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The NASA Global Hawk being towed into the NASA Dryden Flight Research Center hanger, Edwards, California. See results from the recent ATTREX campaigns using the aircraft this issue. Photo courtesy: Tom Tschida, NASA Dryden Flight Research Center.

Contents

Available online

Report on the IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) 2013 Science Workshop - *http://www.sparc-climate.org/publications/newsletter/*

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

Report on the 20th Session of the SPARC Scientific Steering Group 27-30 November 2012, Buenos Aires, Argentina

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The 20th Session of the SPARC SSG (Scientific Steering Group) was held at SIGEN (Sindicatura General de la Nación) in Buenos Aires, Argentina, from 27-30 November 2012, hosted by the 'Centro de Investigaciones del Mar y la Atmósfera', of the University of Buenos Aires.

Opening session and WCRP/ SPARC update

Greg Bodeker (SPARC co-chair) opened the Scientific Steering Group (SSG) meeting by welcoming all participants, particularly those from South America who joined the first session, and thanked the local organisers. A new format for the meeting was introduced, requiring the activity leaders to provide a short report detailing their main scientific achievements, an outlook for the future, and any financial requests for the coming year. These reports were distributed to all participants prior to the meeting, while during the meeting brief scientific presentations were then made in plenary and logistical aspects were discussed separately in small groups with the SSG members. This allowed more focus on coordination and logistical issues. The reports have now been compiled to produce the very first SPARC Annual Report 2012.

Carolina Vera (a member of the WCRP's Joint Scientific Committee (JSC)) provided an update of WCRP activities on behalf of Antonio Busalacchi (JSC Chair), who was unable to attend the meeting. She mentioned the very successful WCRP Open Science Conference (OSC), which took place from 24-29 October 2011, in Denver, USA (**http://conference2011.wcrp-climate.org**). The new WCRP structure was discussed in a short JSC meeting following the OSC, and in further detail at the next JSC meeting, which took place from 17-20 July 2012 in Beijing, China (for more details see the meeting report in SPARC Newsletter no. 40[1]). Under the new structure, six Grand Challenges (GCs) will play a critical role, enabling the development of targeted research efforts that will provide successful results on 5-10 year timescales. Two new councils have also been established, the WCRP Modelling Advisory Council (WMAC) and the WCRP Data Advisory Council (WDAC) (see below for further details). A teleconference later during the meeting with Antonio Busalacchi confirmed SPARC's vital role in the WCRP's GCs. Carolina closed by discussing the emerging Future Earth initiative, to which the WCRP will contribute significantly. Later, she also presented a summary of the one and a half-day local workshop, which took place prior to the SSG meeting (see article later in this issue).

Ted Shepherd (SPARC co-chair) began his presentation by summarizing SPARC's goals and organisation, and then continued by mentioning SPARC's name change (again, see below for further details). He further discussed SPARC's role in the new WCRP GCs. SPARC will contribute to several GCs, including 'Regional Climate Information' (led by the Working Group on Regional Climate), through research focusing on atmospheric circulation changes, and to the GC 'Cryosphere in a Changing Climate' (co-led by CliC, the Climate and Cryosphere project), through the Polar Climate Predictability Initiative (PCPI, see below). SPARC will also contribute to the GC 'Science Underpinning the Prediction and Attribution of Extreme Events' (led by GEWEX), as well as to the GC 'Clouds, Circulation and Climate Sensitivity' (led by WGCM, see below), through research focused on circulation analyses, upper tropospheric water vapour, and sulphate aerosol microphysics. Together with GEWEX, IGAC (the International Global Atmospheric Chemistry project), and other research partners, SPARC is expected to take a lead on aerosol-re-

[1]**http://www.sparc-climate.org/fileadmin/customer/6_Publications/Newsletter_PDF/40_SPARCnewsletter_Jan2013_web.pdf**

lated research in support of the GCs.

Monica Rabolli made a presentation on behalf of CONAE (Comision Nacional de Activitas Espaciales, the Argentinian Space Agency), providing an overview of the AQUARIUS satellite mission, a common project between CONAE and NASA. The main scientific goal of this mission is to improve understanding of the interactions between ocean circulation, the water cycle and climate. The satellite was launched on 10 June 2011 and provides global information on sea surface salinity and soil moisture. AQUARIUS instruments also measure sea-ice concentration, rainfall rate, wind speed, water vapour, cloud liquid water content and fires can be detected. These observations have provided detailed information on tropical instability waves, the Amazon outflow plume and hurricanes. Examples from recent studies showed that it was possible to identify hurricane Gordon using AQUARIUS rain rate observations, while hurricane Sandy was observed using water vapour column data. Argentinian research using AQUARIUS data will focus on the Rio de la Plata outflow plume.

Jürgen Scheer presented an overview of the Network for Detection of Mesospheric Change (NDMC: **http://wdc.dlr.de/ndmc/**), which provides a framework for international cooperation to study the mesopause region (extending from 80-100km altitude). The NDMC was established in 2007 through an initiative of the ICSU/WMO-World Data Centre for Remote Sensing of the Atmosphere, which is operated by the German Aerospace Centre. The NDMC is a global programme aimed at identifying and quantifying atmospheric change by monitoring key parameters for the early characterisation of climate signals in the mesosphere. NDMC is focused on coordinating the study of mesospheric variability on all timescales, as well as the coordinated development of improved observation and analysis techniques and modelling of the mesosphere. NDMC science is currently focused on the following topics: (1) planetary waves, (2) gravity waves, (3) vertical coupling, (4) inter-hemispheric coupling, (5) infrasound, (6) climate change signal detection, and (7) network intercomparison. Jürgen presented some results from various NDMC studies and then finished by making proposals for collaborations between SPARC and the NDMC.

SPARC activity reports

Ted Shepherd presented the new Chemistry Climate Modelling Initiative (CCMI) on behalf of Veronika Eyring. The initiative, jointly supported by IGAC and SPARC, was discussed with the community and plans were approved at a workshop that took place from 21-24 May 2012, in Davos, Switzerland. The specific goals of the Davos workshop were to: (1) assess improvements in process-oriented evaluation and understanding of Chemistry Climate Models (CCMs; extending the CCMVal approach to the troposphere), (2) identify observations for model evaluation and new methods for improved comparability between models and observations, and (3) define community-wide simulations in support of the upcoming WMO Ozone and future IPCC Climate Assessments, as well as for process studies. The outcome of the workshop is described in further detail in a recent SPARC Newsletter article[2]. More generally, the goals of CCMI are to: (1) promote the use and development of global models that include chemistry and dynamics of the stratosphere and troposphere, as well as a coupled ocean, such models are expected to become more common; (2) to compare tropospheric, stratospheric and coupled chemistry-climate models with observations, as well as with each other; and (3) to better coordinate stratospheric and tropospheric modelling activities and to address specific scientific questions in the context of comprehensive stratosphere-troposphere resolving models including atmospheric chemistry. A CCMI website has been created (**http://www.pa.op.dlr.de/CCMI**) and a 2nd workshop was held in Boulder, USA, from 14-16 May 2013. Veronika Eyring and Jean-François Lamarque act as co-chairs of the activity, and a CCMI scientific steering committee has been formed.

Claire Granier, a member of the IGAC Scientific Steering Committee and SPARC liaison, presented a short overview of IGAC's main projects, including CCMI, to which IGAC is strongly committed. IGAC proposed that Veronika Eyring and Jean-François Lamarque are formally recognized as co-chairs of CCMI and intends to comment on the CCMI leadership plan to ensure the widest possible IGAC engagement. Allen Goldstein (incoming IGAC co-chair) was also involved in supporting the 2nd CCMI workshop. CCMI science will be vital to IGAC's focus on air pollution and climate, which is a theme of growing importance for IGAC. As part of the International Geosphere-Biosphere Programme (IGBP), IGAC will be integrated into the Future

[2] Eyring *et al.* (2013) Overview of IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) Community Simulations in Support of Upcoming Ozone and Climate Assessments. *SPARC newsletter* No. **40**

Earth initiative, but this will not affect IGAC's commitment to CCMI.

Paul Newman presented the 'Lifetimes of Halogen Source Gases' activity. This SPARC activity is the first re-evaluation of the lifetimes of ozone-depleting substances (ODSs) since 1998 (WMO/UNEP Ozone Assessment, 1999) and first in-depth modification since 1994 (Kaye *et al.*, 1994[3]). Results show that different approaches result in different lifetime estimates, but overall there is good consistency, and uncertainties have been significantly reduced, through, for example, the re-evaluation of photochemical data. The lifetime estimates of certain species, for example CCl_4 and CFC-11, have changed significantly since the last WMO Ozone Assessment. The third draft of the report has been completed and reviewed, and work on the final report is in progress. The lifetimes recommendations will be finalized in mid-2013 and new ODS scenarios will be completed for the CCMI activity after this finalization. Results from this activity will also be included in the upcoming 2014 WMO/UNEP Ozone Assessment.

Julie Arblaster presented the SOLARIS-HEPPA activity (SOLARIS: SOLAR Influences for SPARC, HEPPA: High Energy Particle Precipitation in the Atmosphere) on behalf of Katja Matthes and Bernd Funke. She started by presenting results from a joint study looking at recent solar spectral irradiance variability and its impact on climate modelling[4]. The main uncertainty in spectral solar irradiance lies in the 220-400nm wavelength range, where substantial differences between different satellite measurements remain. While the number of numerical simulations taking into account spectral solar irradiance is increasing, comparisons of available model simulations are hampered by slightly different experimental setups, motivating new coordinated SOLARIS-HEPPA simulations. Using measurements from the SORCE (SOlar Radiation and Climate Experiment) satellite instrument leads to simulated atmospheric temperature responses being up to three times larger than when using other data. Julie also reported on the HEPPA-II coordinated intercomparison study, which suggests that the proton forcing (*i.e.* direct influence of solar proton events) is well represented in the participating models and should be considered in all models. In contrast, electron forcing data constraining ionization below 100km remains uncertain. Ongoing efforts are focused on constructing an observations-based energetic particle precipitation (EPP) NOy source parameterization for models with lids below 100km. In 2013, the SOLARIS-HEPPA activity aims to publish a white paper, continue the HEPPA model-measurement intercomparison study, evaluate the solar cycle signal in the CCMI hindcast simulations as well as in satellite observations, and provide recommendations for including EPP indirect effects in low-top models.

Karen Rosenlof reported on the WAVAS-2 activity (WAter Vapour ASsessment 2), which focuses on two main topics: (1) super saturation and *in situ* measurement data quality, and (2) upper troposphere and stratosphere climatologies, trends and radiative effects. As part of topic 1, controlled, refereed, blind intercomparisons of the principal airborne field instruments were made using the AIDA chamber, and strict quality checks of in-situ aircraft observations of relative humidity showed that many of the highest relative humidity values (except at very low temperature) are questionable (AquaVIT White Paper, 2009[5]; Krämer *et al.*, 2009[6]). This work shows that at very high relative humidities even state-of-the-art instrumentation introduces uncertainties that are too large, and thus many field measurements indicating supersaturation may not be reliable. There is therefore a strong need to improve current field instrumentation. The shifts in aircraft measurements generally preclude their use for trend analyses. However, comparisons with a stable satellite record may be useful for verifying or discounting extreme aircraft campaign anomalies. The second focus of this activity has been recently reorganised and now falls under the leadership of Gabrielle Stiller. This topic aims to analyse and combine long-term satellite observations of stratospheric water vapour for use as model boundary conditions, as well as for model comparison. They are currently aiming to produce a satellite climatology using SAGE II, HALOE and Aura MLS observations. Gaps in this data set may be filled with ACE, SAGE III and possibly other, shorter period satellite records. Ultimately, the aim is to perform trend and variability analysis on these data, and to carry out an assessment of uncertainties. An authors' meeting is to be held in

[3]Kaye, J. A., S. A. Penkett, F. M. Ormond (eds.) (1994) Report on Concentrations, Lifetimes, and Trends of CFCs, Halons, and Related Species. NASA Reference Publication 1339, Washington, D.C.

[4]Ermolli *et al.*, 2013: Recent variability of the solar spectral irradiance and its impact on climate modelling. *Atmos. Chem. Phys.*, **13**, 3945-3977

[5]**https://aquavit.icg.kfa-juelich.de/WhitePaper/AquaVITWhitePaper_Final_23Oct2009_6MB.pdf**

[6]Krämer *et al.*, 2009: Ice supersatuarations and cirrus cloud crystal numbers. *Atmos. Chem. Physics*, **9**, 3505-3522

Boulder, USA, in 2013, to finalize a review paper covering super saturation and data quality issues.

Michaela Hegglin and **Susann Tegtmeier** presented progress on the "Data Initiative". This activity focuses on comparing stratospheric and upper tropospheric/lower stratospheric satellite measurements of many important species, and is carried out in close collaboration with the satellite science teams. The comparison entails determining a zonal and monthly mean climatology using all available overlapping data, and then comparing the individual satellite records to this climatology. This allows a characterisation of measurements from individual instruments, while statistical analyses of the differences also provide an overall assessment of the respective species. Michaela presented the results of the water vapour analysis and provided an overview of the status of the activity. The activity is hoping to finish its final report in late 2013.

Johannes Staehelin presented the status of the SI2N initiative, which focuses on understanding past changes in the vertical distribution of ozone. The activity is supported by SPARC, the International Ozone Commission (IO_3C), Integrated Global Atmospheric Chemistry Observations (IGACO-O_3/UV), and the Network for the Detection of Atmospheric Composition Change (NDACC). A challenge for this project is to assess the consistency of satellite measurements suitable for deriving reliable information on ozone profile changes. This is particularly difficult since chemical ozone depletion reversed during the second part of the 1990s as a result of the successful implementation of the Montreal Protocol. Research is conducted by several working groups focusing on improving satellite observational records from the past decade, producing long-term merged satellite data series, data quality assessment of long-term ozonesonde records, and the analysis of long-term ground-based observations (including Umkehr, lidar, microwave and FTIR observations). A final review meeting will be held in Helsinki, Finland, in September 2013. The activity will present its final results through special issues of three journals (*Atmospheric Chemistry and Physics*, *Atmospheric Measurement Techniques* and *Earth System Science Data*), which will be published in time for the 2014 WMO/UNEP Ozone Assessment.

Dian Seidel presented an update of the stratospheric temperature trends activity. A NOAA team produced a new record of stratospheric temperatures derived from AMSU (Advanced Microwave Sounding Unit) and SSU (Stratospheric Sounding Unit) instruments. These data show remarkable differences compared to an earlier analysis by the UK Met Office, particularly in terms of the evolution of stratospheric temperature between 25-45km after the middle of the 1990s. The agreement between stratospheric satellite temperature records and chemistry climate models is also rather poor for this period. A Nature article by Thompson *et al.*[7] called into question our understanding of observed stratospheric temperature trends, which are thought to be caused by changes in ozone, carbon dioxide, and, at lower altitudes, also by water vapour. The activity encourages the publication of independent methods for merging SSU and AMSU data, and will attempt to recover tapes of overlapping SSU observations from the UK Met Office. They may also link with work on stratospheric reanalysis activities.

Joan Alexander (SPARC co-chair, as of 1 January 2013) presented progress of the SPARC gravity waves activity. Gravity waves influence global circulation and climate through changes in gravity wave momentum forces in the stratosphere and mesosphere, which can lead to changes in stratospheric and tropospheric circulation. Over the past year global distributions, and seasonal and interannual variations of gravity wave momentum fluxes in various global data sets and model estimates were analysed and compared in a project supported by the International Space Science Institute (ISSI). Because gravity waves are intermittent events, accurately determining gravity wave momentum fluxes requires information regarding both the amplitude and frequency of occurrence of wave events. Models that fully resolve the middle atmosphere were found to have similar gravity wave momentum fluxes, likely because they require similar forces to obtain realistic circulations. However, a simple increase in horizontal resolution is insufficient to produce realistic gravity wave fluxes. Other factors such as dissipation, model numerics, and vertical resolution also need to be improved. The analysis indicated that (1) observed fluxes decrease more rapidly with height than parameterized fluxes; (2) waves that can be observed have longer horizontal wavelengths and may dissipate lower in altitude; (3) the CAM5 global model's stratosphere acts as a "sponge" layer, and therefore dissipation is unrealistic; and (4) even high resolution models still under-resolve important orographic waves. The ISSI group is preparing a new paper compar-

[7]Thompson *et al.*, 2012: The mystery of recent stratospheric temperature trends. *Nature*, **491**, 692-6972

ing intermittency in gravity waves in models and observations. In future, the activity will focus on gravity wave forcing on circulation using global assimilation methods, as well as regional foci on wave source regions, including high latitude southern hemisphere winter waves and tropical waves.

