponater**), and as a driver of the recent tropical expansion (**Chaim Garfinkel**). Results from a new generation of fully coupled stratosphere-troposphere-ocean models were presented allowing the study of feedbacks between stratospheric change and the oceans (**Blanca Ayarzagüena**, **Nour-Eddine Omrani**, **Rongcai Ren**). Other studies focused on the tropical tropopause layer (TTL), addressing questions such as what can be done to narrow the gap between the observed and modeled TTL and how can a better tropical stratosphere improve tropospheric climate and weather forecasts. Using idealized model experiments, **Edwin Gerber** showed that the TTL is largely controlled by tropical processes with an asymmetric impact of synoptic waves on the TTL annual cycle.

Day 3: Stratospheric Ozone

A major topic in the stratospheric ozone session was the use of long-term ozone datasets to derive robust stratospheric ozone trends. New combined ozone datasets have recently become available, such as the ESA-Climate Change Initiative total ozone climate data record covering the period 1995-2015 (**Melanie Coldewey-Egbers**), and trends from different instruments at Northern Hemisphere mid-latitude stations were presented (**Sophie Godin-Beekmann**). In line with the WMO/UNEP Scientific Assessment of Ozone Depletion 2014, the extended datasets suggest the beginning of a recovery of upper stratospheric ozone (but with low significance), while no significant increase of global total column ozone was reported (keynote lecture by **Wolfgang Steinbrecht**). Confirmation of these results will require continuing long-term high-quality observations and analysis.

Moreover, it is important to assess the stability of long-term ozone profile records. In order to detect ozone trends of 3%/decade due to the decline of ozone depleting substances there are requirements with respect to the stability of individual instruments and the quality of the reference dataset (**Daan Hubert**, **Mark Weber**). Observations of recent changes in stratospheric composition between observations and models, however, the flight-to-flight variability is not captured by models. A new value of Br_y=19.5-22.5ppt was added to the bromine budget for 2013, indicating no trend (**Bodo Werner**). Chemistry-climate simulations show that both ozone depleting substances (ODSs) and greenhouse gases, like CO_2, N_2O, and CH_4 have affected and will further affect the ozone layer of ozone and temperature with dynamics as the main driver below 30km, while above 30km a positive correlation exists, with photochemistry being the driver (**Toshihiko Hirooka**). The El Niño-Southern Oscillation (ENSO) was shown to be an important factor for regional tropical ozone trends that might be misrepresented in zonal mean data (**Peter Braesicke**).

Figure 7: Participants of the SHARP2016 workshop in Berlin.

indicate slow decreases of chloroflourocarbons, halons, chlorine, and bromine, confirming the success of the Montreal protocol. An observed increase in HCl in the recent past could be attributed to stratospheric dynamical variability and is not in contradiction to the Montreal Protocol. The atmospheric abundance of the uncontrolled very short-lived substance CH_2Cl_2 is, however, increasing rapidly, and needs to be monitored. The MP has already shown some benefits, since without the Montreal Protocol the March 2011 Arctic ozone loss would have been comparable to Antarctic ozone loss (**Martyn Chipperfield**). Airborne measurements of Br_y in the TTL show good agreement (**Wolfgang Steinbrecht**). With declining ODSs, N_2O, and CH_4 will become more important in future. The effect of a future increase in N_2O on ozone depends on the greenhouse gas scenario, with no stratospheric NO_y change expected for the strongest RCP8.5 scenario (**Stefanie Meul**). Decreasing ODSs will lead to higher polar spring total ozone, while a concurrent greenhouse gas increase will enhance this effect due to an increase in the eddy forcing associated with enhanced sea surface temperatures (**Martin Budde).** The role of dynamical variability for ozone was demonstrated for the tropical quasi-biennial oscillation (QBO) that leads to a negative correlation

Day 4: Stratospheric Water Vapour

While progress has been made in the understanding of processes governing the entry of water vapour into the stratosphere, this understanding is still incomplete (keynote lecture by **Stefan Fueglistaler**). Large-scale transport and temperature seem sufficient to explain the most prominent features of stratospheric water vapour (SWV), with horizontal advection playing an important role, particularly in cold regions, and recent trajectory-based model studies give reasonable answers. Likewise, general circulation models with correct tropopause temperatures simulate reasonable SWV. However, challenges remain regarding the importance of temporal versus spatial temperature variance, the unexplained variability in the observational record, for example the year 2000 water vapour drop, the existence of evidence for the importance of various transport pathways, and the efficiency of cirrus dehydration. A wealth of new observational datasets, also with improved quality have become available from tropical *in situ* measurements (**Holger Vömel**) as well as from satellite measurements (SCIAMACHY, **Katja Weigel**, and MIPAS, **Stefan Lossow**). A systematic analysis of almost all available datasets, performed as part of the SPARC WAVAS-II initiative, has led to a better characterisation of instrumental biases and drifts (**Karen Rosenlof**). A detailed comparison of the Boulder Frost-Point Hygrometer SWV series with satellite, airborne measurements from the MACPEX campaign, and model simulations showed partially excellent agreement, but also problematic periods and local effects (**Dale Hurst**). Using CCM simulations as a transfer standard, **Michaela Hegglin** presented a combination of multiple datasets to study variability on longer time scales than one individual dataset can provide. Comparisons between simulations and observations show qualitative agreement but still differences in quantitative terms.

When laid over the mean 'tape recorder', SWV exhibits tape recorder anomalies due to ENSO, the QBO, or stratospheric major warmings. The latter may lead to an additional dehydration signal of 0.1-0.3ppmv, depending on the phase of the QBO at the tropical tropopause (**Martin Riese**). An indirect effect of decadal solar variability was shown on tropical lower stratospheric water vapour, with a negative correlation of about 25 months after solar maximum (**Gabriele Stiller**). A comparison of water vapour in CCM simulations showed that the cold-point temperatures in models play a crucial role for SWV, largely explaining the spread among models. A multi-model CCM analysis of SWV variability due to the Asian Summer Monsoon, ENSO, and QBO was presented by **Markus Kunze**, and due to the effect of volcanic eruptions by **Patrick Jöckel**. **Sabine Brinkop** also used CCM simulations with specified dynamics to show that sea surface temperatures and related upwelling, as well as the QBO and the synoptic situation contributed to the drop in SWV after the year 2000. To better understand the driving mechanisms of SWV in the models, further diagnostics, *e.g.*, isotopologues, were implemented (**Roland Eichinger**), as well as comprehensive observational datasets for model evaluation. In future, an increase of SWV is projected following a warming of the TTL, however, an increase in convective ice lofted into the stratosphere could also play a role (**Andrew Dessler**), as well as methane oxidation in the upper stratosphere (**Andrea Stenke**).

Reference

Langematz, U. and the SHARP consortium, 2011: Stratospheric Change and its Role for Climate Prediction (SHARP): A contribution to SPARC, *SPARC Newsletter*, **36**, 32-35.

Workshop on Dynamics, Transport, and Chemistry of the UTLS Asian Monsoon

7-10 March 2016, Boulder, Colorado

William Randel[1], Laura Pan[1], Jianchun Bian[2], Chiarra Cagnazzo[3], Rolf Müller[4], and Michelle Santee[5].

[1]NCAR, Boulder, Colorado, USA, **randel@ncar.edu**, [2]IAP/CAS, Beijing, China, [3]ISAC-NRC, Rome, Italy, [4]Forschungszentrum, Jülich, Germany, [5]NASA JPL, Pasadena, California, USA

The upper troposphere-lower stratosphere (UTLS) of the Asian summer monsoon (ASM) region is characterized by a continental-scale anticyclonic circulation, which is dynamically active and coupled to monsoonal convection. The monsoon anticyclone exhibits anomalous chemical and aerosol characteristics, linked to the outflow of deep convection and the large-scale circulation, and strongly influences the global UTLS composition during boreal summer. Ongoing increases in regional surface emissions enhance current scientific interests. There is substantial work in the research community aimed at improving understanding of the behaviour of the UTLS monsoon region using observations and models. Key topics that are poorly understood include dynamical and chemical coupling with convection, three-dimensional transport pathways from the surface to the stratosphere, composition/reactive chemistry in the monsoon region, as well as microphysics and the tropopause aerosol layer. There are plans for aircraft-based field experiments and enhanced *in situ* sampling in the near future, which promise novel data to address these questions. To summarize current understanding and plan for future activities, a workshop was held from 7-11 March in Boulder, Colorado, USA, focused on "Dynamics, Transport and Chemistry in the UTLS Asian Monsoon". The workshop was aimed at synthesising observations from satellites, aircraft, and balloons; modelling from regional to global scales; and developing key questions for the focus of future research. The workshop was attended by ~50 scientists and students who are actively engaged in UTLS monsoon research. This summary provides a brief overview of the key topics and discussions; a list of workshop participants and the individual presentations made at the workshop can be found here: **www2.acom.ucar.edu/asian-monsoon**.

Dynamics

The ASM system plays a dominant role in large-scale climate variability influencing over half of the world's population. Monsoon-related droughts and floods, and effects of enhanced aerosols and poor air quality are serious environmental hazards. The monsoon circulation and water cycle are driven by atmospheric heating tied to convection, with complex behaviour across a wide range of space-time scales. New research is recognizing the importance of the UTLS as an integral component of the monsoon system.

Monsoon dynamics and aerosol interactions

One aspect of monsoonal behaviour emphasized over recent decades regards the feedback effects of atmospheric aerosols, especially absorbing aerosols (*e.g.,* black carbon), which regulate and interact with heat sources and influence circulation and water cycles. Deep convection and aerosol feedbacks are strongly coupled with circulations extending to the UTLS, and new work focuses on quantifying dynamical and radiative feedbacks and coupling with lower altitudes. Improved understanding of the UTLS region and its impact on dynamical, chemical, and radiative behaviour at lower levels is a major research goal (**Bill Lau**).

Anticyclone behaviour, stratosphere-troposphere exchange (STE), and the tropopause

The UTLS monsoon anticyclone is an inherently unstable circulation pattern, with sub-seasonal modulation of the anticyclone centre and 'eddy shedding' as key aspects of observed variability (in both dynamics and constituents). Discussions at the workshop focused on understanding bimodality of the anticyclone (with centres over Tibet and Iran), and quantifying the relationships between shifting of the anticyclone, large-scale

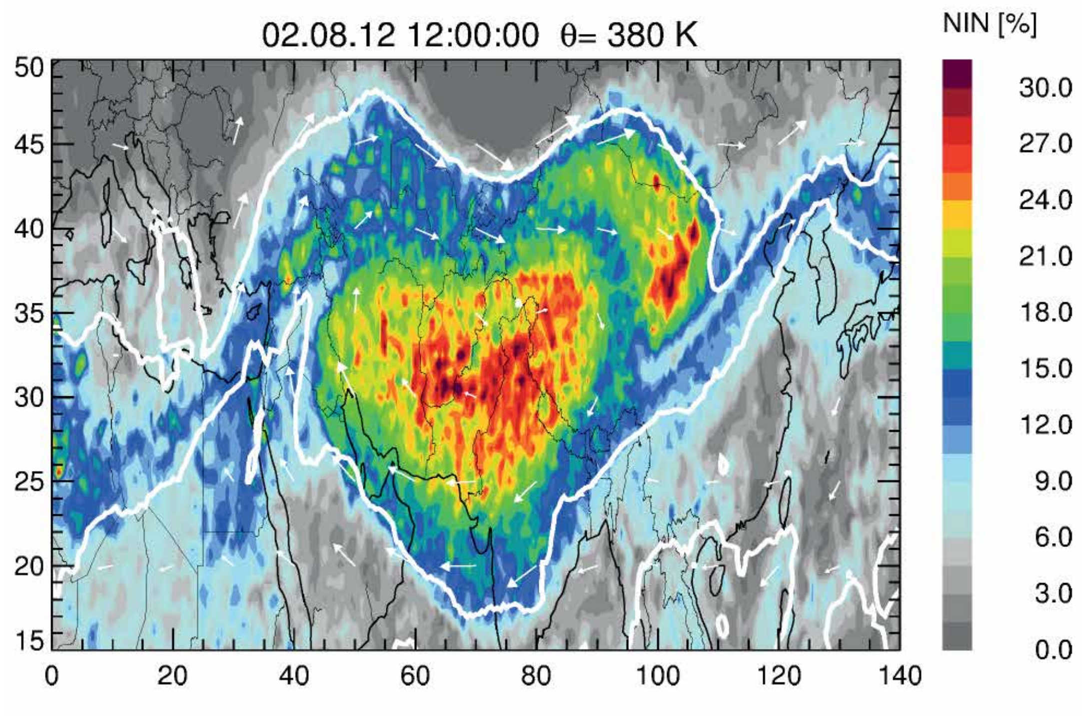


Figure 8: Distribution of the fraction of air originating from Northern India at the 380K potential temperature level on 2 August 2012 from a CLaMS model simulation with emission tracers. The 4.5PVU surface roughly marks the edge of the anticyclone and is shown with a white line (details discussed in Vogel *et al*., 2015, doi:10.5194/acp-15-13699-2015).

precipitation and convection, and Rossby wave dynamics. El Niño/ Southern Oscillation (ENSO) influences interannual variability, although interactions are complex. Further work aims at evaluating STE and behaviour of the tropopause linked to monsoon dynamics (**Yimin Liu**, **Chiara Cagnazzo**, **Mathias Nuetzel**, **Rongcai Ren**, **Yutian Wu**, **Pengfei Zhang**).

Transport

Transport associated with the ASM anticyclone was the most discussed topic during the workshop. Using different approaches and tools, the participants addressed and explored several issues and questions.

Anticyclone transport boundaries and pathways from the boundary layer

To quantify transport and confinement within the anticyclone, it is important to identify its boundaries. Discussions included the use of geopotential height, stream function, jet structure, and isentropic potential vorticity (PV) gradient to identify the edge of the anticyclone. Analyses of the thermal tropopause and cold point show that the ASM tropopause is higher than the equatorial tropopause during this season. Quantifying preferred transport pathways from the boundary layer to the UTLS anticyclone is important for understanding driving processes and identifying dominant source regions. Various approaches show that the southern flank of the Tibetan Plateau is a key region for boundary layer air to enter the anticyclone. The pathways and time scales for air in the anticyclone to enter the stratosphere are topics of active research.

Influence of convection on the UTLS

Calculations estimating the influence of deep convection on the UTLS can be made using backward or forward trajectories coupled with (diurnally-resolved) brightness temperatures from geostationary satellites (as a proxy for deep convection). Preferred source regions for the monsoon are the chronic deep convective regions over the South China Sea and Bay of Bengal. Global calculations of 'convective influence' demonstrate that most of the tropical upper troposphere has intersected convection within the previous ~2-5 days.

Transport and mixing tied to monsoon circulations

The global behaviour of UTLS mixing during boreal summer was discussed based on various mixing diagnostics. The ASM anticyclonic flow plays a key role for mixing of higher latitude lower stratospheric air into the low latitude tropical tropopause layer (TTL), influencing the seasonal cycle, and may also contribute to cross-equatorial transport. Transport through the anticyclone may be evaluated using tracers and diagnostics based on meteorological analyses (such as identifying manifolds or Lagrangian Coherent Structures). **Figure 8** provides an example of a diagnostic of the impact of Northern India source regions on UTLS composition, based on the Lagrangian CLaMS model. The large fraction of Northern India emission at the 380K level is consistent with the effective pathway of uplifting near the southern flank of the Tibetan Plateau.

Composition and Chemistry

Large-scale behaviour of chemical composition from satellite observations

The ASM impact on UTLS composition has been documented by satellite measurements, especially from the decade-long records from limb-sounding the MLS, MIPAS, and ACE-FTS instruments. These datasets reveal strong signatures of enhanced

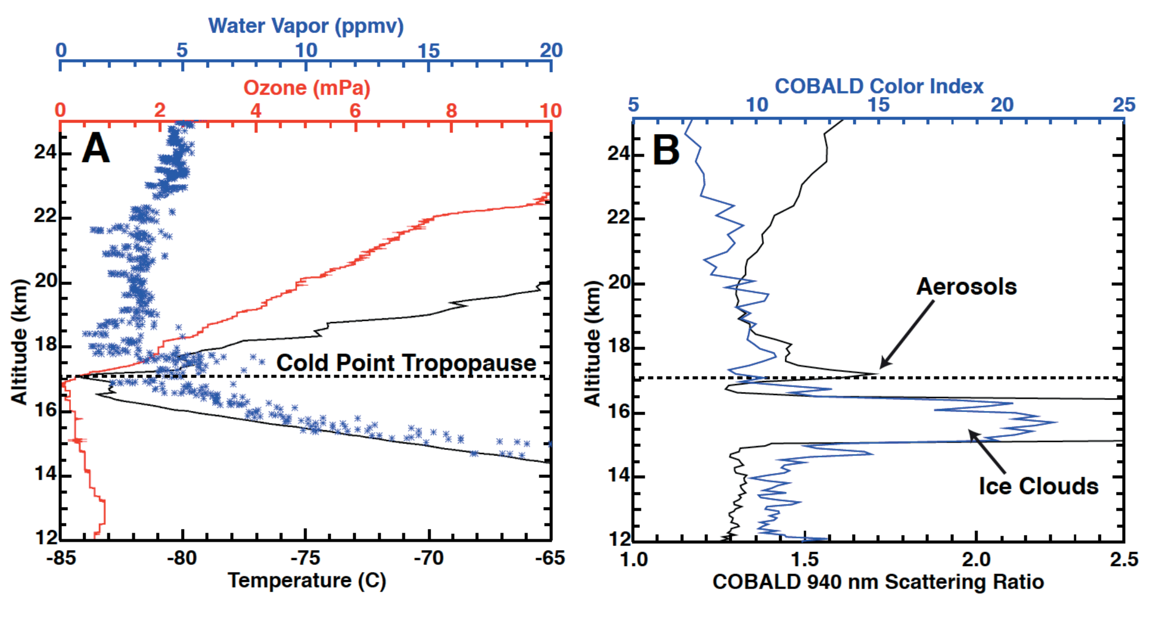


Figure 9: An example of balloon measurements from Hyderabad, India, from 13 August 2015, showing the complexity of ASM UTLS reflected in (a) temperature, ozone, and water vapour, and (b) cirrus and the aerosol layer. The data shown are from an integrated payload of ozonesonde, Cryogenic Frost-point Hygrometer (CFH), optical particle counters (OPC, data not shown), and Compact Optical Backscatter and AerosoL Detector (COBALD). This flight was coordinated by TiFR, NASA Langley, the University of Wyoming, and Indian National Atmospheric Research Laboratory. Figure courtesy Jean Paul Vernier and colleagues.

The analyses presented involve Lagrangian models (**Ken Bowman**, **Bernard Legras**, **John Bergman**, **Paul Konopka**, **Rolf Müller**, **Baerbel Vogel**), chemical transport and chemistry-climate models (**Suvarna Fadnavis**, **Laura Pan**), diagnostics from dynamical fields and idealized tracers (**Marta Abalos**, **Clara Orbe**) and studies combining trajectory model calculations and observations (**Brice Barret**, **Klaus Gottschaldt**, **Mike Fromm**, **Nathaniel Livesey**).

boundary layer tracers within the anticyclone. The observations also show synoptic-scale variability in numerous species with stratospheric or tropospheric origins and the combination of species provides a fingerprint of source regions for the UTLS. Observations of pollution tracers (such as CO from MLS or PAN from MIPAS) demonstrate transport and eddy shedding events tied to dynamical circulations (**Michelle Santee**, **Gabi Stiller**, **Mijeong Park**, **Federico Fierli**, **Suvarna Fadnavis**, **Jiali Luo**).

In situ observations from aircraft and balloons

Limited *in situ* measurements from in-service aircraft have provided detailed composition measurements, including short-lived hydrocarbon species that demonstrate rapid transport (a few days) from the boundary layer to the upper troposphere (10-12km). However, the lack of such measurements above ~12km limits the understanding of transport to higher altitudes. There are limited measurements of reactive nitrogen in the monsoon UTLS, and poor understanding of the contributions of near-surface emissions versus lightning generation. Campaign-based balloon measurements of water vapour, ozone, aerosol, and cirrus information (from COBALD backscatter measurements) have been made in the monsoon region over China since 2009,

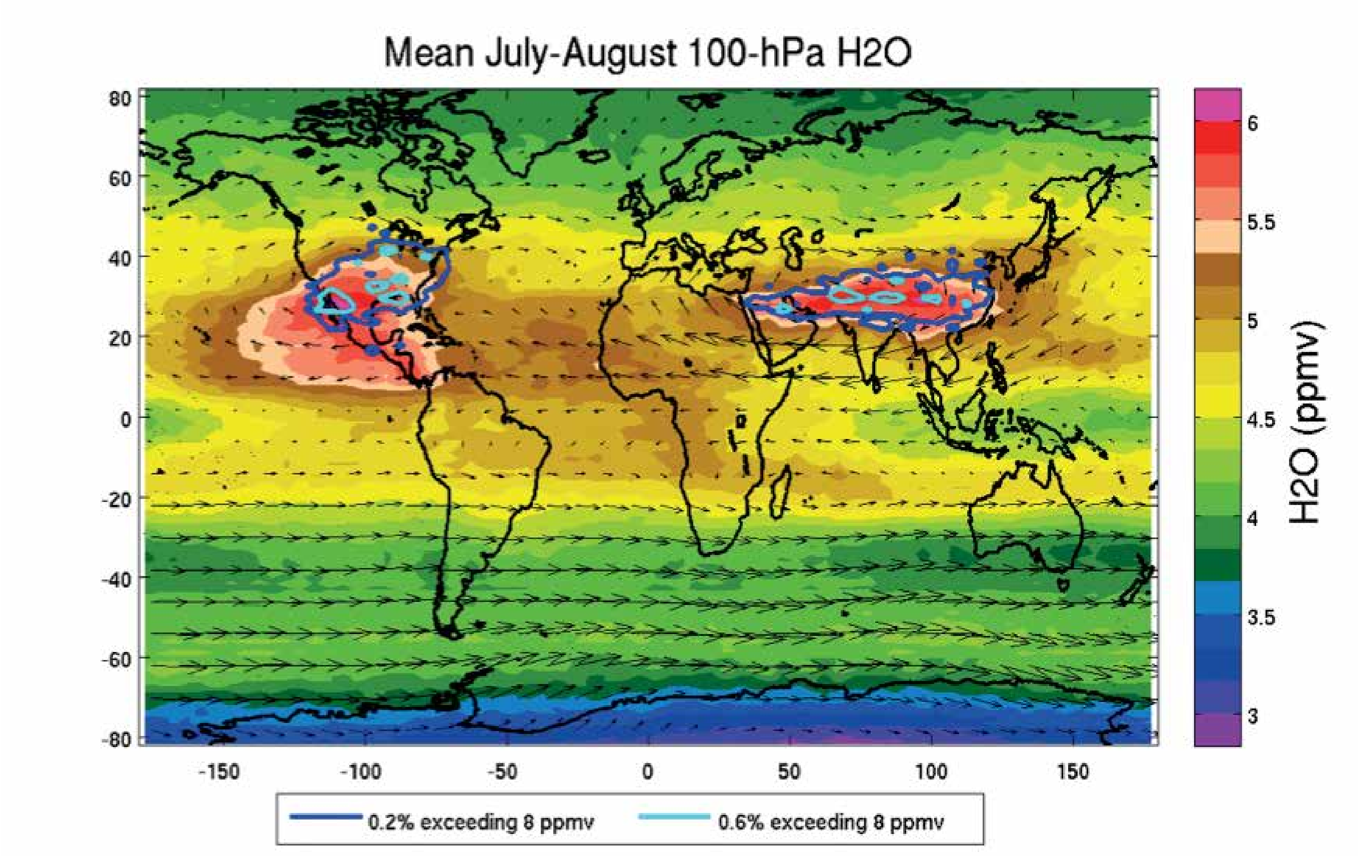


Figure 10: Colours show climatological average July-August water vapour at 100hPa, highlighting maxima over the Asian and North American monsoon regions. Colour contours indicate incidences of extreme outliers (individual measurements above 8ppmv at 100hPa). Results are derived from MLS observations during 2004-2012. Arrows indicate corresponding average circulation at 100hPa.