Mark Baldwin began his presentation on the DynVar (Dynamical Variability) activity, on behalf of Elisa Manzini, by asking several fundamental questions related to dynamical coupling of the stratosphere and troposphere: What is the role of dynamical and radiative coupling with the stratosphere in extended-range tropospheric weather forecasting and in determining long-term trends in tropospheric climate? By what mechanisms do the stratosphere and troposphere act as a coupled system? What will the role of the stratosphere be as climate changes? In an attempt to answer some of these questions, DynVar has focused much attention on the analysis of the role of the stratosphere in CMIP5 output. Key results from DynVar activities (described in Manzini *et al.*, 2012[8], and Charlton-Perez *et al.*, 2013[9]) confirm previous projections, which indicate that by the end of the 21st century, lower stratospheric polar winds will weaken at high latitudes and strengthen at low latitudes. Categorising models as high- or low-top did not reveal significant differences in simulated polar winter stratospheric changes. Interestingly, the CMIP5 models were found to be more usefully subdivided according to projected winter polar stratospheric changes, since changes in the strength of the winter polar vortex can be an important factor for the projection of surface changes. In terms of mean climate, the skill of high- and low-top model ensembles was found to be similar, but the skill in simulating stratospheric climate variability on daily, interannual and decadal timescales was significantly better in the high-top ensemble. This is particularly the case in regions and seasons during which wave-driven stratospheric dynamical variability is substantial. In addition, in the extra-tropical lower stratosphere, the region most critical for communicating stratospheric changes to the troposphere, the mean climate was almost identical between low- and high-top ensembles. The DynVar activity held its 3rd workshop in Reading, UK, from 22-24 April 2013 (see report, this issue).

David Jackson presented developments in the SPARC Data Assimilation (DA) activity, out of which two new SPARC activities (SNAP and S-RIP, see below) are evolving. The activity held a workshop in Socorro, USA, in June 2012 (see the article in SPARC newsletter No. 40[10]). At the workshop, two new areas of potential research were proposed: (1) an intercomparison of the missing body force due to sub-grid scale gravity wave drag (which may partly be dealt with by the Gravity Wave activity, see above), and (2) a study of model vertical resolution, although this would need to be further refined to become realistic, for example, by focusing on the impact of vertical resolution on the QBO. A study looking at the changes in surface ozone simulated by the GEOS-CHEM model when assimilating MLS and TES satellite ozone observations was presented. Results indicate that biases decrease by 5-15%, although more work is required to understand what the data assimilation can tell us about vertical mixing. At present, the interaction between the chemical data assimilation and satellite retrieval communities is still rather informal, but the activity is aiming to further develop links between the two. The DA group will also produce a summary report on the representation of the stratosphere in numerical weather prediction models.

Emerging activities

Markus Rex reported on the progress of the Stratospheric Sulfur and its Role in Climate (SSiRC) activity. Since the SSG meeting in Zürich, in which SSiRC was endorsed as an emerging SPARC activity, a white paper has been published, a kick-off meeting took place, and an implementation plan has been developed. This activity will improve our understanding of the processes that sustain the stratospheric aerosol layer (largely made up of sulphur), as well as their variability and long-term changes. SSiRC will include the following major components: *in situ* aircraft and balloon measurements, ground-based remote sensing, satellite remote sensing, microphysical lab studies, process and global modelling, and a database housing all related data. Results from new research examining how sulphur is transported into the stratosphere were presented. They indicate that one of the most efficient pathways for sulphur transport to the stratosphere may be in the tropical Western Pacific. In this region, extremely low ozone mixing ratios

[8]Manzini *et al.*, 2012: Stratosphere-troposphere coupling at inter-decadal time scales: Implications for the North Atlantic Ocean. *Geophys. Res. Letters*, **39**, DOI: 10.1029/2011GL050771

[9]Charlton-Perez *et al.*, 2013: On the lack of stratospheric dynamical variability in low-top versions of the CMIP5 models. *J. Geophys. Res.*, **118**, DOI: 10.1002/jgrd.50125.

[10]**http://www.sparc-climate.org/fileadmin/customer/6_Publications/Newsletter_PDF/40_SPARCnewsletter_Jan2013_web.pdf.**

suggest very low OH levels (the so-called "OH-hole"), a feature which is expected to slow the oxidation of key tropospheric species, including SO_2 and its precursors, and thus might provide a potentially efficient pathway for these species to enter the stratosphere. Further measurements and modelling studies are needed to confirm these results. The SSiRC implementation plan was extensively discussed and SSiRC was approved as a new SPARC activity.

David Jackson reported on the SNAP activity (Stratospheric Network on Assessment of Predictability), on behalf of Andrew Charlton-Perez. This activity aims to quantify: (1) current skill in extra-tropical stratospheric forecasts, (2) the extent to which accurate forecasts contribute to improved tropospheric predictability, and (3) the partitioning of any gains in predictability between improvements in initial conditions and the forward forecast. Critical questions include: Is it really stratospheric influence or other model changes that improve tropospheric forecast skill? Is the improvement due to improvements in the modelled stratosphere or to the observations? Results are likely model dependent, and therefore prompts the question of how generic are improvements? Further questions include: Are stratosphere-troposphere coupling effects important throughout the winter season or only when major stratospheric dynamical events occur? How far in advance can major stratospheric dynamical events be predicted and usefully add skill to tropospheric forecasts? Which stratospheric processes, both resolved and unresolved, need to be simulated to gain optimal stratospheric predictability? To address these questions, multiple model comparisons and case studies will be needed. SNAP has recently formed a Steering Committee, held an initial workshop from 24-26 April 2013 in Reading, UK (see article, this issue), and will write a review paper on the role of the stratosphere in predictability. The planned stratospheric predictability modelling experiments are expected to start in June 2013.

Continuing on, David discussed the plans of the SPARC-Reanalysis/Analysis Intercomparison Project (S-RIP), on behalf of Masatomo Fujiwara. Reanalyses contain key information on the time-evolving state of the atmosphere and are widely used by a large community. At present, several reanalysis products exist, and S-RIP is a coordinated activity aimed at comparing these data sets for various "key" diagnostics. The activity aims to: (1) understand the causes of differences between reanalyses; (2) use the results to provide guidance on appropriate usage of various reanalysis products in scientific studies; (3) better coordinate with data users, which hopefully will lead to improvements in the next generation of reanalysis products; and (4) establish a closer collaboration between the data users and reanalysis centres. Over the past year S-RIP research activities have been discussed at several meetings, including the 2012 DA workshop (see above), and the activity held a planning workshop from 29 April to 1 May 2013 in Exeter, UK (see report, this issue), where the final S-RIP report structure, time schedule, analysis guidelines, and chapter lead authors were discussed. The final activity report is planned to be finished by 2015.

Other Presentations

On behalf of Scott Osprey, Neal Butchart and Kevin Hamilton, **Ted Shepherd** presented a proposal for a new SPARC activity focused on modelling the Quasi-Biennial Oscillation (QBO). The QBO is directly linked to how well a model simulates circulation and transport of chemical species throughout much of the atmosphere. QBO variability is a function of model discretisation, diffusion, resolved waves, and various parameterization schemes (*e.g.* gravity waves, convection). Very few models are able to produce internally-generated QBOs, and there has been little recent progress to improve this aspect. The proposed plan included the design of a coordinated set of numerical experiments to systematically explore the effects of: (1) vertical resolution, (2) resolved waves, (3) parameterized small-scale (gravity) waves, and (4) diffusion, on the morphology of the tropical QBO and projected changes thereof. Similar experiments with intermediate complexity models, which can explore the parameter space more efficiently than GCMs, were also welcomed. The goal of the activity would be to provide a better understanding of what is needed to produce a reliable QBO in climate models, in terms of model details such as vertical resolution, wave parameterizations, *etc*. The SSG strongly affirmed the importance of these goals. However, it was felt that any SPARC efforts focusing on the QBO had to be closely integrated with DynVar, given the strong role of the QBO in many DynVar research topics, and the recommendation was therefore made to bring these issues to the attention of DynVar at its workshop in April 2013, to help inform DynVar's future plans, rather than launching a separate QBO initiative.

Ted also presented an update on the WCRP Polar Climate Predictability Initiative (PCPI). In polar regions the agreement between models and observations is generally poor, and some observations remain puzzling. For example, in September 2012 a record sea-ice minimum was observed in the Arctic, while a record sea-ice maximum was observed simultaneously in the Antarctic. The PCPI is aimed at understanding such differences and whether sources of climate predictability on seasonal and decadal time scales exist in the polar regions, since they are of importance to global climate. Although several international programmes focusing on the polar regions already exist, the WCRP brings a global perspective and adds significantly to the global modelling capacity. PCPI will constitute a major sub-initiative of the 'Cryosphere in a Changing Climate' GC (see above), and will work synergistically with the World Weather Research Programme's Polar Prediction Project, which is focused on polar predictability from hourly to seasonal scales. To this end, they will share a common project office. Key scientific questions include: How predictable is Arctic climate? Why are the Arctic and Antarctic climates changing so differently from each other and from global climate? Why are climate models generally unable to describe important observations in polar regions? What are the implications of polar climate change for low latitudes? Is the stability of the ice sheets changing? New measurements and modelling capabilities in combination with significant community interest will hopefully help answer these questions. A planning meeting was held in Toronto, Canada, in April 2012, and a draft implementation strategy was published in November 2012.

In his report on the Working Group on Numerical Experimentation (WGNE), **David Jackson** summarized WGNE feedback regarding requests from specific SPARC activities. WGNE provides general support for work on improving stratospheric physics and the understanding of errors in numerical simulations. To this extent, WGNE could possibly verify S-RIP analyses against their own analyses, since these may be quite different from reanalysis data. This aspect could become integrated into the S-RIP activity, or WGNE could initiate a complementary study. In terms of an investigation of model vertical resolution, WGNE has some previous experience researching the effects of vertical resolution in the Tropical Tropopause Layer and may be willing to refocus on such a topic in response to SPARC requests. WGNE also offered to help design numerical experiments looking into gravity waves. It was mentioned that WGNE focuses on improving the understanding of the sources and physics of convective and shear-generated gravity waves, and it was suggested that a link could be made with Global Atmospheric System Studies (GASS, part of GEWEX), which has a wide research scope including a focus on convection, aerosols and gravity waves.

Ted Shepherd made a presentation on the Working Group on Coupled Modelling (WGCM) on behalf of Veronika Eyring. The WGCM's broad mandate covers reviewing and fostering the development of coupled climate and Earth System Models, coordination of model experiments and intercomparisons (*e.g.* CMIP5), as well as the promotion and facilitation of model validation. Experience from CMIP5 was briefly summarized. CMIP5 produced an extremely large volume of data, which was managed and made available through the Earth System Grid Federation (ESGF) architecture. In a parallel effort, the obs4MIP database was created for model comparison purposes. This database mainly contains gridded, monthly-average NASA observational data. In tandem with WGNE, the WGCM has put together a model metrics panel to focus on model performance metrics and to liaise with other WCRP groups. Brief results regarding the simulation of stratospheric ozone by CMIP5 models was also presented. In contrast to CMIP3, where half of participating models used a prescribed stratospheric ozone climatology, all CMIP5 models considered either prescribed time-evolving ozone (*i.e.* past ozone depletion and future ozone recovery), or simulated ozone changes interactively, resulting in substantial improvements in simulated stratospheric ozone. This progress led to a more realistic representation of the effects of anthropogenic forcings on stratospheric temperatures and subsequent impacts on tropospheric climate. The representation of tropospheric chemistry in CMIP5 models was largely addressed by the Atmospheric Chemistry-Climate Model Intercomparison Project (ACCMIP), coordinated by Jean-François Lamarque and Drew Shindell.

Standing in for Kaoru Sato, **Greg Bodeker** presented the main aims and goals of the recently created WCRP Data Advisory Council (WDAC). WDAC will act as a focal point for all WCRP data and observation activities and will advise the JSC on all issues pertaining to observations and climate data. The council will also coordinate high-level aspects across the WCRP, ensuring cooperation with the WCRP's main partners, such as the Global Climate Observing System (GCOS), and other observing programmes. Furthermore, WDAC will work together with WMAC (see below) to promote effective use of observations for model comparison and to address issues related to the coordinated development

Figure 1: Participants of the 20th SPARC Scientific Steering Group meeting, Buenos Aires, Argentina.

of data assimilation, reanalysis, observing system sensitivity experiments, and of paleoclimate data. At the first WDAC meeting it was concluded that (1) there is a significant need for measurements of ocean biogenic trace gas and aerosol emissions; (2) a more uniform and formal approach needs to be established for assessing the quality of observational data sets used to validate models; (3) global environmental change data sets, both from models and observations, should be made available through the ESGF; (4) funding agencies need to ensure the long-term storage, management and preservation of collected data; and (5) efforts need to be made to improve the traceability of data sets. There was also discussion regarding the governance of the ESGF, which is an open source effort to provide a robust, data distributed and computation platform enabling world wide access to peta/exa-scale scientific data. The need for a thorough assessment of reanalysis water vapour data sets was endorsed. Furthermore, the ESA SPARC Initiative (SPIN) will be invited to present their approach to WDAC. WDAC's 2nd meeting took place in Darmstadt, Germany, from 4-5 March 2013.

Ted Shepherd reported on the WCRP Modelling Advisory Council (WMAC), who, in partnership with the WCRP core projects and working groups, will serve as a focal point for WCRP modelling activities and will advise the JSC and WCRP community on all issues pertaining to modelling. It will regularly assess modelling capabilities within WCRP; identify gaps, overlaps, opportunities for synergy as well as provide advice on priorities for modelling across the WCRP. WMAC aims to facilitate effective communication on modelling issues both within the WCRP and with the broader community. In addition, it will promote capacity development in terms of model development, evaluation, and application. Outcomes of the first WMAC meeting included: (1) WMAC will form a task team with IGBP on prediction of the Earth system; (2) WMAC and the WGNE will act complementarily: WGNE is focused mainly on atmospheric modelling while WMAC addresses the Earth system as a whole; and (3) interactions with end users would generally be dealt with in the existing modelling groups, but if WMAC identifies gaps, it would advise the JSC on appropriate action. It was emphasized that the WMAC is primarily an advisory body and will not take on activities itself.

Shigeo Yoden presented results from a meeting on Sudden Stratospheric Warmings (SSWs) that took place in Kyoto, Japan, in February 2012. He also advertised: (1) a WCRP Regional Workshop on stratosphere-troposphere processes and their role in climate, which took place in Kyoto, Japan, from 1-3 April 2013; (2) the Asia Oceania Geosciences Society meeting, held from 24-28 June 2013, which had a Middle Atmosphere Science session; (3) a SSW symposium that took place during the Davos Atmosphere and Cryosphere Assembly, held from 8-12 July 2013 in Davos, Switzerland; and (4) a meeting during the International Association of Geomagnetism and Aeronomy's General Assembly, to be held in Merida, Mexico, from 26-31 August 2013.

Pablo Canziani advertised the WCRP Special Workshop on Climatic Effects of Ozone Depletion in the Southern Hemisphere: Assessing the evidence and identifying gaps in the current knowledge. The workshop took place from 25 February to 1 March 2013, in Buenos Aires, Argentina (see article this issue).

SPARC items

The SPARC Data Center was established in 1999 and contains a number of important SPARC data sets (see **http://www.sparc-climate.**

org/). A mirror website and ftp database are maintained at Kyoto University, Japan, providing both an external backup and enhanced accessibility. Marvin Geller recently submitted a proposal to NASA for three years of further funding for the SPARC Data Center. The submitted proposal will also serve to continue research activities related to high vertical resolution radiosonde measurements (archived at the SPARC Data Center). A workshop regarding the scientific analysis of these observations was held from 27-29 May 2012 at Stony Brook University. Marvin also proposed a three-year transitioning strategy, which could be applied to migrate the data from the SPARC Data Center to the British Atmospheric Data Centre to ensure the continuity of the provision of these data to the community. At the end of the three transition years, all data storage would cease at Stony Brook University.