more recently including particle counter measurements. A similar measurement campaign was conducted from five launch sites in India last year, and **Figure 9** shows an example of balloon data from Hyderabad, India. While limited in sampling, these provide a novel ground-truth evaluation of satellite measurements, quantitative estimates of supersaturation and cloud microphysical processes, and aerosol behaviour (**Angela Baker**, **Jianchun Bian**, **Jean Paul Vernier**, **Shradda Dhungel**).

Impacts on stratospheric water vapour

The Asian and North American monsoon regions are characterised by enhanced water vapour in the lower stratosphere (**Figure 10**) and frequent occurrence of cirrus near the tropopause. Observational and modelling studies are aimed at understanding the contribution of large-scale circulation versus extreme deep convection in maintaining these patterns. Trajectory studies based on meteorological reanalyses, incorporating convective influence, are able to capture the broad-scale water vapour and cirrus behaviour. Temporal variations in lower stratospheric water vapour are closely tied to temperatures and dehydration on the equatorward (cold) side of the anticyclone. However, extremely moist air in the lower stratosphere is observed (infrequently) in satellite measurements (and field campaigns), demonstrating the direct influence of extreme convection. The relative influence of large- versus small-scale processes on UTLS water vapour and clouds is an outstanding research topic (**Michael Schwartz**, **Rei Ueyama**, **Wuke Wang**, **Bill Randel**).

Aerosols and Clouds in ASM region

The Asian Tropopause Aerosol Layer (ATAL) was discovered based on satellite lidar measurements. It is an annually occurring feature that may be strengthening over time as a result of growing Asian pollution. Several balloon-based measurement campaigns have made direct measurements of the ATAL, with results showing reasonable agreement with satellite-derived observations. Recent measurements, including aerosol backscatter and particle size distribution measurements, suggest that the ATAL may be primarily composed of sulphate aerosols. Global aerosol modelling studies (incorporating climatological surface precursor emissions) show reasonable agreement with satellite and *in situ* measured aerosol behaviour, and suggest a modest radiative impact for the ATAL (**Jean Paul Vernier**, **Terry Deshler**, **Jianchun Bian**, **Simone Brunamonti**, **Teresa Jorge**, **Ru-Shan Gao**, **Pengfei Yu**, **Mian Chin**).

Outstanding questions

The last half day of the workshop was aimed at discussions on outstanding questions and strategies for future measurement and modelling activities. Some of the key questions include:

1. How will the monsoons (including the UTLS circulation) evolve in a changing climate? What are the impacts of increasing pollution over south east Asia?
2. What controls the strong upward circulations in the monsoon? What are the specific influences of aerosols?
3. Is the monsoon anticyclone bimodal in location or intensity? If so, what are the links to convection, 3D circulation, and transport?
4. What is the altitude profile of convective outflow in the monsoon regions? How can we best characterize the full spectrum of convection?
5. What are the relative roles of deep convection and large-scale circulation in pumping boundary layer air to the tropopause level? What is the time scale for air within the ASM anticyclone to enter the stratosphere?
6. What is the relationship and coupling between ASM 3D circulation and the monsoon Hadley cell, and with the stratospheric Brewer-Dobson circulation? What are the relationships between vertical and horizontal transport?
7. What reactive chemistry and aerosol growth processes occur in the UTLS? Is there an anthropogenic signal in the ATAL? Is the monsoon a pathway for transport of sulfur to the stratosphere?

The workshop discussions provided an updated picture of the state of the science regarding ASM UTLS research. The discussions also provided useful input for the StratoClim project, which is making an active effort to target some of these questions in an upcoming airborne field campaign (campaign plan overviewed by **Markus Rex**).

Report on the Workshop on Atmospheric Blocking

6-8 April 2016, University of Reading, UK

Giacomo Masato[1,2,3], Tim Woollings[4], Olivia Romppainen-Martius[5], John Methven[2], and Ben Harvey[2,3]

[1]Marex Spectron LTD, [2]University of Reading, Reading, UK, **b.j.harvey@reading.ac.uk**, [3]National Centre for Atmospheric Science, UK, [4]University of Oxford, Oxford, UK, [5]University of Bern, Bern, Switzerland

Atmospheric blocking plays a crucial role in modulating the variability of the mid-latitude circulation, particularly from sub-seasonal to annual and interannual timescales. Blocking also heavily affects weather conditions at the surface, being associated with largescale cold spells during winter and persistent heatwave episodes during summer.

During the Workshop on Atmospheric Blocking, over 100 experts from 22 countries (**Figure 11**) gathered to discuss recent advances in our understanding of blocking, its impacts and its representation in numerical models. Topics spanned from weather to climate timescales, and from theoretical developments to the latest operational capabilities.

Each of the three days of the workshop addressed a key topic: blocking identification and diagnostic tools, past trends and impacts of blocking, and the representation of blocking in numerical models and future projections.

Brian Hoskins opened the first day with a historical review onftheories of blocking, starting with the

Figure 11: Participants at the Workshop on Atmospheric Blocking held in Reading, UK.

early ideas of Rossby (who drew comparisons between blocking and hydraulic jumps) up to more recent interpretations involving Rossby wave breaking and the role of diabatic processes. **Mischa Croci-Maspoli** presented a review of the wide range of blocking diagnostics currently employed, as well as stressing the influence of model resolution and moist processes on blocking behaviour.

One of the most recent diagnostics to be developed focuses on so-called local wave activity (LWA). The approach essentially measures the 'waviness' of the quasi-geostrophic potential vorticity field (**Clare Huang**), and resembles rather closely the blocking climatologies commonly found in literature (**Patrick Martineau**). Other techniques such as GPS radio occultation observations can be applied to identify blocking, relying on the excellent coverage of satellite data (**Lucas Brunne**r). Covariant Lyapunov vectors can also be employed to study the dynamics of blocking regimes (**Sebastian Schubert**).

Diabatic processes are observed to be an important mechanism for blocking formation and maintenance. Latent heat release is observed to be present for up to 70% of blocking events considering a period of seven days prior to blocking formation (**Stephan Pfahl**), while warm conveyor belt outflows significantly increase prior to the Atlantic Ridge and European Blocking regime (**Christian Grams**). Non-linear dynamics also play an important role in blocking occurrence. In particular, the interaction between planetary waves and synoptic-scale eddies is useful in determining the developing phase of the North Atlantic Oscillation (**Dehai Luo**).

Blocking can be related to Rossby waves, whose stationarity is at the base of extreme meteorological events such as recent flooding event and heatwaves over Europe (**John Methven**). Indeed, Northern Hemisphere heatwaves can be linked to large amplitude, quasi-stationary Rossby wave packets which, under certain conditions, become resonant with stationary forcing on the synoptic scale (**Georgios Fragkoulidis**). Statistical space-time clustering methods can also be employed, showing that the persistence of blocking-like (*i.e.* Rossby wave-breaking) events is due to the eddy-mean flow feedback (**Christian Franzke**).

The Madden-Julian Oscillation has an influence on important factors contributing to blocking formation, such as Rossby wave-breaking and the North Atlantic Oscillation (**Stephanie Henderson**). Away from the tropics, the Pacific jet stream and its retraction along the zonal direction is found to be associated with the occurrence of amplified ridges downstream (**Melissa Breeden**). Likewise, atmospheric rivers (whose influence is observed over the coastal regions of North America) also tend to occur and are affected by the presence of atmospheric blocking over the east Pacific (**Elizabeth Barnes**).

Past trends and impacts of blocking, as well as its link with extreme events were the dominant themes of day two. **Ricardo Trigo** discussed the precipitation patterns associated with blocking over the European region, highlighting the differences between dipole blocks and stationary ridges: while atmospheric instability is crucial to drive the positive rainfall anomalies over southern Europe, moisture availability is the main driver at higher latitudes.

Middle East snowstorms are found to be connected with the presence of blocking over Europe, with a characteristic north-east to south-west tilt (**Yao Yao**). Moreover, central European flood events are associated with blocking occurrence, whose stationarity and interaction with cloud diabatic processes is key to the persistence of such events (**Sina Lenggenhager**).

Changes in blocking properties seem to have occurred towards the end of the 20th century, with more persistent (although weaker) events (**Anthony Lupo**). Trends are also detected for the high-latitude Greenland blocks, whereby increased frequencies are observed after the 1980s, particularly in summer (**Edward Hanna**). However, other studies suggest no significant trends in blocking occurrence can be found (apart from localized cases), as this is embedded within large natural variability signatures (**Etienne Dunn-Sigouin**). Strong inter-annual variability is observed in particular over the Euro-Atlantic sector, with negative and positive phases of the North Atlantic Oscillation driven by the occurrence of high- and low-latitude blocking (**Young-Oh Kwon**).

Atmospheric blocking occurs in the Southern Hemisphere too, with the main region lying across the southern Pacific Ocean (**James Renwick**). Blocking is found to influence the climate of southern Australia, with associated cut-off lows bringing precipitation there (**Caroline Ummenhofer**). A strong link between blocking and the behaviour of the South Atlantic Convergence Zone is also observed, with large rainfall anomalies taking place over Brazil (**Regina Rodrigues**).

Cold outbreaks in the mid-latitudes are often dependent on the behaviour of the polar stratospheric vortex, which in turn can be preceded by the occurrence of blocking (*e.g.*, the Aleutian High during late January 2014, **Stephen Colucci**). Different blocking precursors tend to drive wavenumber-1 versus wavenumber-2 Sudden Stratospheric Warmings (SSWs), which are also modulated by the presence of El Niño (**David Barriopedro**). Interestingly, the blocking-SSW causality can also be detected by employing an idealized dynamical core model where the tropospheric stationary wave forcing is varied (**Daniela Domeisen**).