Joan Alexander discussed ideas for a new SPARC implementation plan, which needs to be prepared to address new science foci, the WCRP's restructuring, including the Grand Challenges, as well as SPARC's new mandate. This might imply finding a new structure under which SPARC research activities may be integrated (*i.e.* a replacement of the themes in the present implementation plan). The implementation plan should envisage a time frame of approximately 10 years.

The contribution of SPARC to aerosol-related research under the WCRP GCs was also discussed. There are different aspects regarding the influence of aerosols on climate and climate change, one being related to aerosol, cloud and precipitation interactions. SPARC's involvement in this aspect of the "Clouds, Circulation and Climate Sensitivity" GC was discussed at the CCMI workshop (held in Boulder, USA, from 14-17 May 2013). It was also suggested that SPARC may want to connect with AeroCom activities, with mention of a possible collaborative workshop. In addition, SPARC may want to consider greater focus on studies looking at transport and circulation changes that might lead to changes in precipitation patterns.

Carolin Arndt made a short presentation about SPARC communication activities, including the SPARC website (**http://www.sparc-climate.org/**), SPARC eNews and the SPARC Newsletter. Website statistics show that from August to November 2012 the SPARC website was viewed over 9 500 times. To avoid overloading the SPARC community with emails from the SPARC office, workshop and meeting announcements are usually advertised on the SPARC website and then included in the eNews bulletin (sent out via email to about 400 recipients approximately every 2 months). To be sent out through the eNews, announcements need to be sent to the SPARC Office a few weeks before the event takes place (or the deadline for registration expires), so as to reach the SPARC community in a timely fashion.

Carolin Arndt then continued by reporting on ideas for expanding SPARC's capacity development strategy. Several mechanisms were identified, such as mentoring and visiting programmes for scientists from developing countries and the establishment of a SPARC capacity development fund. The possibility of networking with potential partners such as START, APN and the ICTP, amongst others, was also proposed. However, since no SSG members are directly engaged in SPARC capacity development activities it was decided to postpone the discussion of suitable topics to include new SSG members who will begin terms from January 2014. Furthermore, after considerable investigation, it was found that establishing a SPARC capacity development fund at the ETH Zürich (the SPARC Office's current host institution) would not be feasible.

Joan Alexander introduced a joint SPARC-IGAC workshop on Atmospheric Chemistry and the Asian monsoon. The Asian summer monsoon plays a significant role in chemistry-climate interaction, however experimental studies in the region are extremely challenging. The goal of the workshop is to improve collaborative efforts across the international community. This workshop took place in Kathmandu, Nepal, from 9-12 June 2013.

Carolin Arndt and **Greg Bodeker** discussed SPARC's new name, "Stratosphere-troposphere Processes And their Role in Climate", which was selected after consultation with the SPARC community (the SPARC acronym will, however, remain unchanged). For the new SPARC logo, a competition has been run. Initially the SPARC community was asked for contributions and then professional designers were asked to provide and adapt new versions. The SPARC SSG and activity leaders were asked to vote on several options and the final version will be launched at the SPARC General Assembly in January 2014.

Fiona Tummon presented the progress of the implementation of the SPARC community data base, which is currently in the final stages of development. The concept of a new SPARC members' database was presented by Greg Bodeker at the 19th SPARC SSG meeting, held in Zürich (see SPARC newsletter No. 39[11]). Implementation of the database with an additional web-interface is planned for mid-2013.

The SPARC Office team agreed to produce the first SPARC annual report using updated material from the activity leaders. The demand for such a document and the time required for its preparation will be assessed. The annual report is now available online[12].

Greg Bodeker presented plans for the next SPARC General Assembly, which will take place from 12-17 January 2014 in Queenstown, New Zealand. The outline of the scientific programme was also discussed with Veronika Eyring and Adam Scaife, co-chairs of the Scientific Organising Committee.

After a short discussion regarding action items, **Greg Bodeker** asked the participants about their thoughts on the new format of the SPARC SSG meeting (*i.e.* a short description of activities being provided before the meeting, and then separation of scientific presentations and programmatic discussions during the meeting). All participants approved of the new procedure.

The next SSG Meeting will take place from 19-21 January 2014 in Queenstown, New Zealand, following the 5th SPARC General Assembly.

[11]http://www.sparc-climate.org/fileadmin/customer/6_Publications/Newsletter_PDF/39_SPARCnewsletter_Jul2012_web.pdf

[12]http://www.sparc-climate.org/fileadmin/customer/6_Publications/ProgPlan_PDF/SPARC_Annual_Report_2012_small.pdf

Report on the Regional WCRP/SPARC Workshop with focus on the Southern Hemisphere and South America

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From 26-27 November 2012 the Workshop on Southern Hemisphere and South American Climate was held in Buenos Aires, Argentina, back-to-back with the SPARC SSG Meeting, hosted by the "Centro de Investigaciones del Mar y la Atmósfera" (CIMA). SPARC provides expertise in several key areas related to climate variability and climate change, such as dynamical variability, ozone, stratosphere-troposphere dynamical coupling, gravity waves, temperature trends, and data assimilation, amongst others. The southern hemisphere (SH), and in particular South America, are regions of the world in which research of these key themes is highly relevant, and needs to be expanded and strengthened because the current South American research community addressing these issues is relatively small. The main goal of the Workshop was to gather local researchers interested in different aspects of current and future SPARC research together with participants of the SPARC SSG meeting to promote interaction among researchers and to identify the main SPARC-related research topics of relevance to the region. The Workshop included 22 oral talks and 5 posters, with contributions from Argentina, Brazil, Uruguay, Bolivia, Colombia and Uruguay, combined with contributions from SPARC scientists. The Workshop agenda was broad, covering several different research topics.

Gravity Waves

Biases in SH middle atmosphere winds still exist in many climate models, but in other types of models these biases have been reduced through the application of gravity wave drag parameterizations. One of the key observational quantities used to constrain gravity wave (GW) parameterizations is wave stress or wave momentum flux (MF). **Alejandro La Torre** and **Peter Alexander** identified and simulated GW events above the southern Andes and Antarctic Peninsula, with significant MF occurring at low levels and then decreasing with height. Partial reflection, wave breaking and absorption at critical layers seem to explain the momentum deposition accompanying decreases in GW MF. A prevailing negative zonal component of MF was observed almost everywhere, in agreement with the orographic source hypothesis.

Joan Alexander discussed the challenge of observing GWs globally because of the high spatial and temporal resolution required to constrain their role in the momentum budget. A recent international intercomparison organized with the help of SPARC and the International Space Science Institute, made significant progress in constraining momentum fluxes using both global-scale measurements of GW momentum fluxes in the SH, super-pressure balloon measurements in the SH high latitudes, and model simulations. She presented evidence that small islands in the Southern Ocean could contribute significantly to the orographic gravity wave drag missing in the models around 60°S (see **Figure 2**).

Guillermo Scheffler and **Manuel Pulido** used a variational data assimilation technique to determine the middle atmospheric gravity wave drag (GWD) produced by unresolved GW in the MERRA reanalysis. The multiyear GWD evaluation shows a characteristic latitudinal dependence, with a strong deceleration centre at 60° in the winter hemisphere, and a weaker deceleration centre at 30° in the summer hemisphere. An intensification of the summer deceleration centre of GWD over the last 20 years was found in the MERRA reanalysis.

Ozone

Elian Wolfram described the ozone monitoring and research related to ozone impacts that are currently being carried out in Argentina. Recently, the Ozone DIAL and SAOZ instruments of the Atmospheric Observatory of Southern Patagonia (OAPA) radiometer joined NDACC (Network for the Detection of Atmospheric Composition Change). Observations were used to analyse extreme and persistent ozone holes that develop over the southern tip of South America. **Susana Díaz** presented an analysis of the monthly time series of total ozone column (TOC) at 20 stations in Antarctica and South America from 1979-2011. She showed that events where TOC remains below 220DU for several days occurred during September and October at all stations analysed. **Roberto Rondanelli** presented results of a two-year effort to produce ozone soundings in the Santiago area in Chile, mostly to understand the diurnal cycle of urban photochemistry and transport in the region, particularly during summer. Observations highlight the role of the residual layer as a chemical reservoir for ozone and precursors during the night, which can then be transported and activated by the thermally driven circulation during the day. Some cases show evidence of stratospheric intrusions, although the physical processes related to these events are not yet clear.

Aerosols

Pablo Ristori described the new multi-wavelength lidar network and associated instruments currently being installed at the main Patagonian airports in Argentina. Their goal is to monitor the presence of atmospheric ash emitted by Andean volcanoes, like the recent eruption of the Puyehue Cordón Caulle volcano, whose aerosol plume reached as far as Buenos Aires city (see **Figure 3**). These lidars are being developed by the Lidar Division of CEILAP-Buenos Aires and are going to be operated by the National Weather Service. This new technology provides real time information to airports, airlines, the Buenos Aires Volcanic Ash Advisory Centre and the research community.

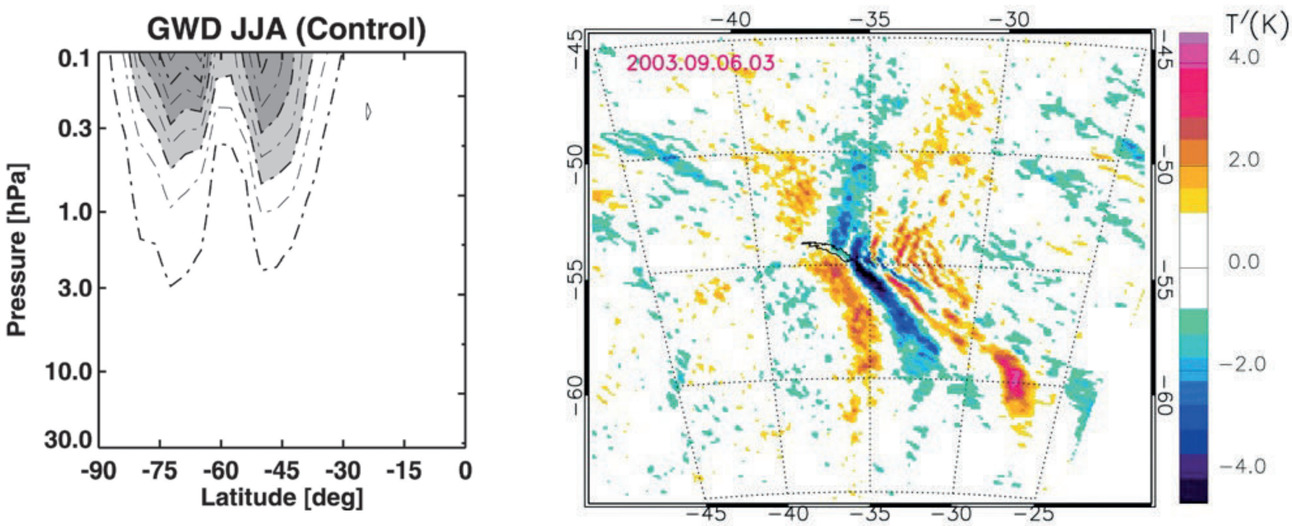


Figure 2: Left: Missing drag near 60°S due to lack of resolved topography is associated with zonal wind biases in models (figure from McLandress *et al.*, 2012). Small Islands in Southern Oceans will provide some missing flux. Right: Orographic Waves over South Georgia Island observed as AIRS TB anomalies (figure from Alexander *et al.*, 2009).

Dynamics of Stratosphere-Troposphere Coupling

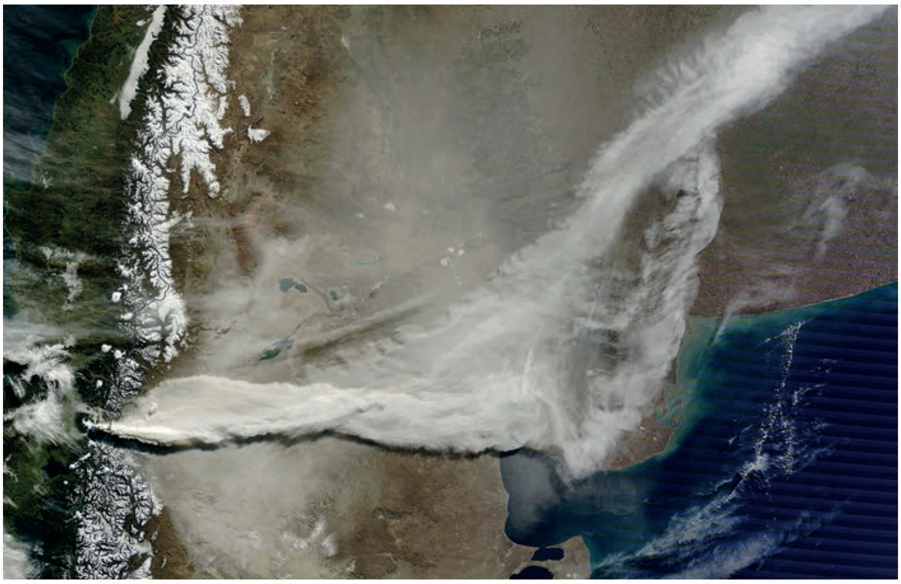
Carolina Vera presented recent evidence that stratospheric dynamics can alter tropospheric SH circulation, which in turn can impact South American climate. The coupling of stratosphere-troposphere dynamics is, however, not yet well understood. **Mark Baldwin** showed that geopotential height might not be the right variable to describe vortex dynamics, instead, he suggested considering a metric based on polar tropopause variability. Anomalous upwelling/downwelling over the polar cap can be thought of as a mechanical "plunger effect", with the anomalous upwelling/downwelling that extends through the tropopause into the troposphere being driven by Rossby waves.

Climate Variability in the SH

Mark also pointed out that the availability of analysis and tracking algorithms has improved our knowledge of cyclogenesis and cyclone trajectories over the SH and, in particular, over South America. Despite this, we still don't fully understand all regional aspects of these systems. High-resolution regional models are useful tools for examining cyclones and cyclogenesis in specific regions, but improvements are still needed so that the physical processes governing these systems are properly represented in these models. In addition, **Carolina Vera** showed that the activity of the Southern Annular Mode has a large influence on south eastern South American climate on intraseasonal, interannual and decadal timescales. Such influence can act synergistically or destructively in combination with the influence of tropical Indian-Pacific convection variability. She also showed that stratosphere-resolving models, such as those contributing to the WCRP/SHFP-CHFP (Stratospheric-Resolving Historical Forecast Project-Climate-Systems Historical Forecast) Project, can predict larger seasonal signals in the SH circulation than models with poor vertical resolution in the stratosphere. **Marcelo Barreiro** showed that knowledge of the state of the tropical oceans improves seasonal predictability of the South American Climate.

Climate Change

Julie Arblaster and colleagues examined shifts in the distribution of ozone and winds in 46 CMIP5 models, separating between those with prescribed ozone (NOCHEM) and those with interactive or semi-offline chemistry (CHEM). They found that in the high-mitigation RCP2.6 scenario ozone recovery dominates and the SH extra-tropical jet shifts equatorward, although this change was assessed as weak, as it is found only in some models (see **Figure 4**). In the business-as-usual RCP8.5 scenario the greenhouse gas (GHG) effect prevails and the SH extra-



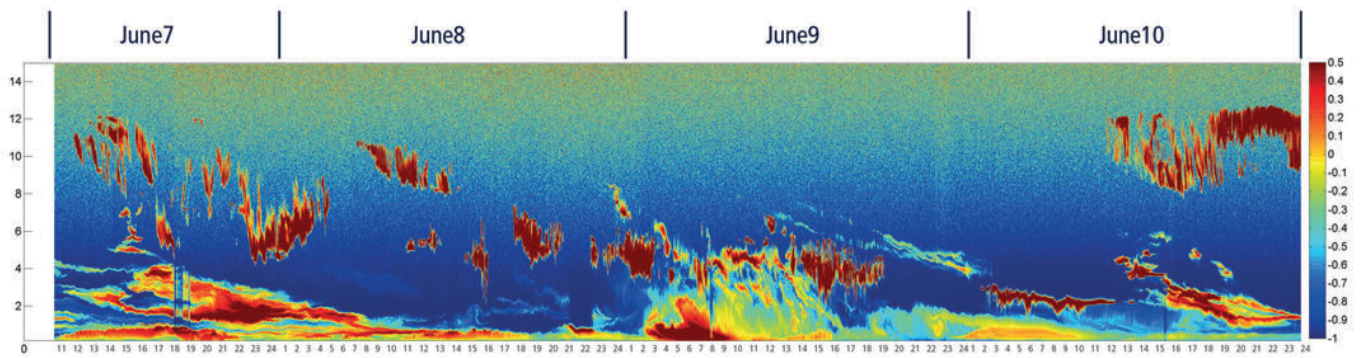


Figure 3: Top: Volcanic aerosol plumes over Patagonia. Satellite image TERRA June 13, 2011 14.35 UTC, [**http://rapidfire.sci.gsfc.nasa.gov/gallery/**]. Bottom: Aerosol attenuated backscatter at 1064nm measured with a lidar system in Buenos Aires. Atmospheric boundary layer, volcanic ash layers and high level clouds can be observed (figure from Ristori *et al.*, 2012).

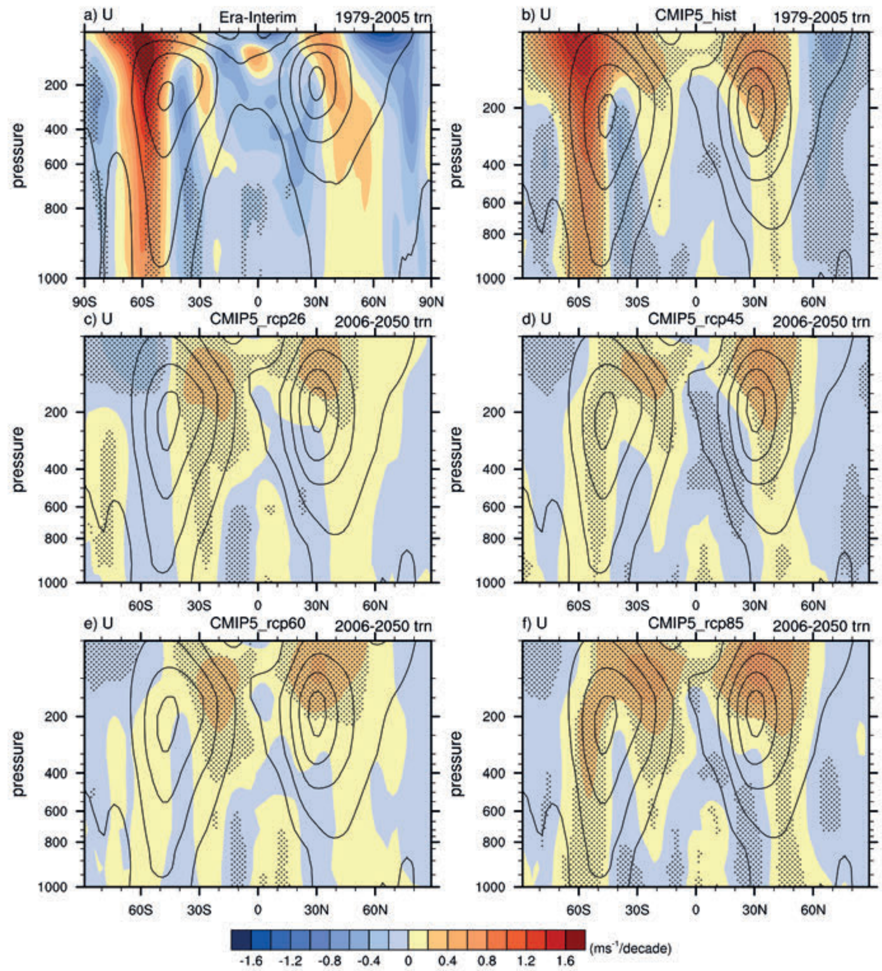


Figure 4: Long-term mean (thin black contour) and linear trend (color) of zonal mean DJF zonal winds for (a) ERA-Interim from 1979–2005; (b) CMIP5 (all models listed in Table 1 in Eyring *et al.,* 2013, except those noted with #), and (c), (d), (e), (f): same as (b), but for the four RCPs over 2006-2050. Contour intervals of climatological wind are 10m/s starting from -20m/s. Trends which are statistically significant at the 5% level (95% confidence) are stippled (figure from Eyring *et al.,* 2013).

tropical jet shifts poleward, a result assessed as robust across all models. In addition, differences between CHEM and NOCHEM models are not large, and are clouded by other model characteristics. **P. González** presented an analysis of the positive precipitation trends observed in south eastern South America during the second part of the 20th century using different climate simulation experiments. She suggested that the effect of ozone depletion might be as or more important than that of GHGs on the South America precipitation trend. **Dian Seidel** presented a new data set of middle- and upper-stratospheric temperatures based on a reprocessing of satellite radiances from the Stratospheric Sounding Unit. The data set provides a view of stratospheric climate change during the 1979–2005 period that is strikingly different from those of earlier data sets. The new data call into question our understanding of observed stratospheric temperature trends and our ability to test simulations of the stratospheric response to emissions of GHGs and ozone-depleting substances.

Model Biases

Ted Shepherd discussed the fact that climate models generally do not provide robust projections of circulation-driven aspects of climate change in the mid-latitudes. Mid-latitude circulation is subject to strong internal variability, leading to non-robust decadal-timescale trends, an issue that needs to be taken into account in regional climate projections. In addition, model errors in both mean climate and climate variability at mid-latitudes are most likely largely related to errors in parameterized atmospheric processes. Breaking the feedback loop between mean circulation and resolved eddy fluxes helps identify the errors. A strong emphasis is needed on improving models and better understanding climate variability.

Final Remarks

Large-scale variability and circulation change in the SH exhibit hemispheric patterns that can impact the regional climate of South America, Africa, Australia-Oceania, and Antarctica, on time scales ranging from days to decades. It would be warmly welcomed if SPARC could support future initiatives that provide a framework for research coordination of SH climate variability and predictability.

Many monitoring (ozone, UV, aerosols) activities are currently underway in southern South America, mainly to support meteorological services and environment agencies. There is a need to build partnerships between scientific and operational communities in order to accelerate the development of climate information and tools relevant to societal needs (climate services).

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The NASA Airborne Tropical TRopopause EXperiment (ATTREX)

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We report here on recent airborne measurements in the tropical tropopause layer (TTL, ~13-19km) provided by the NASA Airborne Tropical TRopopause EXperiment (ATTREX). ATTREX is a five-year airborne science program focused on the physical processes occurring in the TTL, which ultimately determine the composition and humidity of air entering the stratosphere. The long-range (16 000km), high-altitude (20km) Global Hawk (GH) unmanned aircraft system is equipped with twelve instruments measuring clouds, water vapour, meteorological conditions, chemical tracers, chemical radicals, and radiation. The overall ATTREX project is managed by the NASA Ames Research Center, and the Global Hawk program is managed by Dryden Flight Research Center (DFRC). ATTREX flights were conducted from DFRC in southern California into the deep tropics during autumn 2011 (three flights) and late winter 2013 (six flights). Planned flights from Guam in winter and early-summer 2014 will provide extensive measurements in the western Pacific TTL.

Radiative transfer calculations show that even small changes in stratospheric humidity have climate impacts that are significant compared to those of decadal increases in greenhouse gases (Forster and Shine, 2002; Solomon *et al.*, 2010). Future changes in stratospheric humidity and ozone concentration in response to changing climate are significant climate feedbacks. While the tropospheric water vapour-climate feedback is well represented in global models, predictions of future changes in stratospheric humidity are highly uncertain because of gaps in our understanding of physical processes occurring in the TTL. The composition and humidity of the TTL are controlled by a complex interplay between slow, large-scale transport, rapid convective transport, atmospheric waves, cloud processes, and radiative heating (see **Figure 5**). High spatial-resolution measurements of TTL composition are sparse in comparison to other climatically important parts of the atmosphere, partly because the high altitude of the TTL limits sampling with aircraft. Furthermore, the use of satellite measurements of TTL composition for assessing physical processes is complicated by the characteristically strong vertical gradients in this region.

The overarching goals of ATTREX are (1) to improve our understanding of how deep convection, slow large-scale ascent, waves, and cloud microphysics control the humidity and chemical composition of air entering the stratosphere, and (2) to improve global-model predictions of feedbacks associated with future changes in TTL cirrus, stratospheric humidity, and stratospheric ozone in a changing climate. ATTREX is providing an unprecedented dataset of high spatial-resolution measurements of TTL composition necessary to achieve these objectives.

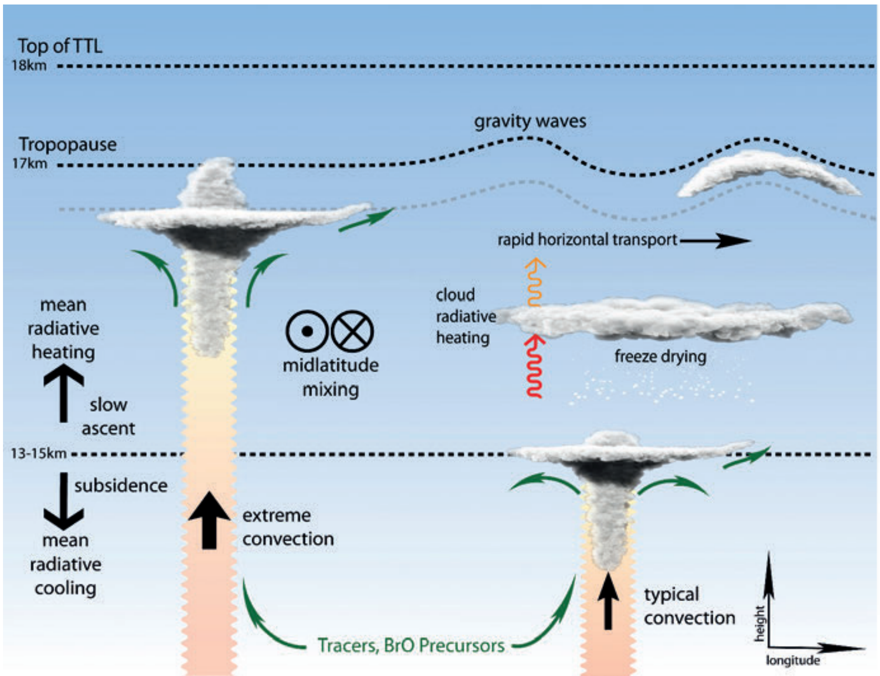


Figure 5: Schematic diagram showing TTL physical processes, including large-scale transport, detrainment from deep convection, gravity waves, thin cirrus, and radiative heating.

Global Hawk Operations

The GH is nearly ideal for sampling the TTL. The aircraft ceiling (ranging from about 54 000feet (~16.5km) shortly after take-off to 62 000feet (~18.9km) in the latter part of the flight) permits sampling through the depth of the TTL and into the lower stratosphere. The range of the GH permits sampling large regions of the Pacific TTL even with flights originating in southern California (see **Figures 6 and 7).** As demonstrated on the ATTREX flights, frequent vertical profiling through the TTL can be conducted with the GH. The payload capacity (~680kg) is adequate for carrying remote-sensing and in situ instruments necessary to make key TTL measurements (see payload section below). Inmarsat and Iridium satellite-based communication systems are used for command and control of the GH and its payload. The GH also includes a Ku satellite link for high-speed communication with the payload. Using these communications systems, investigators remotely monitor their instruments, optimize settings for the conditions being sampled, and correct problems that arise. The real-time data downloaded to the GH Operations Center is also extremely useful for aircraft operations. While the aircraft was flying at cruise altitude, the real time Cloud Physics Lidar (nadir) and Microwave Temperature Profiler measurements of clouds and temperature below the aircraft were used to decide when and where to execute vertical profiles in order to sample the cloud regions with particle and trace-gas instruments. Real-time data from the *in situ* instruments was also useful for determining the conditions the GH was sampling. The real-time direction of the aircraft was facilitated by support from the GH pilots and mission manager who accommodated numerous requests for flight plan changes from the scientists.

It should be noted that operation of the GH presents certain challenges. Take-offs and landings are not possible with strong cross-runway winds, icing conditions in the area, in precipitation, or with standing water on the runway. As with other high altitude, long-wing aircraft (such as the ER-2), flying in convective regions is subject to restrictions. The GH was also not designed for flying in the extremely cold tropical tropopause air that is critical for ATTREX science objectives, necessitating mitigation measures to ensure that critical aircraft components are not exposed to the extreme outside temperatures. The GH operation is also dependent on the functionality of multiple satellite communications systems that are not necessarily required for operation of manned aircraft. Despite these constraints, the GH has turned out to be an excellent platform for achieving the ATTREX objectives.

ATTREX Global Hawk Payload

The ATTREX payload was designed to address key uncertainties in our understanding of TTL composition, transport, and cloud processes affecting water vapour. Measurements of water vapour, cloud properties, numerous tracers, meteorological conditions, and radiative fluxes are included (see **Table 1**). Instruments were chosen based on proven techniques and size/weight accommodation on the GH.

The very dry conditions present in the tropical tropopause region (water vapour concentrations as low as ~1ppmv) represent a significant challenge for accurately measuring water vapour. Discrepancies between water vapour concentrations measured with different instruments have plagued past attempts to accurately quantify the humidity of the stratosphere and TTL (SPARC, 2000; Peter *et al.*, 2006; Weinstock *et al.*, 2009). In the very dry conditions associated with the cold tropical tropopause, the discrepancies have been as large as a factor of two in water vapour concentration. A ground-based comparison of airborne instruments conducted in 2008 showed much better agreement than had been seen in stratospheric measurements (Fahey *et al.*, 2009). The resulting implication is that unknown or underestimated systematic errors are associated with operation of these instruments on moving platforms in the upper troposphere and lower stratosphere (UTLS).

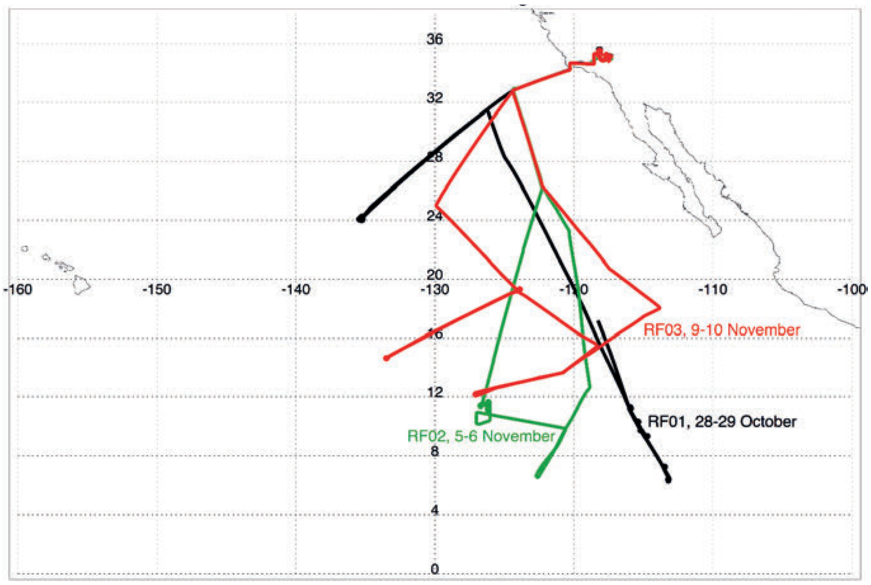


Figure 6: Flight paths for 2011 ATTREX flights.