The anthropogenic contribution has been analysed as well, and contrasting results have been found. Little changes in the imposed blocking conditions can potentially drive exceptional rainfall in Colorado, USA, due to the increase in anthropogenic drivers (such as moisture-carrying capacity of a warmer atmosphere, **Pardeep Pall**). On the other hand, blocking frequency does not seem to significantly change under anthropogenic climate change during European summers (**Dann Mitchell**).

Modelling blocking and its future projection were the focus of day three's activities. The ability of climate models to simulate blocking has improved over generations of models, from AMIP1 up to CMIP5, although serious biases remain in many models (**Paolo Davini**). Several cases were shown where improvements in model dynamics (**Tim Woollings**) and/or physics (**Kerstin Hartung**) have led to improved blocking, but successful European blocking simulation cannot be guaranteed, even in state-of-the-art models (**Keith Williams**).

Increasing atmospheric resolution can improve the representation of blocking, but only robustly for several models in spring (**Reinhard Schiemann**). European blocking biases still affect Numerical Weather Prediction models in the form of forecast "busts". These forecasts show sensitivity to dynamics around the globe (**Tess Parker**), with many of these cases sharing a common bias of weaker than observed convective activity upstream over North America (**Mark Rodwell**).

Reliable forecasting of blocking on seasonal timescales is clearly needed for predicting impacts such as the 2010 Russian heatwave (**Lisa-Ann Quandt**). Seasonal forecasting systems are making encouraging progress in this regard, giving skilful forecasts of winter Atlantic/European blocking (**Panos Athanasiadis**). European blocking can certainly be influenced by sea surface temperatures, for example, showing sensitivity to the sharpness of the Gulf Stream front (**Chris O'Reilly**).

While there is some qualitative agreement on future changes in blocking, there remains considerable spread between models (**Aleksandr Timazhev**). Several studies focused on the impact of Arctic warming on blocking. Climate models can reproduce recent winter cooling over northern continents but don't robustly show a change in blocking (**Seok-Woo Son**). Often the clearest response to Arctic warming is the change in blocking impact associated with changing thermal advection (**Blanca Ayarzagüena**). Idealised studies show blocking activity weakening and shifting equatorward with the jet as the Arctic warms, in a manner that contrasts the natural variability (**Pedram Hassanzadeh**, **Alex Burrows**).

The workshop was organised by the new World Weather Research Programme (WWRP) working group on Predictability, Dynamics, and Ensemble Forecasting, and the organisers are indebted to SPARC for administrative support. The workshop was free to attend thanks to generous contributions from WCRP, IAMAS/ICDM, NCAS-Climate, ERC, and the Universities of Bern and Reading, all of whom are gratefully thanked. A perspective paper summarizing developments in our understanding of atmospheric blocking and outstanding research questions discussed during the workshop is planned to be submitted in the near future.

The 2nd Workshop on Stratospheric Sulfur and its Role in Climate

Stefanie Kremser[1] **and Larry Thomason**[2]

[1]Bodeker Scientific, Alexandra, New Zealand, **stefanie@bodekerscientific.com**, [2]NASA Langley Research Center, USA

A workshop held in support of the SPARC Stratospheric Sulfur and its Role in Climate (SSiRC) activity was hosted by **Markus Rex** at the Alfred Wegener Institute (AWI) in Potsdam, Germany from 25-28 April 2016. The meeting was attended by about 70 scientists from 14 countries, including a number of students and other early career scientists. The workshop consisted of oral and poster presentations as well as focused small groups and more broad ranging plenary discussions (see **http://www.sparc-ssirc.org**). A review of SSiRC's history was provided by **Larry Thomason**, including an overview of SSiRC's activities since becoming a SPARC activity in 2012 as well as new and ongoing activities. These include evolving modelling activities and an effort to generate an observation-based sulfur budget for the period 1984-present. Highlights of the SSiRC-sponsored review paper on stratospheric aerosol were presented by **Stefanie Kremser**. Entitled "Stratospheric aerosol: Observations, processes and impact on climate", the paper is one of more than 50 SSiRC-related publications since 2013 and serves as a follow-up to the Assessment of Stratospheric Aerosol Properties (SPARC, 2006). **Claudia Timmreck** provided an overview of the CMIP6 activity VolMIP, the Model Intercomparison Project on the climate response to volcanic forcing, which is affiliated to SSiRC and focuses on assessing the response of the coupled ocean-atmosphere system to well-constrained strong volcanic forcing in state-of-the-art climate models.

Space-based stratospheric aerosol measurements

A focus of the workshop was on recent developments in space-based measurements of aerosol and its precursors. An overview of the current and planned satellite missions by NASA was given by **Ken Jucks**, including operational aerosol products from the Ozone Mapping Profiler Suite (OMPS) in the near future and a SAGE-III flight aboard the International Space Station beginning in 2017. **Ghassan Taha** presented OMPS aerosol extinction coefficient measurements from a preliminary algorithm, which compare favourably with OSIRIS measurements; refinements are planned before a formal release of the data. The ALTIUS ESA mission is planned for 2020 to measure atmospheric concentration profiles of trace gases in the upper atmosphere with the potential to observe stratospheric and upper tropospheric aerosols and clouds (**Filip Vanhellemont**).

GOMOS products are undergoing a

major revision with the development of an improved retrieval algorithm for GOMOS (AerGom) that focuses on improving the aerosol product (Vanhellemont *et al*., 2016) (**Christine Bingen**). AerGom generally produces a better GOMOS aerosol extinction product and allows for better temporal and spatial resolution. Similarly, there are new stratospheric aerosol extinction coefficient profiles retrieved from SCIAMACHY limb-scatter observations (**Christian von Savigny**). The new dataset spans the entire EnviSat mission from 2002-2012. The globally-averaged agreement with co-located SAGE-II (version 7.0) measurements is within 15% between 16-35km altitude. The SCIAMACHY aerosol extinction data indicate a possibly solar-driven 27-day signature in stratospheric aerosol extinction which has not been previously reported. The dataset is publicly available from the University of Bremen (see **www.iup.uni-bremen.de/scia-arc**). MIPAS measurements (2002-2012) are a key source for aerosol precursor gases such as carbonyl sulfide (OCS) and sulfur dioxide (SO_2) (**Michael Höpfner**). The first global distribution of OCS shows a strong source over the Western Pacific and enhanced values in monsoon regions. MIPAS also shows enhanced SO_2 concentrations in monsoon regions and a strong seasonal variability at 10km at northern mid- and high latitudes. **Sabine Griessbach** showed that MIPAS aerosol measurements reach down to well below the tropopause and can provide cloud-top and -bottom altitudes, but tend to underestimate the cloud-top altitude relative to lidar measurements. **Pasquale Sellito** pointed out that there is potential for using nadir-viewing instruments such as IASI to monitor stratospheric aerosol particularly following volcanic events with the potential for improved spatio-temporal coverage compared to limb-viewing instruments.

It is often assumed that stratospheric aerosol is purely sulfate, possibly with some short-lived ash component. However, **Daniel Murphy**, using PALMS (Particle Analysis by Laser Mass Spectrometry) measurements, demonstrated that aerosol composition is far more diverse than normally considered. From these measurements, approximately 95% of stratospheric aerosol consist of sulfuric acid, with and without metals, as well as organic-sulfate mixtures from the troposphere. Meteoritic material, a common metal component, can be either dissolved or inclusions with a small impact on aerosol optical properties. Organic material from the troposphere has a long lifetime in the stratosphere, accounting for about 30% by mass under stratospheric background conditions.

Field campaigns

While efforts to deploy the Geophysica aircraft in India continues to progress, backup plans have been developed in case permissions are not obtained (**Markus Rex**). The recent StratoClim test campaign in Kiruna, Sweden, was terminated early due to the cancellation of flight permissions by Swedish authorities. During the StratoClim measurement campaign, airborne measurements will be complemented with balloon-borne measurements from sites across southern Asia. **Jean-Paul Vernier** presented results from a recent field campaign - Kelud Ash (or KlAsh), that was completed in June 2014. KlAsh consisted of University of Wyoming Optical Particle Counter (OPC) and ETH Zurich COBALD backscattersonde measurements which were performed as an effort to quantify the climate effects of the February 2014 eruption of Kelud. These instruments inferred the presence of ash three months following the eruption and confirmed CALIOP observations showing a persistent ash layer in the lower stratosphere.

Ground-based and in situ stratospheric aerosol and aerosol precursor measurements

Long-term measurements of stratospheric aerosol made since 1971 from Laramie, Wyoming, USA, are proposed to transition to Boulder, Colorado (about 150km south of Laramie). In addition to the current suite of OPC devices, **Lars Kalnajs** spoke about a new light-weight instrument that is being designed. The cost of the new payload will be lower than $10,000 each. These changes facilitate rapid deployment in the field and potential use when instrument recovery is not certain. A study by **Katie Foster**, comparing the University of Wyoming OPC data to OSIRIS and OMPS extinction coefficient measurements as well as COBALD backscattersonde measurements, found that the OPC-derived extinction values consistently underestimate the satellite-based measured values; a feature which is possibly related to issues fitting the coarse mode aerosol during low aerosol loading periods. **Damien**

Vignelles described a light optical aerosol counter (LOAC) that can be deployed on standard weather balloons. This instrument has been used in several field campaigns since 2013, dedicated to tropospheric aerosol. Stratospheric data are potentially available from 80 flights and are currently being analysed.

An analysis of stratospheric aerosol datasets from lidars based at the Obsérvatoire de Haute Provence, France, combined with other ground-based lidars is now available. Used in conjunction with space-based observations these data suggest that the uplift of polluted air within the Asian monsoon during boreal summer is responsible for a doubling of lower stratospheric aerosol optical depth (AOD) since 1998, following similar trends in ATAL optical depth (**Sergey Khaykin**). Observations from IASI have also been used to derive the column amount and altitude for recent volcanic plumes, with the altitudes being consistent with CALIPSO altitudes (**Elisa Carboni**). Virtually all SO_2 plumes observed by IASI reached the tropopause (Carboni *et al*., 2016). A modelling study presented by Sergey Osipov suggests that severe winter cooling in the Middle East observed at the beginning of 1992, when Red Sea surface temperatures decreased more than 1°K, was a regional climate response to the Pinatubo eruption resulting from a combination of dynamical and direct radiative cooling due to volcanic aerosols.

Long term upper troposphere/lower-most stratosphere measurements by IAGOS-CARIBIC include core measurements of aerosol number concentration, size distribution, elemental composition, and soot concentrations (**Markus Hermann**). These measurements made aboard commercial aircraft also include ozone, water vapour and OCS, a key stratospheric aerosol precursor. Measurements are available from hundreds of CARIBIC flights from 2005-2015 (see **www.iagos.org** and **www.caribic-atmospheric.com** for more information). **Susann Tegtmeier** presented the first observational evidence for the presence of dimethyl sulphide (DMS) in the upper tropical tropopause layer using measurements from the ATTREX campaign in early 2014. These observations confirmed FLEXPART model simulations that suggest the global DMS flux through the tropopause by direct entrainment is not negligible. However, model simulations have large sensitivities to chemical decay and convection schemes and further study is required. Airborne upper troposphere/lower stratosphere (UTLS) measurements by Laser Induced Fluorescence Spectroscopy support low SO_2 concentrations at the tropopause and agree well with satellite-based measurements (**Andrew Rollins**). These results indicate that tropospheric SO_2 is a rather small component of the overall stratospheric sulfur burden.