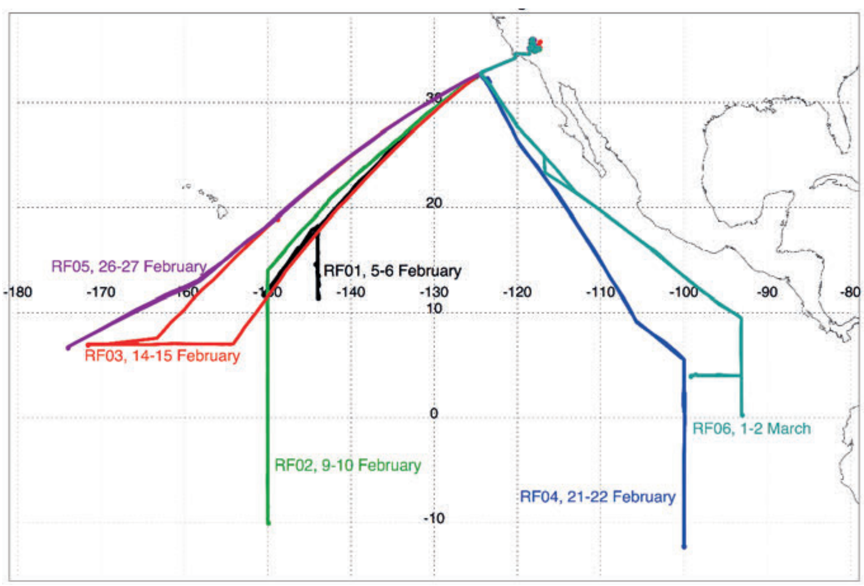


Figure 7: Flight paths for 2013 ATTREX flights. Note the different latitude/longitude range here than in Figure 6.

The ATTREX payload addresses the concerns with water vapour accuracy and reliability by including two water vapour instruments, Diode Laser Hygrometer (DLH) and NOAA Water (NW), both of which have suitable sensitivity for water vapour values as low as 1ppm. The two hygrometers use very different methods and have particular strengths that complement each other. The NW instrument (added to the payload in 2013) provides a closed-cell tunable-diode laser (TDL) measurement that includes the in-flight calibration system used on the NOAA chemical ionization mass spectrometer (CIMS) instrument during MACPEX (Thornberry *et al.*, 2013). Calibration in flight avoids the uncertainty associated with assuming that ground-based calibrations apply to in-flight conditions and that instrument performance is unaffected by the different pressure and temperature conditions in flight. The NW instrument also measures total water concentration using a forward-facing inlet that enhances ice concentration. The DLH instrument provides an open-path TDL measurement by firing the laser from the fuselage to a reflector on the wing and measuring the return signal. The path length (12.2m) is long enough to provide a precise, fast measurement of water vapour. The precision is sufficient to permit detection of fine structure in the TTL water vapour field even at a data rate of 100Hz (corresponding to 1.7m horizontal resolution along the flight path for a typical GH speed of 172m/s). The preliminary NW and DLH data obtained in the 2013 flights suggest a high degree of consistency and agreement for

Table 1: Global Hawk Payload:

Instrument	Investigator	Institution	Measurements
REMOTE			
Cloud Physics Lidar (CPL)	M. McGill	NASA/GSFC	Aerosol/cloud backscatter
Microwave Temperature Profiler (MTP)	M. Mahoney	JPL/Caltech	Temperature profile
Differential Optical Absorption Spectrometer (DOAS)	J. Stutz, K. Pfeilsticker	UCLA/Univ. Heidelberg	O_3, O_4, BrO, NO_2, OClO, IO
IN SITU			
Global Hawk Whole Air Sampler (GWAS)	E. Atlas	Univ. of Miami	CFCs, halons, HCFCs, N_2O, CH_4, HFCs, PFCs, hydrocarbons, etc.
UAS Chromatograph for Tracers (UCATS)	J. Elkins	NOAA/GMD	N_2O, SF_6, CH_4, H_2, CO, O_3, H_2O
NOAA Ozone	R.-S. Gao	NOAA/CSD	O_3
Harvard University Picarro Cavity Ringdown Spectrometer (HUPCRS)	S. Wofsy	Harvard University	CO_2, CO, CH_4
NOAA Water (NW)	T. Thornberry, A. Rollins	NOAA/Cires	H_2O (vapor and total)
Diode Laser Hygrometer (DLH)	G. Diskin	NASA/LaRC	H_2O vapor
Hawkeye	P. Lawson	Spec, Inc.	Ice crystal size distributions, habits
Solar and infrared radiometers	P. Pilewskie	Univ. of Colorado	Zenith and nadir radiative fluxes
Meteorological Measurement System (MMS)	P. Bui	NASA/ARC	Temperature, pressure, and winds

Table 2: ATTREX Global Hawk flights:

Flight	Date in 2011	Flight time (hours)	Tropical sampling region (south of 20 N)	Notes
RF01	28–29 October	21.4	6.3–20°N, 113–120°W	Eastern Pacific TTL profiling
RF02	5–6 November	16.5	6.5–20°N, 119–127°W	TTL cirrus sampled
RF03	9–10 November	23.4	12–20°N, 114–134°W	TTL cirrus and convective detrainment sampled

Flight	Date in 2013	Flight time (hours)	Tropical sampling region (south of 20 N)	Notes
RF01	5–6 February	24.5	11.3–20°N, 142–151°W	Central Pacific TTL profiling
RF02	9–10 February	24.3	10.1S–20°N, 143–150°W	Meridional TTL cross section
RF03	14–15 February	24.5	6.8–20°N, 141–172§W	Central Pacific TTL profiling
RF04	21–22 February	24.6	12.3S–20°N, 100–114°W	Eastern Pacific meridional cross section
RF05	26–27 February	24.4	6.5–20°N, 147–174°W	Central Pacific cold TTL cirrus profiling
RF06	1–2 March	24.1	0.2–20°N, 93–111°W	Eastern Pacific cold TTL cirrus profiling

TTL values less than 10ppm. The UCATS instrument also contains a TDL water sensor; although its precision is only +/-1ppmv, it provides useful information and calibration checks for water vapour >10ppmv.

The ATTREX plan calls for use of the Hawkeye instrument for cloud measurements. Hawkeye is a combination of two imaging instruments (equivalent to the two-dimensional Stereo (2D-S) and Cloud Particle Imager (CPI)) and a spectrometer (equivalent to the Forward Scattering Spectrometer Probe (FSSP)), all of which have been used in the past for airborne cloud measurements. Since engineering work for the Hawkeye wing mount on the Global Hawk was not completed in time, the Fast Cloud Droplet Probe (FCDP) was flown during the 2011 and 2013 flights. The FCDP is similar to the FSSP in that it measures the scattering from individual cloud particles. The FCDP was designed for measuring water droplets, and the uncertainty associated with sizing non-spherical ice crystals is not well quantified. However, the instrument provides accurate measurements of ice concentration in cirrus clouds. The cloud measurements, along with the water vapour and temperature measurements, will be used to test our theoretical understanding of ice crystal nucleation, depositional growth, and aggregation. These processes control TTL cirrus formation and dehydration of air entering the stratosphere. The ATTREX payload provides a number of tracer measurements that can be used to quantify TTL transport pathways and time scales. High temporal and spatial resolution measurements of basic tracers are also included. The NOAA O_3 instrument is a dual-beam UV absorption photometer that provides 2Hz ozone measurements. The Harvard University Picarro Cavity Ringdown System (HUPCRS) provides precise, stable measurements of CO_2 and CH_4. The HUPCRS also includes a CO channel that should provide useful data with some averaging. The UAS Chromatograph for Atmospheric Trace Species (UCATS) provides measurements of N_2O, SF_6, H_2, CO (tropospheric), and CH_4, as well as additional measurements of ozone and water vapour.

The Global Hawk Whole Air Sampler (GWAS) provides 90 gas canister samples that are spaced throughout each flight. The times for the GWAS samples are determined on a real-time basis depending on the flight-plan. Post-flight, gas chromatographic analysis provides a plethora of trace gases with sources from industrial mid-latitude emissions, biomass burning, and the marine boundary layer, with certain compounds (*e.g.* organic nitrates) that have a unique source in the equatorial surface ocean. GWAS also measures a full suite of halocarbons that provide information on the role of short-lived halocarbons in the tropical UTLS region, on halogen budgets in the UTLS region, and on trends of HCFCs, CFCs, and halogenated solvents.

The ATTREX payload also includes radiation measurements, which will be used to quantify the impacts of clouds and water vapour variability on TTL radiative fluxes and heating rates. The spectral solar flux measurements additionally provide information about cirrus microphysical properties. Lastly, the Differential Optical Absorption Spectrometer (mini-DOAS) instrument provides slant-path measurements of BrO, NO_2, O_3, IO, O_4 absorption, and cloud/aerosol extinction at various elevation angles near the limb. These measurements can be converted to vertical trace gas concentration profiles from 1km above to 5km below flight altitude using radiative transfer calculations and optimal estimation techniques. The combination of the mini-DOAS BrO (and IO) measurements, along with GWAS measurements of major halogenated hydrocarbons will provide constraints on the TTL and lower stratospheric Br_y and I_y budgets.

2011 and 2013 Flights

The first ATTREX Global Hawk flights from the Dryden Flight Research Center (DFRC) were made in October and November 2011. Although the focus of the 2011 flight series was evaluating aircraft and instrument performance under the extreme tropical tropopause conditions, useful science-quality measurements in the TTL were obtained. Three long flights into the tropics, with durations ranging from 15 to 24 hours, were conducted (see **Table 2** and **Figure 6**). These flights targeted cold tropical tropopause regions where *in situ* cirrus occurrence was likely, regions downstream of deep convection detraining into the TTL, and regions with strong tracer gradients. Each of the flights included multiple vertical profiles in the tropics (see **Table 2**), typically extending from cruise altitude (54,000-60,000ft) down to 45,000ft (~13.7km). As discussed above, real-time lidar data indicating the altitudes and structures of clouds below the aircraft were used to decide when and where to execute vertical profiles.

As a result of instrument development and integration delays the HUPCRS and Hawkeye instruments were not on board during the 2011 flights. Furthermore, integration and centre of gravity issues prevented inclusion of GWAS and CPL in the first 2011 tropical science flight (28−29 October). The FCDP was flown to provide basic information about the concentration and size of TTL cirrus ice crystals. The NOAA water vapour instrument was not included until the 2013 flights. The ATTREX instruments that were flown performed remarkably well, particularly given that several of them were on the GH for the first time.

The 2011 ATTREX measurements provided unique information about TTL cirrus microphysical properties and ice supersaturation (Jensen *et al.*, 2013). Two classes of TTL cirrus were apparent: (1) vertically extensive cirrus with low ice number concentrations, low extinctions, and large supersaturations (up to approx. 70%) with respect to ice; and (2) vertically thin cirrus layers with much higher ice concentrations that effectively deplete the vapour in excess of saturation. The low-concentration clouds are likely formed on a background population of insoluble particles with low concentrations, whereas the high ice concentration layers (with concentrations up to $10cm^{-3}$) can only be produced by homogeneous freezing of an abundant population of aqueous aerosols. These measurements, along with past high-altitude aircraft measurements, indicate that the low-concentration cirrus occur frequently in the tropical tropopause region, whereas the high-concentration cirrus occur infrequently. The predominance of the low-concentration clouds means cirrus near the tropical tropopause may typically be less effective at dehydrating air entering the stratosphere than is typically parameterized in climate models.

In February through early March 2013, six ATTREX flights were conducted from DFRC into the deep tropics (see **Figure 7** and **Table 2**). Again, the flights targeted cold tropopause regions where TTL cirrus were likely (typically southwest of Hawaii or in the extreme tropical eastern Pacific), and regions with convective transport into the upper TTL. Flights RF02 and RF04 provided surveys of TTL composition versus latitude.

Figure 8 shows an example of the TTL sampling strategy used on these flights. An even greater emphasis was placed on vertical profiling through the TTL than in the 2011 flights. The number of TTL profiles per flight ranged from 16 to 24. As a result of a required reduction of the payload power draw when the

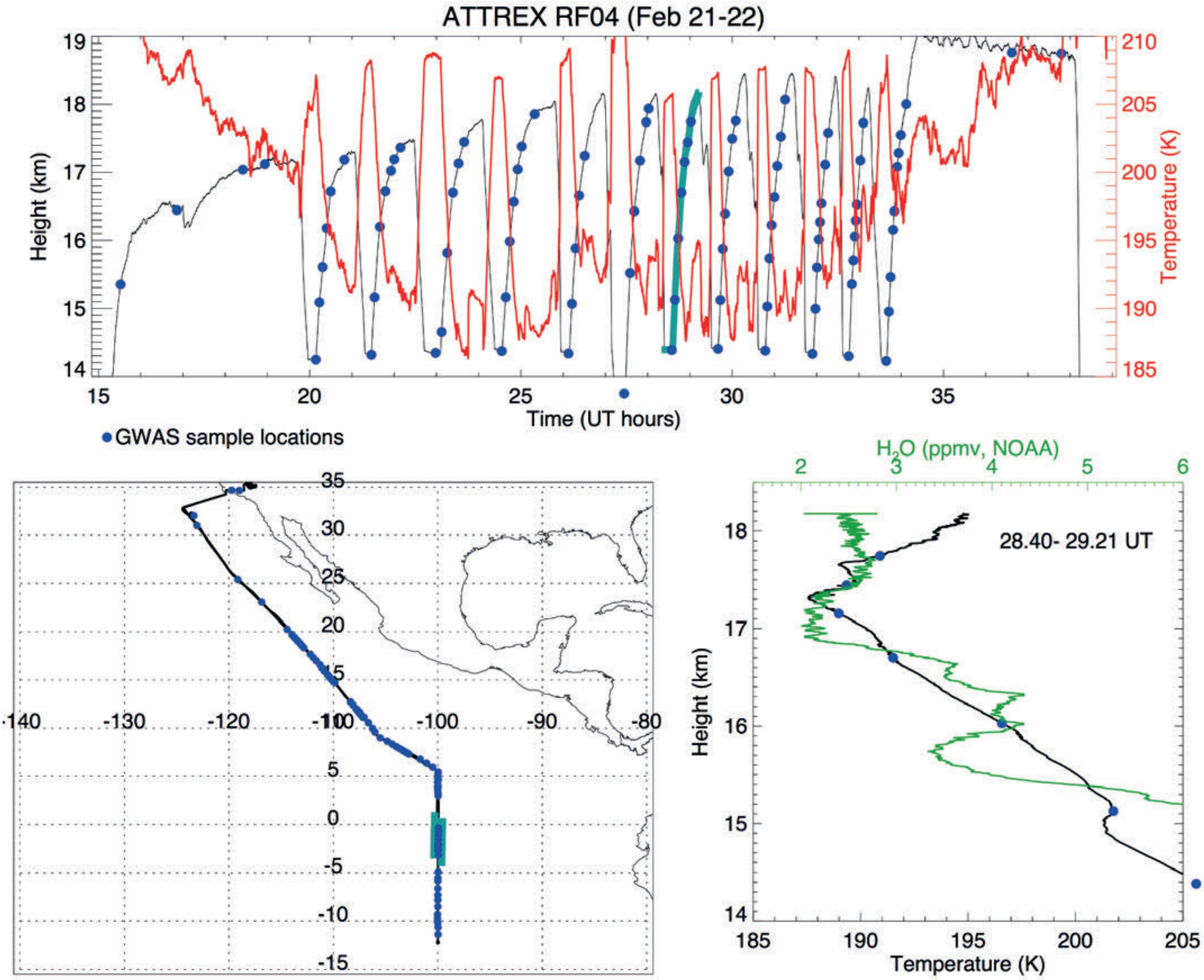


Figure 8: Example of TTL sampling strategy used for the ATTREX flights. Top: time series of height and temperature showing numerous vertical profiles. Bottom left: flight path. Bottom right; Vertical profiles of temperature and water vapour from an ascent just south of the equator. Blue circles on all plots indicate the times/locations of GWAS samples.

engine power is reduced during descents, the GWAS instrument only took samples on ascents. The engineering for the Hawkeye wing mount was still not complete in time for the 2013 flights, and the FCDP was again flown as a substitute.

The tropical tropopause in January 2013 was anomalously cold (zonal mean tropical (15°S–15°N) cold point temperatures as low as about 187K) and elevated (~82.5hPa). The cold, high tropical tropopause was likely the result of multiple processes, including a strong stratospheric sudden warming (SSW), the quasi-biennial oscillation (QBO), and tropical Kelvin waves. **Figure 9** depicts the SSW and QBO effects using Modern-Era Retrospective analysis for Research and Applications (MERRA) analysis data from 20 December 2012 through 20 January 2013 (before and after the SSW). A large planetary wave developed in the northern hemisphere and propagated vertically into the stratosphere (indicated by the green lines in **Figure 9**, which show the Eliassen-Palm flux vectors). The planetary-scale wave deposited easterly momentum in the middle stratosphere, which then caused "poleward" motion in the middle stratosphere (B in **Figure 9**). The poleward motion resulted in sinking in the polar region that rapidly warmed the stratosphere north of about 45°N (hence the expression "stratospheric sudden warming"). The poleward motion (B in **Figure 9**) caused a tropical ascent (at C) that balanced the polar descent. This tropical rising motion (C) led to a ~2K cooling just above the tropical tropopause. In January-February 2013, the QBO was in its easterly phase (westward blowing winds), which also induced an effect on temperature, causing approximately 1-2K colder temperatures (thick blue) at altitudes below the QBO wind minimum (thick orange). It is important to note that the tropopause temperature in the ATTREX sampling region (**Figure 7**) was affected by a number of factors, including the QBO, the SSW, Kelvin waves, and other intraseasonal variations.

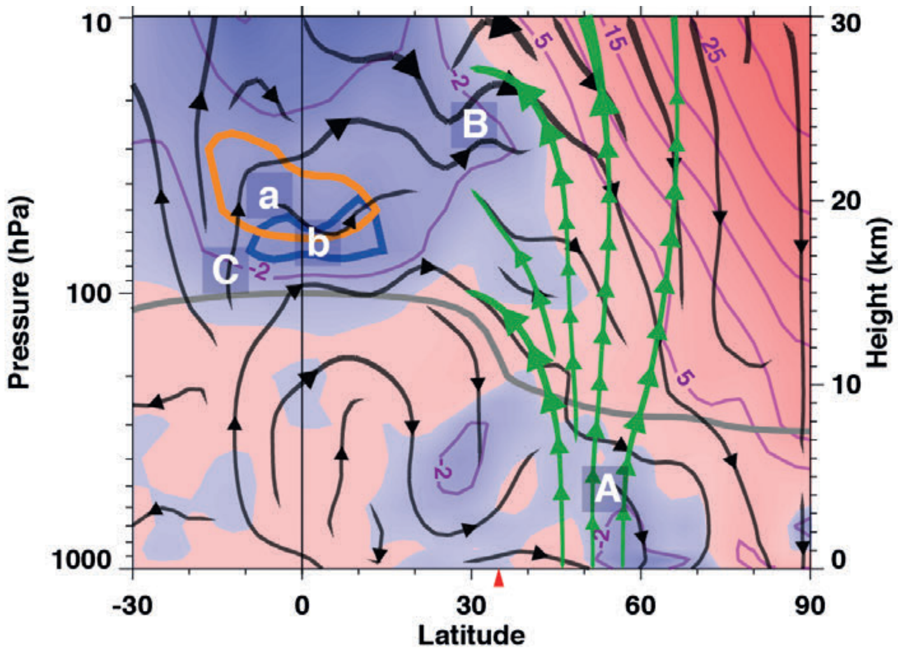


Figure 9: The blue/red colour scale and magenta contours show the zonal mean temperature change between 20 December 2012 and 20 January 2013. The black streamlines show the time-averaged residual circulation (20 Dec. 2012 to 20 Jan. 2013). The green lines show the average Eliassen- Palm flux vectors, and the thick grey line shows the average tropopause (20 Dec. 2012 to 20 Jan. 2013). The thick orange line shows the 21-31 January 2013 5m/s zonal wind contour, and the thick blue line shows the 21-31 January 2013 2K zonal temperature contour after subtracting the 1979-2012 climatology. See text for discussion.

Dry air in the tropopause region associated with the anomalously cold January 2013 tropical tropopause was sampled on multiple ATTREX flights, with water vapour concentrations as low as about 1.5ppmv indicated by both the NOAA and DLH hygrometers. As in past high-altitude aircraft tropical campaigns, *in situ* TTL cirrus were generally encountered when the aircraft was directed into cold tropical tropopause regions. The last flight in 2013 (RF06) provided extensive TTL cirrus sampling in an eastern Pacific tropopause cold pool with minimum temperatures below 185K. **Figure 10** shows temperature, water vapour, relative humidity, and cirrus ice concentration measurements from an ascent through a cirrus layer at the tropopause. Within the cloud layer between 17.5-17.6km where the ice concentration is several hundred particles per litre, the relative humidity was near 100% (within the 15% combined water vapour and temperature uncertainty), and the water vapour was depleted down to about 1.8ppmv. This case is consistent with the cloud and water vapour measurements from the 2011 flight series.

Two flights (RF03 and RF05) extended as far into the western Pacific cold pool as possible given the GH range. These flights nearly reached the international dateline (180°E). Previous measurements have shown that flow around the western Pacific anticyclone that brings air south into the cold tropical region in the vicinity of Hawaii can drive *in situ* TTL cirrus formation (Pfister *et al.*, 2001). Flight RF05 provided a case study of cirrus driven by this flow pattern (see **Figure 11**). As the GH approached the cold tropopause region at the western end of the flight track, a layer between about 16-17.5km was encountered with low ozone (~25−40ppbv) and a cloud with relatively high ice water content. The NOAA total water measurement indicated up to ~20ppmv condensed mass, which is considerably higher than the background water vapour concentration. No convection in the immediate vicinity of the flight track was present with cloud tops above about 15km. However, the low ozone and considerable condensed mass suggest recent convective detrainment near the tropopause. We hypothesize that convective transport of moist, low ozone air to the tropopause must have occurred upstream of the observed cloud in a location where the tropopause was warm enough such that relatively large water vapour concentrations were left behind after ice sublimation. This pool of moist, low-ozone air was then transported around the anticyclone into the cold tropopause region southwest of Hawaii, resulting in the TTL cirrus sampled by the GH. This transport/cloud formation mechanism may be typical for TTL cirrus that occur frequently in the western Pacific.

The ATTREX measurements provide additional evidence for the preponderance of small-scale, wave-driven temperature fluctuations in the tropopause region. Typical small-scale (a few km) variations along the flight track were about 1K peak-to-peak. As expected for a red spectrum, variations were larger at larger scales. Over a few 100km, wavelike variations were as large as 4-5K. Though these scales are greater than the grid size of large-scale models, many of

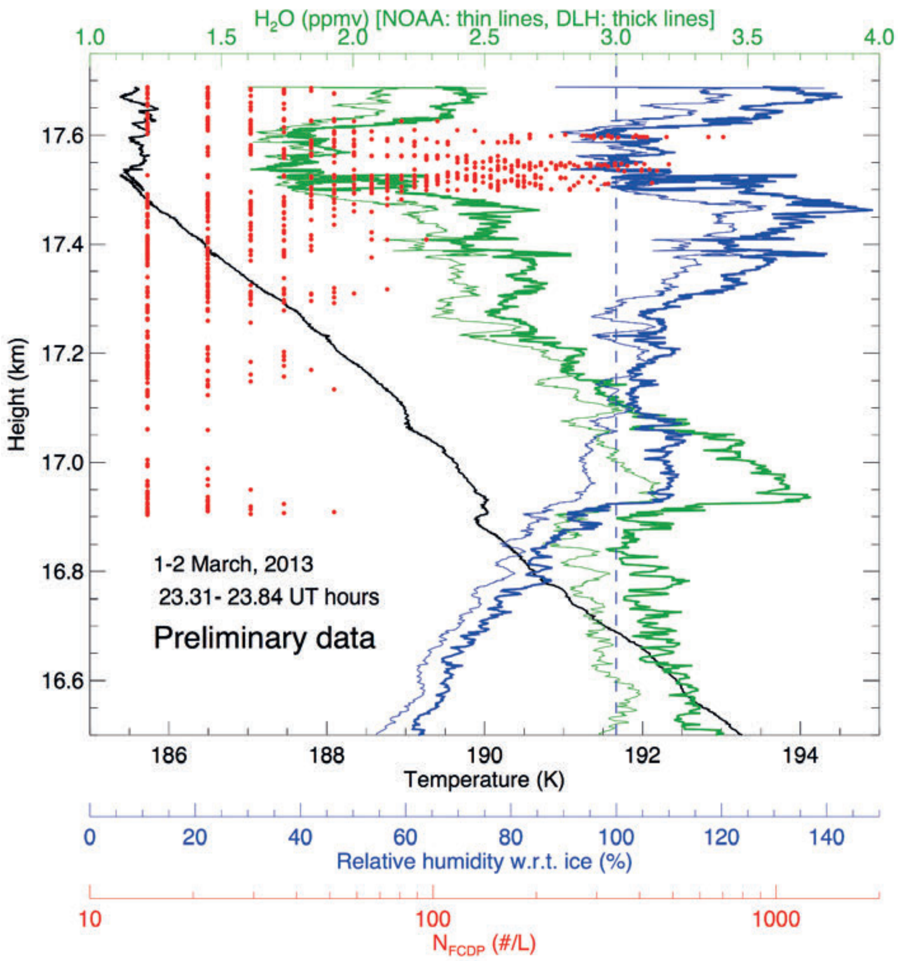


Figure 10: Vertical profile of temperature (black), water vapour (green), relative humidity with respect to ice (blue) and FCDP ice concentration (red dots). The data shown here are preliminary and may well change with further analysis. Within the high ice concentration layer at about 17.5-17.6km, both the DLH and NOAA water instruments indicate relative humidities of about 100%, as expected. Above and below this layer, substantial ice supersaturation is present. The two preliminary water vapour measurements differ by no more than a few tenths of a ppmv.

these fluctuations were not captured by the meteorological analyses. ATTREX provided the opportunity to make multiple samples of the same location. In one case, these samples showed changes of 4-5K in just 3 hours, with changes of nearly 2K in 1 hour. These fluctuations created challenges for flight operations of a temperature sensitive aircraft; previous history of sampling a given region was not always a reliable guide for resampling the same region, even over short time intervals. The small-scale temperature fluctuations are also critical for cloud formation and dehydration processes.

As discussed above, ATTREX tracer measurements will be useful for evaluating pathways and time scales for transport into and through the TTL. **Figure 12** shows a sampling of preliminary GWAS measurements from the 2013 flights. As expected, the vertical gradient of tracer concentration depends on the lifetime of each species. Precise measurements of CO_2 from the HUPCRS instrument and SF6 from the UCATS instrument can also be used for quantifying TTL transport times (*e.g.*, Park *et al.*, 2010).

Outlook

The western Pacific is a critical region to sample for understanding TTL processes. The lowest temperatures and largest radiative heating rates occur in the western Pacific, and this region is where models predict that parcels frequently experience their final dehydration before entering the stratosphere (Schoeberl and Dessler, 2011). The next ATTREX flights will be based from Guam (13.5°N, 144.8°E), with flights in January-February for winter season data collection and then additional flights in early summer (May-June). **Figure 13** shows an example of possible GH flight plans from Guam. The transit from DFRC (orange dotted line in **Figure 13**) will provide an opportunity to fly a long, constant-latitude transect for analysis of tropical waves with scales intermediate between those that can be measured with shorter-range conventional aircraft and those that can be measured with satellite instruments. The western Pacific cold pool is essentially directly overhead at Guam, therefore the full 24-hour GH flight time will be sampling the region of interest for ATTREX (in contrast to the flights from DFRC that required a 6-8 hour transit to reach the tropics). Lagrangian flights along streamlines through the western Pacific cold pool will be used to investigate the full lifecycle of TTL cirrus formation and its impact on the vertical profile of water vapour.

The fact that the ATTREX mission was awarded in 2010 with the intent from the outset to have GH flights from Guam in 2014 has permitted the inception, planning, and approval of two additional aircraft campaigns that will be coordinated with ATTREX. The UK Co-ordinated Airborne Studies of the Tropics (CAST) programme will bring the FAAM BAe-146 aircraft to Guam, with a payload focused on measurements of tracers and halocarbons.

Figure 11: Top: RF05 (26-27 March 2013) flight path extending into cold air in the central-western Pacific. Bottom: ozone and total water concentrations are plotted versus distance along the flight track for the outbound and return section of the flight path shown in magenta in the top panel. As the aircraft approached the cold tropopause region at the far western end of the track, a layer at about 16-17.5km was sampled with relatively low ozone and high ice water content, both of which suggest recent convective injection to near the tropopause.

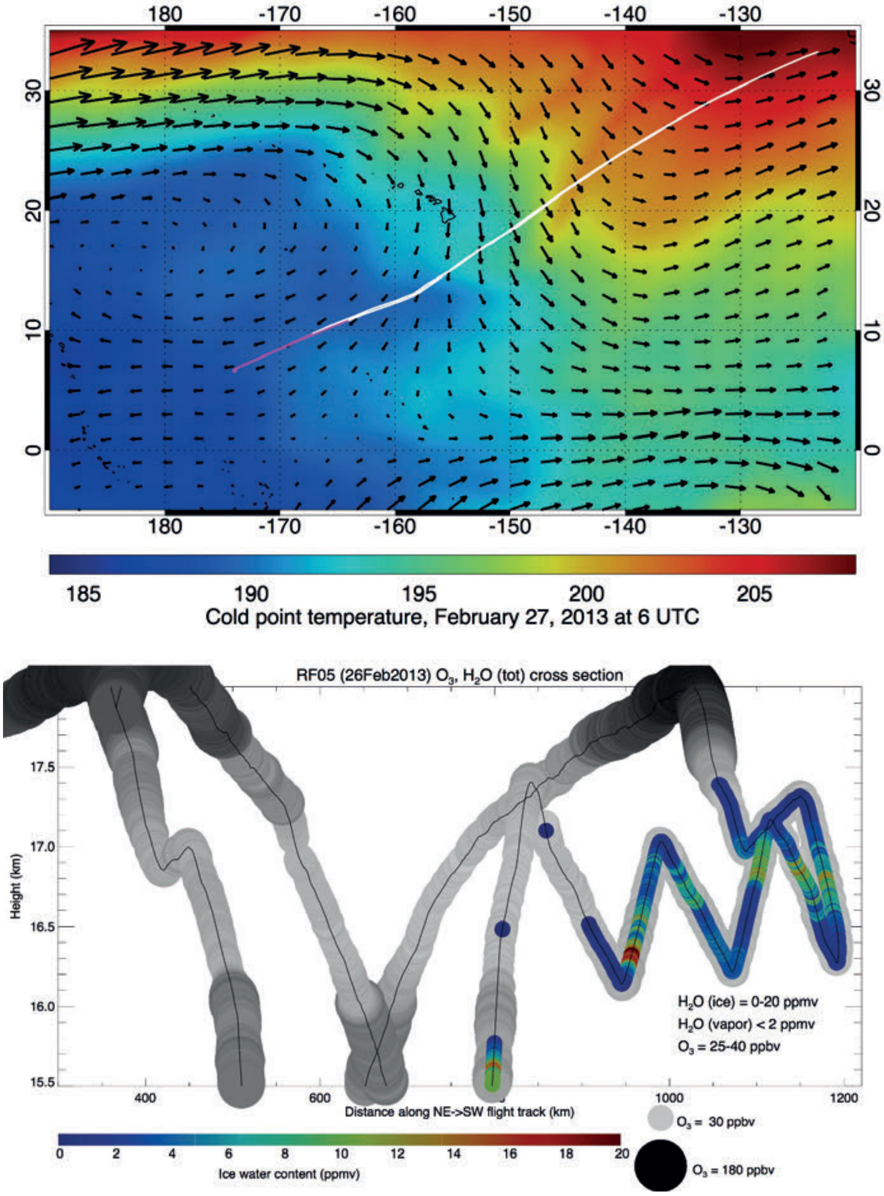
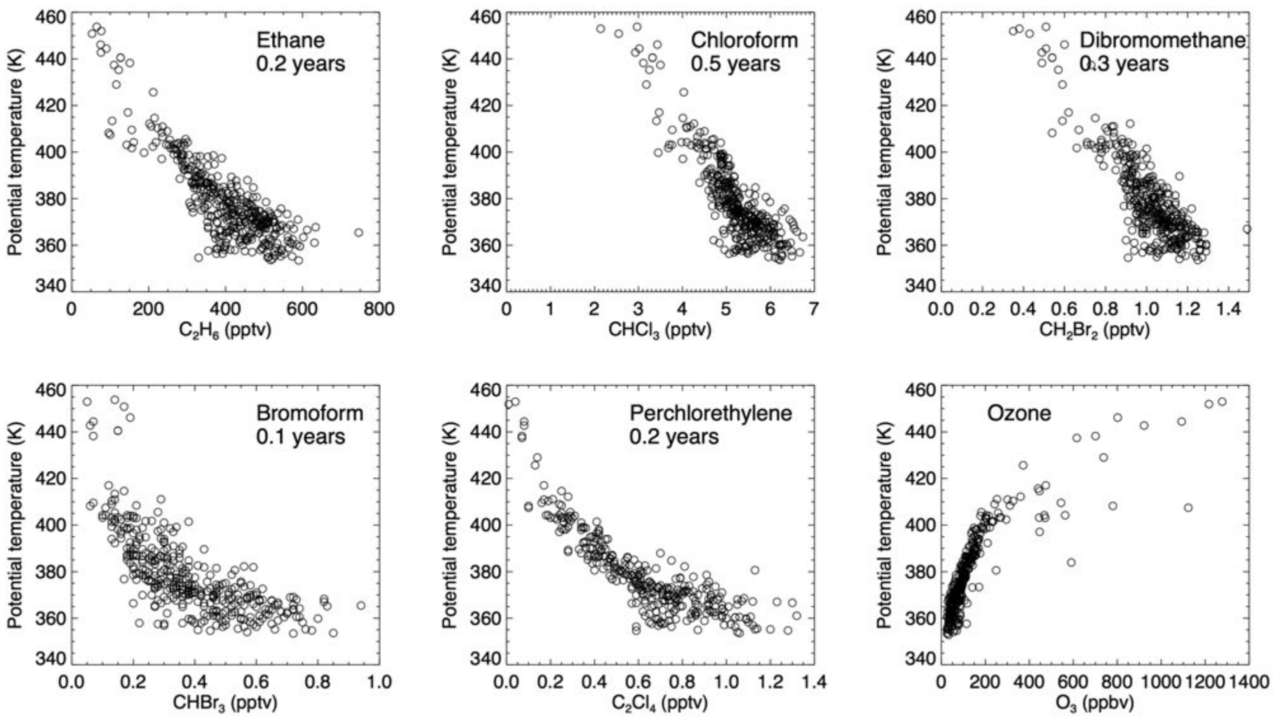