OCS is a primary source gas for stratospheric aerosol in background conditions. Recent ship-borne ocean measurements of OCS in the tropics indicate that it is unlikely that direct OCS emissions from the tropical ocean are the inferred 'missing source' of OCS (**Sinikka Lennartz**). Production of OCS from other source gases such as DMS seems likely but large uncertainties remain. **Corinna Kloss** derived the stratospheric OCS burden for 2012 from OCS measurements made by the ACE-FTS satellite, which agrees well with a model-based study by Sheng *et al*., 2015. Planned OCS measurements in the Asian monsoon region by the Airborne Mid-Infrared Cavity enhanced Absorption Spectrometer (AMICA) will provide another means to verify enhanced OCS within the Asian monsoon anticyclone. As shown by **Annika Günther**, MIPAS measurements of OCS and SO_2 are generally consistent with chemical transport model simulations.

A SSiRC-based effort to produce a long-term stratospheric sulfur burden is under way (**Terry Deshler**). The goal is to provide a temporal history of the gas and particle phase sulfur burden in broad latitude bands in monthly to seasonal averages from 1984 onward. However, some periods lack key measurements and thus it will remain incomplete in that regard. Particle and sulfur gas species measurements from *in situ*, lidars, and satellite instruments will be included. This sulfur burden product should be an excellent resource for testing model-derived sulfur budgets. **Thomas Peter** showed that the SOCOL chemistry-climate model (CCM) represents stratospheric aerosols for background and volcanic conditions well, suggesting a background stratospheric aerosol burden of about 109Gg of sulfur which is about 50% higher than the value estimated in SPARC (2006).

Modelling of stratospheric aerosol and its climate effects

Simulations of the stratospheric aerosol layer using the GEOS-5 CCM that uses a new aerosol radius parameterization and the major sources of stratospheric aerosol were presented by **Valentina Aquila**. These simulations showed that volcanic eruptions and OCS are the main source of stratospheric aerosol extinction and that tropospheric surface and organic carbon are important in the lower stratosphere. **Mian Chin** presented GOCART model experiments showing that volcanic aerosol dominates the total stratospheric aerosol amount even in volcanically-quiet periods. On the other hand, these simulations indicate that anthropogenic aerosol has a pronounced seasonal cycle in the tropopause region and that strong Asian monsoon convection makes transport of lower tropospheric material to the UTLS effective in summer. **Ingo Wohltmann** investigated the contribution of SO_2 to the stratospheric aerosol layer comparing chemical transport model (GEOS-Chem) simulations with trajectory calculations from ATLAS. He found significant differences between the amount of SO_2 reaching the stratosphere in the two models.

An in-depth study of balloon-borne and satellite measurements as well as model simulations was made to characterize the Asian Tropopause Aerosol Layer (ATAL) (**Duncan Fairlie**). Balloon measurements showed that ATAL aerosol is composed of small volatile particles of less than 0.2 micron. The model simulations indicate that regional emissions are a dominant source for ATAL and that the ATAL composition is a combination of sulfate and organic carbon. However, the model results are sensitive to the parameterised treatment of precursors in the convective updrafts, which remain poorly understood. Recent balloon-borne measurements by the POPS instrument verify the presence of the ATAL (**Ru-Shan Gao**) as observed by CALIPSO and SAGE-II. These balloon-borne measurements suggest that aerosol form/grow primarily in the upper troposphere and may primarily consist of organics.

The robustness of winter warming and summer Monsoon reduction following major volcanic eruptions was evaluated by **Alan Robock** for the period 1850-2005 using 23 climate models participating in CMIP5. All model simulations include volcanic eruptions but use a variety of volcanic forcing data. Among the main findings was that volcanic eruptions increase the probability of an El Niño in the year following an eruption and that volcanic eruptions were necessary for the initiation and maintenance of the Little Ice Age by inducing a new Arctic sea ice/ocean circulation state. **Mike Mills** presented a new prognostic stratospheric aerosol capability in the Community Earth System Model (WACCM). Model simulations from 1990-2015 were performed with and without volcanoes and comparisons of model results with lidar and balloon-borne measurements look promising. Comparisons of measurement-based aerosol climatologies and the WACCM-based depictions evoked some debate among workshop participants.

A study to investigate the climate impact of volcanic eruptions depending on latitude based on MAECHAM5-HAM model simulations concluded that Pinatubo-sized extra-tropical eruptions with high injection altitudes can have strong impacts on climate (**Matthew Toohey**). Factors that control the climate impact include the initial aerosol injection height, particularly the altitude above the tropopause, and the season of the eruption. **Sandip Dhomse** showed that the phase of the quasi-biennial oscillation (QBO) modulates the effects of tropical volcanic SO_2 injection. Modelling results indicate that when SO_2 is injected during the easterly phase of the QBO results are consistent with Pinatubo observations. However, when SO_2 injections occur during the QBO westerly phase an enhanced inter-hemispheric asymmetry in stratospheric aerosol occurs. Another model-based study on major volcanic eruptions concluded that the impact on tropical upwelling is larger when aerosols are more confined in the tropical region such as during the QBO easterly phase (**Daniele Visioni**). The QBO phase also affects the aerosol lifetime during the first year after eruptions, when the easterly phase corresponds to a longer aerosol lifetime. Model results also suggest that the partitioning between increased temperature and increased tropical upwelling due to heating by a low latitude volcanic event is dependent on the latitudinal width of the aerosol layer, with a narrow aerosol extent leading to greater upwelling (**Aaron Match**). Model simulations suggested that the ENSO response

Volcanic aerosol has had and will continue to have a major impact on climate and thus human quality of life. Continuously degassing volcanoes that emit material which remains almost exclusively in the troposphere can have a large impact on air quality and thereby impact human health. A model-based study shows that a future Laki-type eruption could lead to a long-lasting degradation of air quality with a high impact on health and mortality rates within Europe (**Anja Schmidt**). Future eruptions, even relatively small events like that of the 2014/2015 Holuhraun eruption, must be investigated using *in situ* measurements to fully understand the impact of a possible larger Laki-like eruption.

to major volcanic eruptions depends on the initial ENSO phase and El Niño type (**Evgeniya Predybaylo**). For instance, the effect of the Tambora eruption on ENSO is less pronounced than the effect of Pinatubo, primarily due to the timing of the eruption. The global aerosol model ECHAM5-HAM was used to understand if there is a limit to SO_2 injection rates for geoengineering above which cooling no longer increases (**Ulrike Niemeier**). Across a variety of injection scenarios, it was shown that there is no upper limit of SO_2 injections but that increasing injection rate increases the particle size and decreases scattering and efficiency and generally lowers the cooling response.

GEOS-5 reasonably simulates the 1991 Mt. Pinatubo and Cerro Hudson volcanic eruptions (**Peter Colarco**), with results suggesting a significant depletion of Antarctic ozone at 13km in the austral spring associated with Cerro Hudson aerosol. **Kristin Krüger** presented model studies indicating that the impact of chlorine and bromine emissions from large eruptions produce rapid stratospheric ozone loss in the tropics (<200DU) and that the volcanic halogens are long-lived in the stratosphere. The results also suggest that measurements of chlorine, bromine, and iodine species during the next volcanic eruptions are relevant to understanding the effects on stratospheric ozone. Results from the UM-UKCA CCM indicate that meteoric smoke particles (MSPs) reduce gas phase sulfuric acid and SO_2 concentrations above 35km and that MSP-core particles dominate the aerosol particle population throughout the stratospheric aerosol layer (**Graham Mann**). Stratospheric aerosol simulations using the EMAC model, where volcanic eruptions based on GOMOS and MIPAS measurements have been implemented into the model, found improved SO_2 depictions and a better representation of aerosol radiative forcing (**Christoph Brühl**).

Outcomes from Breakout Sessions

Aerosol volatility measurements during BATAL 2015 together with enhanced SO_2 levels observed by MIPAS highlight the potential role of sulfuric acid in the composition of the ATAL. It is hoped that aerosol and sulfur-bearing precursor measurements from StratoClim will shed light on the nature and origin of ATAL. An interactive stratospheric aerosol model intercomparison "ISA-MIP" (lead by **Graham Mann** and **Claudia Timmreck**) has been established in the framework of SSiRC. ISA-MIP will compare interactive stratospheric aerosol models using a range of satellite and *in situ* observations to constrain and improve model simulations and provide a sound scientific basis for future work. In the ISA-MIP breakout group the status of the four different experiments were presented and open issues discussed. The goal is to finalize the experiments before the Northern Hemisphere summer break. The stratospheric aerosol climatologies group agreed that a dedicated workshop on stratospheric aerosol climatologies was needed; **Larry Thomason** is organising a meeting which will hopefully take place in late 2016 or early 2017. SSiRC is also planning to coordinate a white paper on the scientific response needed in the event of a major volcanic eruption. **Jean-Paul Vernier** is leading this effort.

SSiRC SSG Meeting

A brief SSiRC Science Steering Group meeting was held after the workshop. Among the topics discussed was a proposal to the International Space Sciences Institute in Bern, Switzerland, which has recently been accepted to support SSiRC science activities. In addition, the preparation of a proposal for the American Geophysical Union for a SSiRC-themed Chapman Conference is moving forward. It was also suggested that a future SSiRC workshop could be hosted by **Juan-Carlos Antuña** in Havana, Cuba, mostly likely in 2019. The SSG noted that the SSiRC Capacity Database still does not have sufficient resources to make it attractive to scientists. It was agreed that a new effort to more densely populate the database would be attempted. Finally, the historic aerosol recovery activity has recovered data from the 1991 NASA airborne aerosol lidar mission that made some of the earliest low latitude observations of the Pinatubo eruption. These data will be available from the NASA Atmospheric Sciences Data Center in the near future.

Acknowledgements

We would like to thank AWI Potsdam for logistical and meeting support as well as WCRP/SPARC, the Max Planck Institut für Meteorologie, StratoClim, and NASA for their travel support.

References

SPARC, Assessment of Stratospheric Aerosol Properties (ASAP), WCRP-124, WMO/TD No. 1295, SPARC Report No. 4, 348 pp., 2006.

Vanhellemont, F., *et al.*, 2016: AerGOM, an improved algorithm for stratospheric aerosol extinction retrieval from GOMOS observations. Part 1: Algorithm development, *Atmos. Meas. Tech. Disc.*, **16**, 1-21.

Carboni, E., *et al.*, 2016: The vertical distribution of volcanic SO_2 plumes measured by IASI, *Atmos. Chem. Phys.*, **16**, 4343-4367.

Sheng, J. X., *et al.*, 2015: Global atmospheric sulfur budget under volcanically quiescent conditions: Aerosol-chemistry-climate model predictions and validation, *J. Geophys. Res.*, **120**, 256-276.

Report on the 1st Atmospheric Temperature Changes and their Drivers (ATC) Activity Workshop

25-26 April 2016, Graz, Austria

Amanda C. Maycock[1], Andrea K. Steiner[2] and Bill Randel[3]

[1]School of Earth and Environment, University of Leeds, UK, **a.c.maycock@leeds.ac.uk**, [2]Wegener Center for Climate and Global Change, University of Graz, Austria, [3]NCAR, Boulder, USA

The SPARC Atmospheric Temperature Changes and their Drivers (ATC) activity has recently evolved out of the long-standing Stratospheric Temperature Trends activity (Randel *et al.*, 2015). The leadership and membership of the activity has been refreshed in light of its new scientific directions, with specific focus on evaluating climate data records and their uncertainties, and the attribution of observed and modelled temperature changes to key radiative and dynamical drivers.