Figure 12 (below): Vertical profiles of a few of the numerous species measured by GWAS (preliminary data). Species shown here have lifetimes ranging from 0.1-0.5 years. The dependence of concentration gradient in the TTL on lifetime is evident.



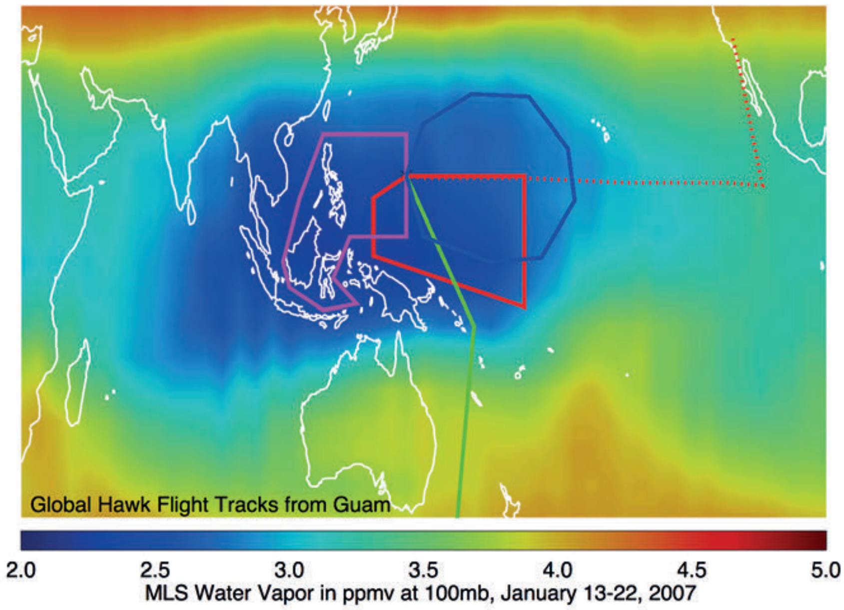


Figure 13: Hypothetical tracks of 2014 ATTREX Global Hawk flights from Guam.

The BAe-146 flights will be primarily used to survey the chemical composition of the boundary layer and lower free troposphere south of Guam down to the ITCZ. The National Science Foundation (NSF) Convective Transport of Active Species in the Tropics (CONTRAST) program will bring the NSF GV aircraft to Guam. The GV payload includes instruments measuring a number of the same tracers measured by CAST and ATTREX instruments. The GV sampling will focus on characterizing the chemical composition and ozone photochemical budget in the primary deep convection detrainment altitude range (about 10km up to the GV ceiling of about 15km). Stacked flights with the three aircraft will provide measurements from the surface to the lower stratosphere.

As with all NASA science missions, the final archived data from ATTREX (due 21 months after each flight series) becomes public immediately. Data from the 2011 ATTREX flight series is publicly available on the Earth Science Project Office archive (espoarchive.nasa.gov). We are hopeful that the ATTREX dataset will be used by many groups for evaluating and improving representations of TTL composition and physical processes in global models.

Acknowledgments

We acknowledge the support of the DFRC GH crew, pilots, mission managers, project managers, and all others who contributed to the project. ATTREX is supported by the NASA Earth Ventures program, with Dr. Ken Jucks as the NASA Headquarters Program Officer. NOAA water and ozone instruments have additional support from the NASA Upper Atmosphere Research Program and the NOAA Climate Program Office.

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Combined SPARC Data Requirements/ SPIN Mid-Term Review Workshop 20-22 February 2013, ESA/ESRIN, Frascati, Italy

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As a scientific user of observational data, SPARC has been going through a process of assessing and summarizing its measurement needs and priorities. Information on the kind and quality of observations needed to support the individual SPARC activities has been collected and summarized in measurement requirement reports. These activity-level reports aim to ensure that future observational data sets meet specific scientific needs. In parallel with this process, SPARC has been engaged in an European Space Agency (ESA)-funded project to develop long-term climate data records of stratospheric temperature, water vapour, ozone, and aerosols, as well as climatologies of short-lived species – the ESA SPARC Initiative (SPIN).

A combined SPARC data requirements/SPIN mid-term review workshop was held at ESA/ESRIN, Frascati, Italy from 20-22 February 2013. During the workshop the activity-level measurement requirements were presented and related topics such as the scientific motivations for present and future measurements, estimated uncertainties, and measurement network design were discussed. In combination with the presentations focused on the data requirements of the SPARC activities, results from various SPIN work packages were shown. This provided a review of phase 1 of the SPIN project on the detailed analysis and maturation of ESA and third party mission satellite data sets by ESA. The outcome of the workshop will help SPARC to synthesize the activity-level measurement requirements developed to date into an integrated document. Such a document will provide coordinated input to international bodies such as GCOS (Global Climate Observing System) and CEOS (Committee on Earth Observation Satellites), help to respond to requests from funding entities, and stimulate greater use and improvement of observational products by SPARC activities.

The meeting was opened by the meeting organisers, **Greg Bodeker**, **Theodore Shepherd**, and **Michael Van Roozendael**, outlining the rationale and goals of the workshop. The first day of the workshop included sessions on ozone, water vapour and aerosols, while the second day was focused on temperature and other trace gases. Each session was followed by a discussion of future measurement needs for the particular species. The workshop ended with a session on other SPARC activities and a final discussion on the priorities of SPARC measurement requirements. All sessions included presentations of the results of the various SPIN activities and presentations on other related activities, both within and outside SPARC.

Ozone

The first part of the ozone session focused on various SPARC and ESA ozone initiatives. The session was opened by **Susann Tegtmeier,** who presented ozone evaluations from 18 limb-viewing satellite instruments within the SPARC Data Initiative. The comprehensive intercomparisons provide an estimate of the uncertainty in the measured field, which is found to be largest in the tropical lower stratosphere and at high latitudes. The initiative on “Past Changes in the Vertical Distribution of Ozone” was introduced by **Johannes Staehlin** who outlined the scientific challenges when determining long-term ozone profile changes based on different observational data sets. In particular, measurements from a network of ground-based instruments were presented and suggested to be a critical independent measure of ozone trends. **Michael Van Roozendael** talked about the Ozone project of the ESA Climate Change Initiative (CCI) programme. The project aims to generate improved series of ozone column and profile data derived from multiple satellite sensors, with a particular emphasis on European and ESA Third Party Mission instruments.

Vitali Fioletov shifted the focus to total ozone variations estimated from satellite and ground-based instruments. He pointed out that long-term drifts in individual data sets are comparable to the expected ozone trends and that even a small observational bias can impact the interpretation of ozone changes (see **Figure 14**). The two following presentations from **Erkki Kyrölä** focused on ozone measurements from the stellar occultation instrument GOMOS. First, the GOMOS bright limb retrieval method (SPIN-Work Package (WP) 17), including a comparison of day- and night-time ozone profiles, was presented. Second, a new merged SAGE II-GOMOS ozone data set covering the years 1984-2011 was introduced. **Jessica Neu** gave the last presentation of the ozone session on satellite measurements of the Upper Troposphere and Lower Stratosphere (UTLS) region including an intercomparison of existing observations and a discussion of availability and analysis of future observations.

Water vapour

Gabriele Stiller opened the water vapour session with an overview of currently available satellite measurements and their intercomparisons carried out within the SPARC Water Vapour Assessment II (WAVAS II). The presentation illustrated the difficulties in developing a consistent, multi-instrument, long-term data set. Water vapour comparisons within the SPARC Data Initiative were presented by **Michaela Hegglin**, including key results on the evaluation of the water vapour tape recorder, polar vortex dehydration, interannual variability, and seasonal cycles (see **Figure 15**). The SCIAMACHY limb scattering water vapour product and its validation by comparisons with occultation data from SCIAMACHY, other satellite data and frost point hygrometer data was introduced by **Alexei Rozanov** (SPIN-WP13). Greg Bodeker pointed out the need for a measurement requirements analysis of stratospheric water vapour during his talk on a water vapour Essential Climate Variable (ECV) review.

Aerosol

During the first part of the aerosol session, current SPARC and ESA aerosol initiatives were introduced. **Michaela Hegglin** showed results from the SPARC Data Initiative aerosol comparisons including a new approach based on scaled aerosol anomalies and a discussion of the value of the different data sets for merging and trend studies. Activities of the ESA Aerosol_CCI project were presented by **Christine Bingen**. The talk included information on a new improved GOMOS aerosol retrieval algorithm and recent progress in data merging activities. In the following presentation given by **Michaela Hegglin** (standing in for Larry Thomason) requirements of *in situ* and remote aerosol data sets from ground-based, aircraft, balloon and satellite platforms were defined based on the

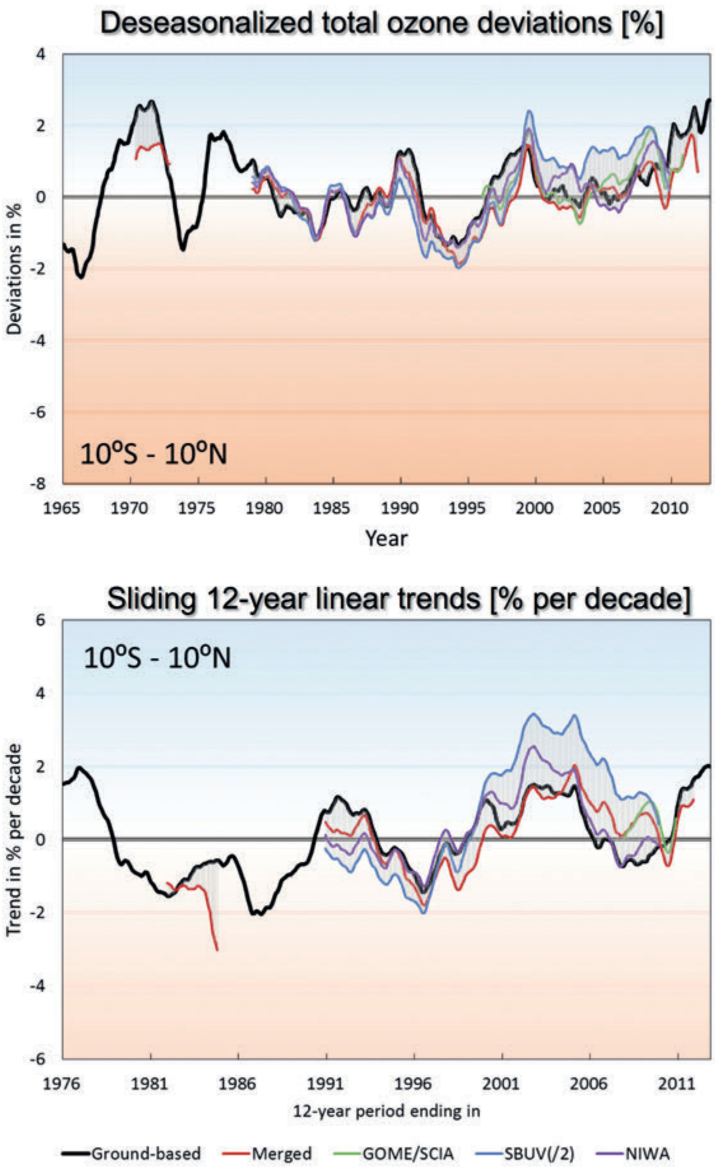

Figure 14: Tropical ozone deviations and trends based on the total ozone zonal mean data sets used in the Ozone Assessment 2010 (Figure 2-2). Shown are deseasonalized, area-weighted total ozone deviations adjusted for solar, volcanic, and QBO effects and smoothed by 12-month running mean (left panel), and corresponding sliding 12-year linear trends [% per decade] (right panel) for 10°S-10°N. Figure courtesy: Vitali Fioletov.

scientific and programmatic goals of the new SPARC activity SSiRC (Stratospheric Sulfur and its Role in Climate).

The aerosol session was continued with two SPIN-WP12 contributions. **Alexei Rozanov** presented the maturation of the SCIAMACHY aerosol product, achieved using an optimized phase function, and it's validation with co-located SAGE II measurements. The development of the new OSIRIS aerosol product (Version 6.00) based on the incorporation of new particle size information was the focus of the talk given by **Landon Rieger**.

Temperature

Bill Randel talked about data requirements of the SPARC temperature trends activity. He pointed out that substantial uncertainties exist when combining different data sets from the NOAA operational satellite instruments, especially for the mid- and upper stratosphere. An overview of temperature measurements in the UTLS by the radio occultation (RO) technique from the CHAMP, GRACE, and TerraSAR-X missions was given by **Torsten Schmidt**.

Presentations on SPIN temperature activities (WP18 and WP14) completed the session. **Ted Shepherd** applied the SSU weighting functions to temperature climatologies from ESA instruments to identify data sets suitable for extending the historical SSU temperature record beyond 2006. **Greg Bodeker** presented a temperature ECV review including a quantitative assessment of measurement requirements based on how uncertainty in monthly mean temperatures is determined by the sampling frequency and random errors.

Other trace gases

Presentations on other trace gases started with a contribution from the SPARC Data Initiative (see online supplementary material for a complete table of species this initative covers). **Susann Tegtmeier** gave an overview of the comparisons of the various nitrogen species and explained the difficulties arising when comparing short-lived gases measured at different local solar times (LSTs). **Jo Urban** reported on trace gas measurements from the Odin satellite and the data records and climatologies derived from those measurements. In a second presentation he talked about short-lived species observed by Odin and the methods applied to correct for their LST dependence (SPIN-WP16). **Nathaniel Livesey** presented an overview of two projects producing long-term records based on observations from multiple satellite instruments. While the Global Ozone Chemistry and Related Datasets (GOZCARDS) project focuses on stratospheric species relevant to ozone decline and recovery, the Mesosphere and Upper Stratosphere Temperature and Related Data (MUSTARD) project aims to produce a unified temperature record.