The ATC activity held its first workshop from 25-26 April 2016 at the Wegener Center for Climate and Global Change at the University of Graz in Austria. The workshop was organized and hosted by new ATC co-chairs **Andrea Steiner** and **Amanda Maycock**. Some funds for travel support were kindly provided by SPARC, which enabled a number of ATC members from North America to join the meeting. Sixteen participants attended the workshop.

The first day of talks focused on the development and evaluation of long-term climate data records using measurements from a variety of satellite platforms, as well as from lidar and GPS Radio Occultation (RO) observations.

Cheng-Zhi Zou discussed the challenges of combining data from multiple satellite instruments that possess distinct viewing characteristics and presented a new combined SSU/AMSU-A stratospheric temperature record spanning 1979-2015 (**Figure 12**). The evolution of global mean temperatures in this merged record agrees quite well with a sub-set of model simulations from the Chemistry Climate Model Initiative (CCMI), however, larger differences were found at northern high latitudes.

Bill Randel further emphasized the challenges of combining satellite temperature records and highlighted the need to consider seasonally- and spatially-resolved differences between datasets to identify possible sources of error and biases. He showed results from two new merged stratospheric temperature satellite datasets using SSU/SABER and SSU/Aura MLS (Randel *et al.*, 2016); there was good agreement in interannual variability between them. However, the two merged datasets show complex latitudinal trend structures and investigations are ongoing to understand these.

Philippe Keckhut presented results of upper stratospheric temperatures from the AMSU instruments on NOAA-15 and -16 satellites that have been corrected for tidal effects rendering temperature timeseries that are in good agreement with lidar measurements at northern mid-latitudes. He also showed that AMSU temperature data from satellites with stable orbits such as NOAA-18, Aqua, and MetOp-A are in good agreement. He further highlighted the important role of dynamical processes, in particular sudden stratospheric warmings

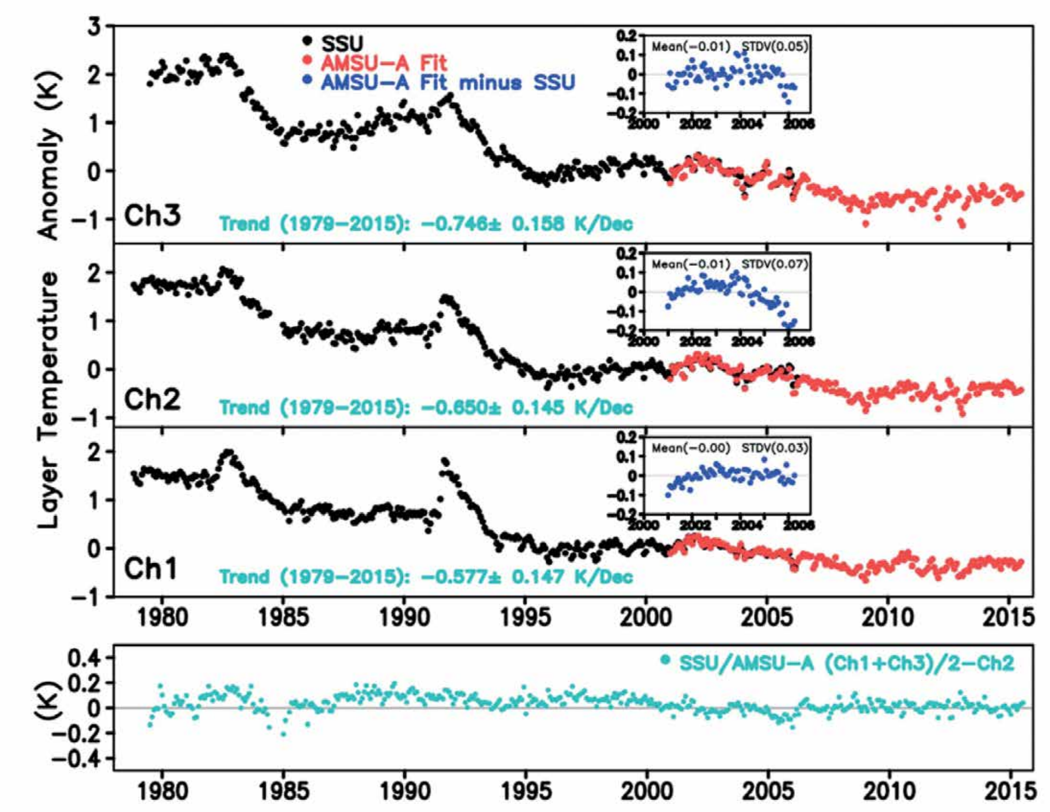


Figure 12: Timeseries of global mean stratospheric temperatures and their linear trends over 1979-2015 for the merged SSU/AMSU-A record sampled for the three SSU channels. Figure from Zou and Qian (2016).

and gravity waves, in determining temperature variability in the stratosphere and mesosphere.

Sergey Khaykin presented results of stratospheric temperature trends over 2002-2015 from Aqua AMSU and GPS RO observations. Trend estimates in the two records were generally found to be in agreement within uncertainty estimates for different latitude zones except for southern high latitudes where larger differences were found. Uncertainties are larger at high latitudes due to large atmospheric variability in this short period.

Andrea Steiner presented a comparison of events in tropical deep convection regions from GPS RO observations with events from a subset of CMIP5/AMIP models forced with observed sea surface temperatures. Large differences in the vertical profiles of temperature of up to several degrees were found between the models and observations in the tropopause region, suggesting that the models struggle to reproduce temperatures in the upper troposphere and lower stratosphere (UTLS).

Torsten Schmidt presented results on atmospheric variability from 14 years (2002-2015) of GPS RO data. He showed signatures of ENSO, QBO, and the solar cycle in UTLS temperatures and tropopause heights. There are plans for the continuation of GPS RO measurements, which is essential since these datasets have strong potential to become a key climate data record with particularly good resolution and accuracy in the UTLS. Torsten's talk was unexpectedly interrupted by an earthquake centred near Vienna that measured 4.2 on the Richter scale on Monday 25 April at 12:28 CEST.

Viktoria Sofieva described results of ozone variability and trends from the European Space Agency (ESA) Ozone-cci project, which has produced a combined satellite ozone dataset (HARMOZ) using measurements from the GOMOS, MIPAS, SCIAMACHY, OSIRIS, SMR, and ACE-FTS satellite instruments. The HARMOZ dataset shows increases in tropical upper stratospheric ozone abundances since the late 1990s, which is broadly comparable with recent trend estimates in datasets analysed by the SPARC SI2N activity (See page 4, this issue). Viktoria also noted that updated versions of some satellite records would motivate a re-evaluation of ozone trends in the future and pointed to the ESA MesosphEO project on a merged mesospheric dataset (2001-present) planned to be provided by next year.

Michael Schwartz provided an update on the MUSTARD project led by JPL, which aims

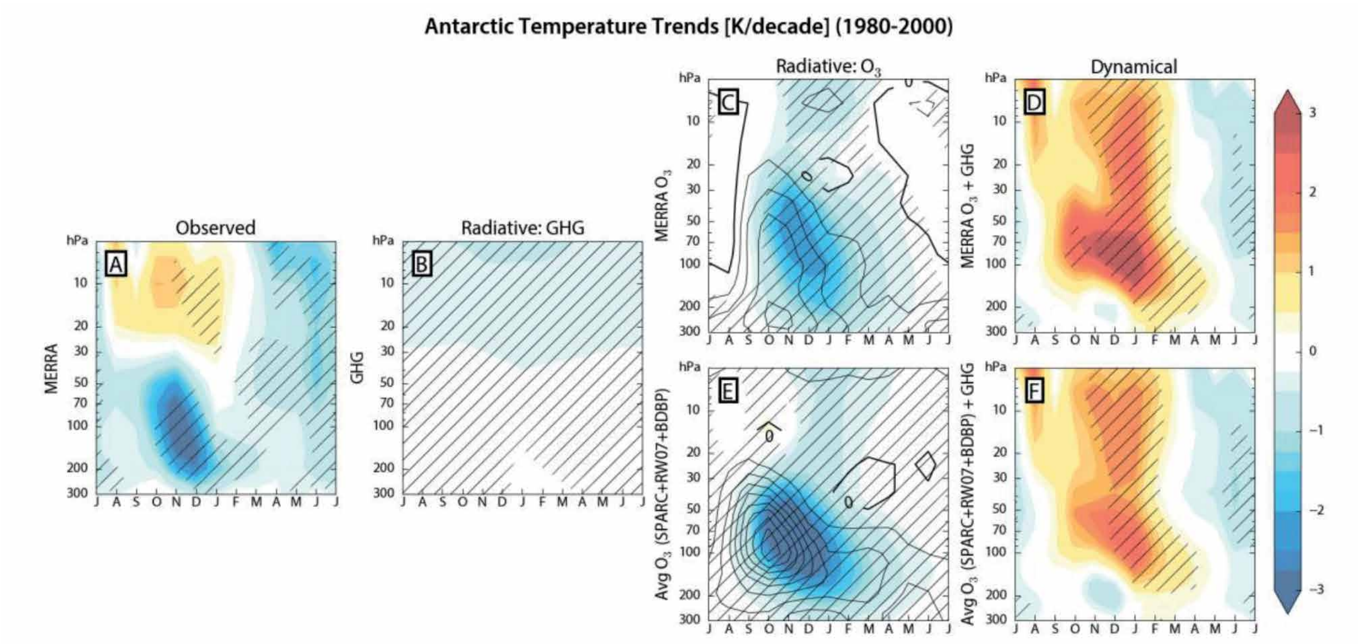


Figure 13: Seasonal evolution of Antarctic (60-90°S) temperature trends (in K/decade) over 1980-2000 in (a) the MERRA reanalysis, (b,c,e) estimates of radiative contributions due to changes in CO_2 and ozone over this period, and (d,f) the dynamical (residual between observed and radiative estimates) component. Figure from Ivy *et al*., 2016.

to produce the first long-term (1992-present) combined satellite record of temperatures in the upper stratosphere and mesosphere based on limb sounding radiometers and occultation instruments. He discussed the major challenges associated with combining multiple temperature records for this altitude region, in particular the potential for biases and drifts due to the time-dependent effects of atmospheric tides and Zeeman splitting of oxygen lines. The MUSTARD temperature dataset is planned to be finalised and available to the wider community within the next two years.

Craig Long provided an update on recent progress of the SPARC Reanalysis Intercomparison Project (S-RIP), for which a special issue is now open for submissions in Atmospheric Chemistry and Physics. Craig explained the complexities underlying the temporal behaviour of stratospheric temperatures in reanalysis products, which are strongly influenced by the philosophy adopted by model centres for assimilating satellite datasets into their systems. The largest differences in global mean temperatures between reanalysis datasets occur above 10hPa, with many showing large step changes coincident with changes in the global observing system. This highlights the need for caution when interpreting longer time-scale variations in these datasets.

The second day of the workshop focused on understanding the drivers of atmospheric temperature changes in observations and models. **Qiang Fu** presented results connected to detecting changes in the strength of the Brewer Dobson Circulation (BDC) through its effects on lower stratospheric temperatures at tropical and polar latitudes. He separated temperature trends in tropical MSU-4 data into a radiative component (carbon dioxide, ozone, water vapour) and pointed to the residual which indicates a strengthening in the BDC in recent decades. He also emphasized the importance of widening of the Hadley cell and tropical belt and its implications in the form of enhanced sub-tropical cooling on global mean lower stratospheric temperature trends.

Diane Ivy presented work separating the radiative and dynamical contributions to observed polar temperature trends over the last several decades (**Figure 13**). She showed that radiative processes alone cannot explain observed polar temperature trends, and that changes in stratospheric dynamics have substantially modulated observed temperature trends particularly in the winter and spring seasons. It is an open question whether these dynamical changes are part of a forced response or whether they represent internal climate variability.

Amanda Maycock discussed the impact of projected ozone recovery on future stratospheric temperature trends using CMIP5 model simulations. She highlighted that the coupling between ozone and greenhouse gas abundances introduces a strong dependence for the impact of future ozone recovery on temperatures to greenhouse gas emissions pathway. For a low greenhouse gas emissions pathway, the effect of ozone recovery overwhelms stratospheric cooling due to rising carbon dioxide leading to near-zero or positive temperature trends in the upper and lower stratosphere over this century.

Plans were formed for the ATC activity to begin work on an overview paper providing information on updated climate temperature records from observations and reanalyses, their consistency, and uncertainties. Preliminary plans were also discussed for some coordinated analysis of atmospheric temperature variability and trends in CCMI models with other interested groups. Updated information about the ATC activity can be found on the SPARC webpage: **www.sparc-climate.org/activities/temperature-changes**.

References

Ivy, D., *et al.*, 2016: Radiative and dynamical influences on polar stratospheric temperature trends, *J. Clim.*, doi:10.1175/JCLI-D-15-0503.1.

Randel, B. *et al.*, 2015: SPARC workshop on Stratospheric Temperature Trends, *SPARC Newsletter*, **45**, July 2015.

Randel, W.J., *et al.*, 2016: Stratospheric temperature trends over 1979-2015 derived from combined SSU, MLS and SABER satellite observations, **J. Clim**., doi:10.1175/JCLI-D-15-0629.1. (data available at ftp://ftp.acom.ucar.edu/user/randel/SSUdata).

Zou, C.-Z., and H. Qian, 2016: Stratospheric temperature climate data record from merged SSU and AMSU-A observations, *J. Atmos. Oceanic Technol.*, submitted.

The GAW/NDACC/SPARC Upper Troposphere and Lower Stratosphere (UTLS) Observation Workshop

Michaela I. Hegglin[1], Geir Braathen[2], Thierry Leblanc[3], Gabriele Stiller[4], Johanna Tamminen[5], Susann Tegtmeier[6], Christiane Voigt[7], and Andreas Engel[8]

[1]University of Reading, Reading, UK, **m.i.hegglin@reading.ac.uk**, [2]WMO, Geneva, Switzerland, [3]NASA JPL, Pasadena, CA, USA, [4]Karlsruhe Institute for Technology, Karlsruhe, Germany, [5]Finnish Meteorological Institute, Helsinki, Finland, [6]GEOMAR, Kiel, Germany, [7]Deutsches Zentrum für Luft- und Raumfahrt, Germany, [8]Goethe-University, Frankfurt, Germany

The GAW (Global Atmosphere Watch) / NDACC (Network for the Detection of Atmospheric Composition Change) / SPARC Upper Troposphere and Lower Stratosphere (UTLS) Observation Workshop, hosted by the World Meteorological Organization (WMO) in Geneva, Switzerland, took place from 24-27 May 2016 and was attended by about 40 participants. The workshop aimed to bring together a diverse group of instrumentalists (from the ground-based, satellite, balloon, and aircraft communities), data analysts, and UTLS experts to synthesize current knowledge of chemical composition measurements in the UTLS. This included how to assess the quality and representativeness of a wide range of UTLS measurements in a more comprehensive and integrative way than has hitherto been made. The main focus was on water vapour and ozone, but extended to other chemical species as well as aerosol and cirrus clouds.

Geir Braathen and **Boram Lee** welcomed the workshop participants to the WMO and then **Michaela Hegglin** gave a brief overview of the importance of the UTLS for ozone and climate science and set the workshop goals. These aimed at addressing the following questions:

- What observations are available from different platforms?
- What are the instrument-specific measurement characteristics (*e.g.*, accuracy and precision, temporal and spatial resolution)?
- How can we assess the representativeness of these observations?
- How can we compare observations from different instruments and in particular

with different resolutions?

- What UTLS-specific validation approaches do we have?
- How much progress has been made on trend analysis?
- What are the impacts of changing dynamics/meteorology on UTLS composition?

Presentations about existing WCRP activities related to UTLS observations also helped set the scene. These include the SPARC Data Initiative (**Susann Tegtmeier**), the SPARC WAVAS-II activity (**Gabriele Stiller**), and the GEWEX G-VAP intercomparison (**Marc Schröder**, remote). These talks highlighted the large uncertainties that still exist in terms of the quality and representativeness of different trace gas measurements, in particular trends in trace gas distributions in the UTLS derived from these observations.

UTLS Chemical Characteristics

Laura Pan introduced the session focused on the general chemical characteristics of the UTLS, discussing chemical trace gas distributions derived from *in situ* observations in the context of varying dynamical situations. In particular, tracer-tracer correlations can be used to yield information about the mixing processes between different regions of the UTLS. Using HALO aircraft measurements to analyse the seasonality of air mass origin, **Peter Hoor** highlighted the importance of Asian monsoon transport, tropospheric intrusions, and large-scale downwelling for the chemical characteristics of the UTLS. **Masatomo Fujiwara** introduced the SOWER (Soundings of Ozone and Water Vapour in the Equatorial Region) programme, which has carried out balloon campaigns from 1998-2016 and targeted various processes impacting UTLS trace gas distributions such as dehydration and quasi-biennial oscillation (QBO)-induced transport and temperature anomalies. Variations of ozone in the Tropical Tropopause Layer as derived from sondes and satellites show little agreement at around 17-18km, but agree better above this altitude (**Bill Randel**). **Holger Vömel** explained the importance of uncertainties for trace gas measurements in the UTLS, discussing the statistical uncertainties of two water vapour measurements from the same balloon flight.

In Situ Observations

Session three started with presentations on balloon-borne *in situ* observations. **Andreas Engel** presented examples of trace gas measurements (N_2O, CH_4, CO_2, SF_6, H_2) from four different cryosamplers, with the measurement quality varying from instrument to instrument. Importantly, the limited number of measurements using these instruments raises issues regarding the representativeness of the global UTLS. **Terry Deshler** reviewed the various campaigns and routine measurements made using Optical Particle Counters (OPC) from balloon sondes. The long-term measurements from Laramie, Wyoming, USA, reveal no apparent difference in trends below and above the tropopause, which is inconsistent with the long-term records from the SAGE instruments. He also presented the upcoming STRATEOLE-2 experiment, which will use a stratospheric balloon with a novel 2km-long cable below to gather information about the small-scale dynamical and microphysical processes occurring in the equatorial UTLS. It will include COBALD, FLASH-B, and temperature instruments. **Herman Smit** then presented a recap of available ozonesonde data, which represent the longest available ozone record for the UTLS, with measurements extending back to the 1970s. He also gave a technical review of the ozonesonde homogenization activity (O3S-DQA), which has led to the development of standard operation procedures and guidelines for re-processing. Herman (on behalf of **Anne Thompson**) also presented the status of the SHADOZ network, which has 13 contributing stations (including five stations that were reactivated from 2014-2016). **René Stübi** reviewed the ozonesonde record from the Meteoswiss Payerne station, whose long-term record is based on three routine launches per week and reveals natural variability of up to 40% in the UTLS. Besides routine measurements, the Payerne station also actively contributes to the technical improvements of sondes, providing important input to the O3S-DQA. **Dale Hurst** presented measurements of water vapour in the troposphere and lower stratosphere using frost-point hygrometers (FPH). A recent comparison of the NOAA FPH with Aura-MLS lower stratospheric records showed a drift between the balloon-borne and satellite-based records, with MLS being moister than the NOAA FPH since 2009. The origin of this drift is currently unknown.

Hans Schlager presented current research topics of aircraft campaigns focusing on UTLS processes and the availability of aircraft data from the HALO database. Intercomparisons of trace gas observations illustrated that exercise protocols can help to improve best practices for comparisons of aircraft measurements. **Stefan Kaufmann** presented a comprehensive dataset

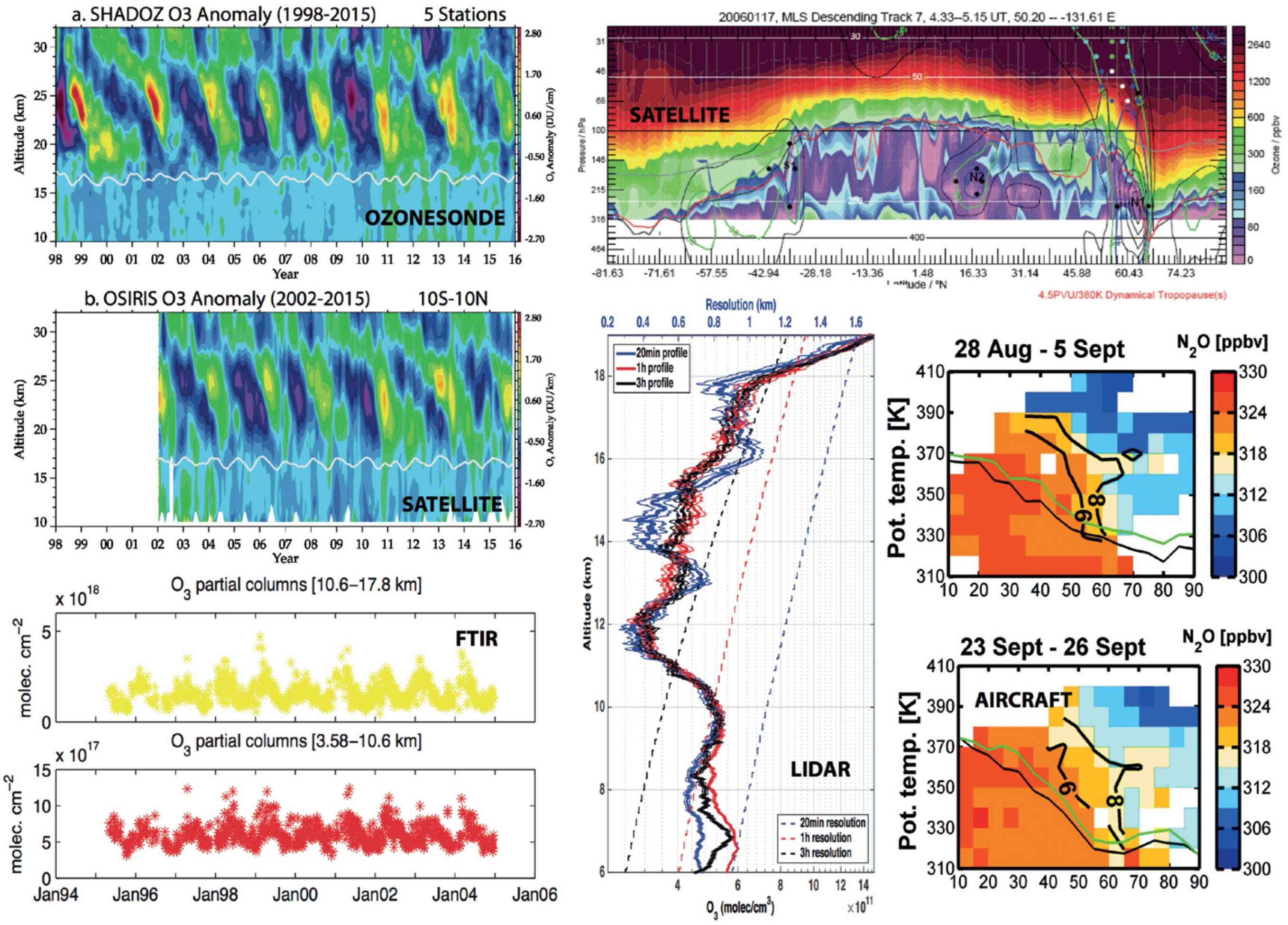


Figure 14: Observations from different measurement platforms illustrating the different spatial and temporal resolutions (and hence information content) they provide. The in situ aircraft observations (lower right) show that the information content from high-resolution observations can be 'spread out' when looking at the data in a suitable coordinate system. (Credit for figure panels, upper left: Bill Randel and Mijeong Park; upper right: Gloria Manney; lower left: Vigouroux *et al.*, ACP 2015; lower middle: Valentin Duflot; lower right: Peter Hoor).

of global *in situ* UTLS water vapour measurements from DLR research aircraft. The intercomparison of different hygrometers shows significant progress in reducing the uncertainties in airborne UTLS water vapour observations. The presentation also highlighted the use of these data for the validation of lidar measurements and ECMWF analyses. The IAGOS-CARIBIC "flying laboratory" is a powerful tool to study the chemical composition of the UTLS using regular atmospheric measurements on passenger aircraft, with more than 100 trace gas species measured (**Andreas Zahn**). Studies using the data from the IAGOS-CARIBIC platform have revealed substantial differences between IAGOS observations and ECMWF water vapour in the lower stratosphere, as well as an increase in dichloromethane from 1998-2012 and have also been used to derive the total bromine budget in the UTLS from very short-lived species (**Harald Bönisch**). **Herman Smit** presented the IAGOS-CORE (MOZAIC) programme, whose basic instrumentation includes ozone, carbon monoxide, water vapour, and aerosol backscatter as well as various additional instrumentation packages that can be selected. IAGOS-CORE water vapour data from 2000-2009 were temperature-corrected and used for a new relative humidity parameterization by ECMWF. A 15-year climatology of Northern Atlantic UTLS relative humidity observations from capacitive hygrometers along with temperature data showed that depending on tropopause definition (thermal or dynamic) ice super-saturation may occur in the lowermost stratosphere (**Patrick Neiss**). No significant trend in water vapour, temperature, or relative humidity with respect to ice was derived from the climatology.

Michael Höpfner gave an overview of over 25 years of balloon and aircraft campaigns using the MIPAS and GLORIA mid-infrared limb-sounding instruments, starting from the first balloon flight in 1989 to the most recent mission during the POLSTRACC campaign in late 2015/early 2016. GLORIA, in contrast to the earlier MIPAS instrument, no longer scans through the atmosphere but provides a 2D image with very high vertical resolution (up to 500m) and wide horizontal coverage. GLORIA was built as a demonstrator instrument for the PREMIER mission proposed to ESA (but was not selected), and the ATMOSAT mission proposed to German national funding agencies. An application of the new Aircore technique to measurements of upper tropospheric and stratospheric mean age-of-air (AoA) was also presented (**Andreas Engel**). The Aircore instruments provide a low-cost alternative to expensive cryogenic air sampling instruments while maintaining high accuracy and good vertical resolution. After the first successful flight from Timmins, Canada, in mid-2015 the long-term time series of AoA observations could be extended with three new data points up to now.

Ground-based Remote Sensing

In the session on ground-based remote sensing **Martine de Mazière** gave an overview of NDACC's activities, emphasising the high quality of measurements and the standards and protocols that are applied to make the results among stations as consistent as possible. NDACC data is used for trend assessment, as reference for the bias and stability assessment of satellite measurements, and for assessment of CAMS (Copernicus Atmospheric Monitoring Service) products. Further improvement of network consistency is planned within the MUSICA project. NDACC also includes 20 stations that make FTIR observations, covering a large latitude range and with many stations' records being 15-20 years long (**Jim Hannigan**). The data records from the UTLS are largely considered to be under-exploited. **Thierry Leblanc** gave on overview of lidar observations of ozone, water vapour, temperature, aerosols, and clouds from various platforms in the USA. He demonstrated that combined ozone and water vapour lidar measurements can be used to analyse troposphere-stratosphere variations. UTLS observations from French lidar stations were compared with satellite measurements and showed that water vapour can be used to distinguish tropical and Asian monsoon air (**Alain Hauchecorne**). Lidar observations from the Maïdo observatory on Reunion Island were used to show that the low uncertainty and high vertical resolution of ozone measurements allow the identification of signals of biomass burning and other seasonal variations (**Valentin Duflot**).

UTLS Satellite Observations

Nathaniel Livesey opened the session on satellite observations by giving an overview of the quality, use, and application of Aura-MLS measurements for UTLS studies. He discussed the problem of how to combine different sources of measurement error into a single number and pointed out the value of a data quality document for the data user. UTLS observations from MIPAS were presented by **Gabrielle Stiller**, who focused on several applications of these data, including studies of biomass burning, pollution plumes, Asian Monsoon transport, and the stratospheric sulphur budget. **Kaley Walker** introduced the large suite of trace gas species measurements available from the ACE-FTS and ACE-MAESTRO instruments. Recently improved data quality and error budgets allow a detailed study of UTLS processes such as volcanic influence on upper tropospheric water vapour, Asian Monsoon transport of trace species, the quantification of biomass burning plumes from forest fires, and upper tropospheric trace gas distributions. Updated and improved SCIAMACHY observations of ozone, nitrogen dioxide, water vapour, and aerosol, have recently been produced and used to study tropospheric columns (**Alexei Rozanov**). A new pointing-correction has been applied to OSIRIS measurements, which has resulted in greatly improved trend estimates of upper stratospheric ozone from merged OSIRIS/SAGE-II records (**Adam Bourassa**). Viktoria Sofieva gave an overview of the quality of ozone observations evaluated within the ESA Ozone-CCI project. The instruments were judged to be useful for UTLS studies, in particular for process-oriented evaluations related to the Asian monsoon, seasonal cycles, and the QBO.

Intercomparison Methods

In the last session of the workshop, different methodologies were introduced for comparisons between different kinds of instruments in the highly variable UTLS. **Thomas von Clarmann** discussed the wide range of techniques applied by different satellite groups to characterise data and report error. He highlighted the need for common, well-established, and clear uncertainty quantification and the importance of closely collaborating with data providers. **Ruud Dirksen** introduced the GRUAN network, which aims for high-quality climate-relevant observations with transparent data processing, traceable calibration, and good documentation. The priority products of GRUAN are temperature, water vapour, pressure, and wind. **Jean-Paul Vernier** (remote, for Michael Pitts) demonstrated how combined SAGE-II, GOMOS, and CALIPSO satellite data records can be used for monitoring volcanic aerosols, which are relevant for climate. **Jessica Neu** presented the SPARC Data Initiative comparison between limb and nadir sounder ozone climatologies, accounting for their very different vertical resolutions. She also gave a short overview of other available methodologies that aim to minimize geophysical variability in measurement comparisons. The latter included tracer-tracer correlations, using models as transfer-functions, and chemical data assimilation as a means to estimate measurement uncertainty. **Gloria Manney** concluded the first part of the workshop with a talk on the jet-based coordinate system (JETPAC), which is used to classify measurements according to their distance from the upper tropospheric jets or tropopause height, similar to the use of the equivalent latitude framework.

Overview

On the last day of the workshop participants split into breakout groups to discuss the following topics:

What are the characteristics of the different instrument techniques?

Different data products with various levels of resolution and accuracy are available. The conclusion was that for a thorough comparison, a primary focus is needed on climate-relevant parameters such as ozone, water vapour, aerosols, methane, and cirrus clouds. For the detection of long-term trends a lower limit of 30 years of data was discussed, ideally available as a merged data product (where records from individual instruments covering the entire period do not exist). The traceability of datasets (*e.g.,* long-term traceability and consistency of calibrations) was identified as very important parameter, and something that is especially problematic for older data. Finally, for the attribution of trends (*e.g.,* through changes in particular UTLS processes) of other species, such as carbon monoxide or NO_x, chemical and dynamical tracers would be required.

How do we carry out a consistent error assessment for different instrument techniques?

A common terminology is a key requirement to make progress in instrument error assessment. This includes developing proper definitions of precision, accuracy, and uncertainty error of a measurement. To this end, experience should be drawn from the metrology community, since it could be potentially useful to find consensus. Furthermore, high quality documentation of measurement system characteristics is important for the traceability of new data products and proper application by data users. Ultimately, communication between data users and the measurement community is encouraged.

How can we compare observations from different instrument techniques?

It is relevant to distinguish between the measurement needs for process studies and trend studies. Process-oriented validation diagnostics applied to instrument intercomparisons can be used to test the physical consistency of observations with respect to reproducing various atmospheric processes. Seasonal cycles, QBO, water vapour tape recorder, and ENSO-related variations were highlighted as diagnostics and the available datasets should be tested on a range of temporal and spatial scales. Multiple evaluation techniques such as tracer-tracer correlations, probability density functions, and jet-based, tropopause-based, equivalent latitude, or Lagrangian coordinate systems would improve the comparability among instruments.

The workshop concluded with short presentations and a plenary discussion of the breakout group topics. Given the importance of the UTLS for climate, the workshop participants agreed on the need to conduct a comprehensive intercomparison of observations from the diverse range of instrument techniques and platforms that exist. Such an activity would yield a consolidated understanding of the quality and representativeness of different observations in the UTLS and would ideally build the basis for achieving a better understanding of past long-term changes in UTLS trace gas distributions and the processes that affect them.

SPARC meetings

12-15 September
WGNE/SPARC Drag Processes Workshop
Reading, UK

26-30 September
SPARC QBO Workshop
Oxford, UK

17-19 October
SPARC DA Workshop
Victoria, BC, Canada

19-21 October
S-RIP 2016 Workshop
Victoria, BC, Canada

31 October - 1 November
SPARC Grand Challenges Workshop
Berlin, Germany

30 November - 3 December
WAVAS II Meeting
Karlsruhe, Germany

Open Call for SPARC SSG Nominations

Submit your nomination for SSG membership through the SPARC website: **www.sparc-climate.org/about/leadership/**

Deadline: 30 September 2016

Summer School on Atmospheric Composition and Dynamics

28 Nov – 3 Dec 2016, La Réunion Island
See **http://lacy.univ-reunion.fr/formation/summer-school** for more details

SPARC-related meetings

30 July – 6 August
41st COSPAR Assembly
Istanbul, Turkey

31 July – 5 August
13th AOGS Annual Meeting
Peking, China

4-9 September
Quadrennial Ozone Symposium
Edinburgh, Scotland

14-16 September
International Symposium on the Whole Atmosphere
Tokyo, Japan

19-23 September
CLIVAR Open Science Conference
Qingdao, China

2-4 November
WGCM Model Hierarchies Workshop
Princeton, USA

12-16 December
AGU Fall Meeting
San Francisco, USA

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

Publication details

Editing
Fiona Tummon

Design/layout
Petra Bratfisch & Fiona Tummon

Print & distribution
ETH Zurich, ISSN 1245-4680

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)
Universitaetsstrasse 16
CH-8092 Zurich
Switzerland
office@sparc-climate.org