Other SPARC activities

Measurement requirements for other SPARC activities were discussed in the next session, starting with a presentation from **Ted Shepherd** on the SPARC Chemistry-Climate Modelling Initiative (CCMI). He talked about planned and existing efforts to improve the comparability between models and observations. An extension of the CCM Validation Diagnostic (CCMVal-Diag) tool, an open source pack-

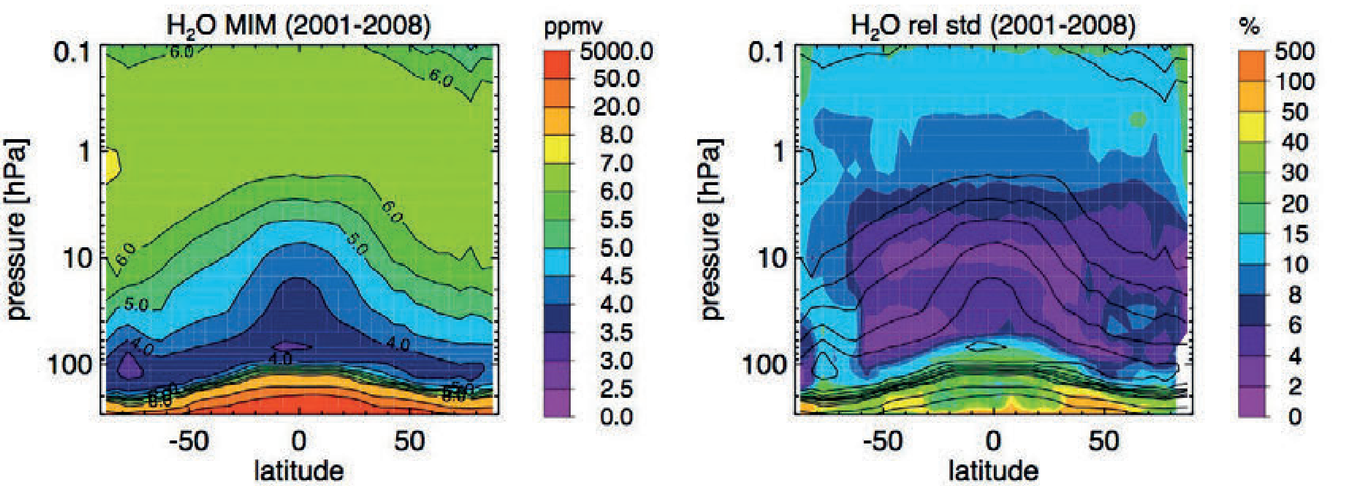

Figure 15: Summary of the water vapor annual zonal mean state for 2001-2008 based on the annual zonal mean cross-sections of the multi-instrument mean (MIM) (left panel), and relative standard deviations with respect to the MIM (right panel). Black contour lines in the right panel repeat the MIM distribution. Instruments included in the MIM are SAGE II, SAGE III, HALOE, POAM III, ACE-FTS, Aura-MLS, MIPAS, SAGE III, SMR, and SCIAMACHY. Figure courtesy: Michaela Hegglin.

age that facilitates the evaluation of global models, was introduced by **Irene Cionni**. Updates of the CCMVal-Diag package are planned to include new analysis of the representation of tropospheric chemical processes, chemistry-aerosol interactions and the impact of climate change. Data requirements of the SPARC Dynamical Variability activity (DynVar) focus on measures of variability at all scales, their connection to tropospheric sources and derived diagnostics of the Brewer-Dobson circulation as explained by **Elisa Manzini**.

A combined presentation on data requirements for stratospheric chemistry Data Assimilation (DA), and the SPARC DA working group, was given by **Quentin Errera**. He pointed out the importance of continuous trace gas profile and wind observations and the visibility limits impeding gravity wave observations. **Bernd Funke** presented open science questions in the SOLARIS+HEPPA (SOLAR Influences for SPARC + High Energy Particle Precipitation in the Atmosphere) activity and resulting data requirements including, amongst others, continuous long-term monitoring of UV radiances and future NO_x measurements in the polar winter. An overview of the Equatorial Atmosphere Radar (EAR) Data Facilities at Kototabang, Indonesia, was given by **Eddy Hermawan**, who pointed out the potential use of the EAR for SPARC activities with a focus on the UTLS. The final presentation by **Peter Preusse** identified data requirements of the SPARC gravity wave activity such as super-pressure balloon campaigns, new radars, and worldwide, high-resolution radiosondes.

Final discussion

It was noted that the "golden age" of measurements will continue to be a key reference period for model and reanalysis validation and that a clear statement of the value of existing data is needed. One important need mentioned in various presentations and discussions is for future follow-on satellite missions targeting global and vertically resolved trace gas and temperature observations. Additionally, opportunity missions of short duration and heritage instrumentation have been suggested as low-cost gap-fillers. During the discussion of satellite trace gas observations, the importance of the accuracy of diurnal scaling factors for short-lived species, the value of UTLS constraints on surface source inversion, the need for high-resolution measurements in the UTLS, and the impact of sampling biases and vertical resolution were identified.

The importance of ground-based and balloon sampling networks and their need for further support was highlighted. During the following discussion the significance of an optimally designed ozone network, the need for balloon measurements of stratospheric aerosol, and the value of the combined balloon-hygrometer data set produced in WAVAS II were identified. Further data needs include, amongst others, estimates of the Brewer Dobson circulation, additional SSU retrievals, gravity wave parameters, stratospheric winds, and NO_x measurements in the mesosphere and lower thermosphere. The general part of the discussion concluded that a systematic characterization of all sources of error for single measurements is needed. Furthermore the need for measurements and models to "meet in the middle" and for an expansion of Obs4MIP efforts were identified.

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WCRP Special Workshop on Climatic Effects of Ozone Depletion in the Southern Hemisphere: Assessing the evidence and identifying gaps in the current knowledge
25 February - 1 March, 2013, Buenos Aires, Argentina

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A WCRP Special Workshop on the 'Climatic Effects of Ozone Depletion in the Southern Hemisphere: Assessing the evidence and identifying gaps in the current knowledge', was convened at the Pontificia Universidad Católica Argentina, Buenos Aires, Argentina, from 25 February to 1 March, 2013.

The workshop aims were to discuss our current understanding of Southern Hemisphere ozone depletion, in particular high latitude ozone depletion, its impacts on hemispheric climate and relative role with respect to greenhouse gas (GHG) induced climate changes. Discussions were initiated from results published in the 2010 UNEP/WMO Scientific Assessment of Ozone Depletion and research published since. The workshop was supported by WCRP, the Agencia Nacional de Promoción Científica y Técnica (Argentina), the National Science Foundation (USA), NASA (USA) and the Pontificia Universidad Católica Argentina.

The main conclusions from the last Ozone Assessment, relevant to the workshop topics, can be summarized as follows:

1. There is new and stronger evidence for radiative and dynamical links between stratospheric change and specific surface climate changes.
2. Changes in stratospheric ozone, water vapour and aerosols all radiatively affect surface temperature.
3. Observations and model simulations show that the Antarctic ozone hole caused much of the observed southward shift of the Southern Hemisphere midlatitude tropospheric jet during summer since 1980.
4. This southward shift has been linked to a range of observed climate trends in the Southern Hemisphere mid- and high latitudes during summer.
5. The influence of stratospheric changes on climate will continue even after ozone is no longer affected by emissions of ozone depleting substances.
6. Future recovery of the Antarctic ozone hole and increases in GHGs are expected to have opposing effects on the Southern Hemisphere mid-latitude jet.

Workshop aims

There was overall consensus in the stratospheric and climate communities that the current state of our understanding of Southern Hemisphere ozone had to be thoroughly evaluated and discussed in order to consolidate our views on the issues at hand. This was necessary to identify future research needs, both in light of the expected ozone layer recovery over the coming decades and ongoing climate changes being driven by sustained increases in GHGs and other environmental processes, such as deforestation, desertification and land-use changes that impact climate. Furthermore, different WCRP core projects also agreed that given the scope of issues, the discussion had to be interdisciplinary, bringing together the SPARC, CLIVAR and CliC communities.

The driving questions of the workshop were:

1. How well do we understand the mechanisms relating Antarctic ozone loss to tropospheric climate in the Southern Hemisphere?

2. How will GHG increases and ozone depletion/recovery interact in future, and what will their impacts be on the polar vortex and on tropospheric climate?
3. What don't we know, and what observing or research programs need to be undertaken?

In order to foster an environment for the much required exchange of ideas and interdisciplinary interaction, the scientific organizing committee (Gareth Marshall, Thando Ndarana, Paul Newman, Manuel Pulido, Marilyn Raphael, Gianluca Redaelli, James Renwick, Robyn Schofield, David Thompson, Anne Thompson, Darryn Waugh, Shigeo Yoden, with Alan O´Neill and Pablo Canziani co-chairs) determined that the workshop dynamics should return to the historical roots of scientific meetings, following the concept of the famed early 20th Century Solvay Conferences. A strong emphasis was thus placed on rigorous discussion after each invited keynote presentation. The oral sessions were organized around specific topics:

I Stratospheric ozone variability and impact on climate
II Processes I: tropospheric climate and weather events
III Processes II: cryosphere, ocean circulation and carbon uptake
IV Modelling and predictions

For each topic, two or three keynote speakers were invited to deliver a review talk, followed by an extended period of discussion and debate. In practice, the exchange of views tended to start within the keynote speaker presentations, leading to excellent results. The session chairs did a wonderful job of conducting the debates, while session rapporteurs took note of all proceedings.
Over 50 participants from Australia, New Zealand, South Africa, USA, France, Germany, Italy, Russia, United Kingdom, Japan and Argentina attended the workshop. The keynote speakers were:

Session I: Sophie Godin, Darryn Waugh, Steve Rintoul (rapporteur: Peter Braesicke)
Session II: Edwin Gerber, Ryan Fogt (rapporteur: Ulrike Langematz)
Session III: Marilyn Raphael, Gareth Marshall, Wenju Cai (rapporteur: Darryn Waugh)
Session IV: Michael Sigmond, Nathan Gillett (rapporteur: James Renwick)

Research presentations were facilitated through poster sessions, held in an adjoining room, where coffee breaks and food were served for extended viewing. Over 30 posters were presented and displayed for the duration of the workshop. PDF versions of the posters presented are available at: **http://www.uca.edu.ar/index.php/site/index/es/uca/investigacion-viejo/pepacg/wcrp-special-workshop/poster/**

Furthermore, a special session, chaired by early career scientists and PhD students, was held before the concluding session. During this session they presented and discussed early career perspectives on the topics discussed, as well as the future of the field. These perspectives are also reported below.

During the final session the rapporteurs presented summaries of each session. The final conclusions of the workshop were also actively discussed during this final plenary session, providing further interesting insights by allowing all different aspects to be viewed together.

Main Workshop Conclusions

Session I: Stratospheric ozone variability and impact on climate

State of Knowledge

Ozone observations and modelling:
- Severe ozone depletion has occurred in the Antarctic spring stratosphere caused by anthropogenic ozone depleting substances (ODSs) – the Antarctic ozone hole.
- The Montreal Protocol has been successful in reducing the amount of ODSs in the atmosphere, but the return to pre-1980 levels will take decades. The Antarctic ozone hole should return to 1980 levels in the 2050-2070 period.
- By 2100, models predict an ozone "super-recovery" in the SH mid-latitudes as a result of an increase in the strength of the Brewer-Dobson Circulation, and a decrease in ozone loss rates in the upper stratosphere due to stratospheric cooling. Both of these effects are driven by increasing levels of GHGs.

SH climate
- There have been large changes in the SH summer climate over the last thirty years, from the surface all the way through to the stratosphere, and from polar regions to the subtropics.
- Many of the recent SH climate changes have been attributed to the ozone hole causing an increasingly positive trend in the Southern Annular Mode (SAM), or a poleward shift in the jet during austral summer and autumn.
- Other important changes in climate, which appear to be ozone driven, have been noted, in particular (1) a winter reversal of the jet in the stratosphere has been delayed from late spring to summer, (2) through impacts on the SAM, the jet changes have affected Antarctic surface temperatures, with a warming

over the Antarctic Peninsula and a cooling in East Antarctica, especially in austral summer, (3) in conjunction with GHG increases, the jet changes have likely induced changes to the pattern of regional mid-latitude drying and mid- to high-latitude moistening observed in the Southern Hemisphere, and (4) changes in the Hadley and Ferrel cells´ circulation patterns have been observed.

- Models (ranging from idealized atmospheric models to climate models with interactive chemistry) indicate that the ozone hole is the primary cause of the observed changes, which lie outside the range of natural variability of the SH extra-tropical summer climate.
- The cause of the recent positive trend in the SAM during austral autumn is not currently understood and may simply be the result of natural climate variability.
- Ozone loss and GHG increases have both driven the recent positive trend in the SAM during austral summer. Ozone recovery over the next decades will impose a negative forcing on the SAM, thus dampening the positive influence of a continuing rise in GHG concentrations. Therefore, while increasing GHGs are expected to cause an overall warming of the Southern Hemisphere, SAM-related past trends in summer climate will likely weaken, and maybe even reverse, contingent on the extent of changes in GHG forcing.

Impacts on the SH Ocean

- The wind stress curl is changing, with the zero line shifting poleward, which induces an intensification of the super gyre.
- Observations support this intensification (ocean temperature trends are consistent from 1960-2007). The position of the tropospheric jet is a significant driver of oceanic changes in response to the ozone losses of the past decades, through the ocean's thermal response to the position of the atmospheric jet, and the ocean's dynamical response to changes in tropospheric temperature.
- How these two ocean response processes are represented within models explains, to a large extent, the spread among current climate models.
- There are different potential mechanisms driving these processes, but these are not yet understood. A key necessity for reducing uncertainty is to improve our understanding of the tropospheric variability within models for a given stratospheric ozone perturbation.

Future Research Questions

- Can we prioritize observations? At what sampling rates do we need the different observations: sub-daily, daily, weekly, monthly? Do we need more ocean measurements?
- Are there coherent changes in all quantities in the Earth system?
- Is ozone behaving like we think it is supposed to? What is the effective equivalent stratospheric chlorine doing? Are chlorine and bromine declining as we think they should do?
- What will the relative roles of ozone and GHGs be in future?
- Linearity of the response to GHG and ODS changes: how linear/non-linear and uncorrelated/synergistic is the atmospheric response to their changes?
- How do we define the Hadley Cell?
- Can we trust reanalysis products? How should we tackle variability and trend studies with reanalysis?

Session II: Processes I: tropospheric climate and weather events

State of Knowledge

- West Antarctic temperatures have risen, and these temperatures are sensitive to the strength and position of the Amundsen-Bellingshausen Seas Low (ABSL). A minority of climate models suggest that ozone depletion has contributed to the deepening of the ABSL.
- Although the SAM is a hemispheric-scale mode of variability, its impact varies significantly at the regional level.
- Predominant spatial patterns in the relationship between the SAM and elements of the SH surface climate exist, but can reverse sign on decadal time scales. Such sign changes appear to be due to internal climate variability, which in particular could be related to the phase and amplitude of planetary wave-3 over the Southern Ocean.
- This has implications for identifying a robust methodology using the Antarctic ice core record to generate a proxy of the SAM, and on the level of certainty with which we can ascribe future projections of Antarctic climate and related predictions of sea level rise.
- In future, there are likely to be opposite SAM trends in austral summer (negative) compared to other seasons (positive). This may lead to increased summer melting for regions with a predominant negative SAM temperature relationship (East Antarctica), while over the Antarctic Peninsula there is likely to be

greater winter accumulation.

Future Research Questions

- What is the natural variability of SAM? What are the causes of the SAM trends in austral autumn?
- What causes the variability/deepening trend of the ABSL? Is there a possible contribution of asymmetric modes of variability?
- How do zonal mean ozone asymmetries affect climate?
- There is a need for further studies investigating the regional variability and trends to better assess the climate response to ozone forcing.

Session III: Processes II: cryosphere, ocean circulation, and carbon uptake

State of Knowledge

- On average, observed sea-ice extent around Antarctica has been increasing. This increase has not been uniform - there are large regions of significant increase and significant decrease. The causes of the changes in sea ice extent are not fully understood, however, they appear to be mediated by changes in surface wind speed and direction, as well as ocean currents. The changes in winds may be associated with the strength of the ABSL, as well as the strength and polarity of the SAM.
- Although observations of sea-ice indicate that Antarctic sea ice extent has been increasing, all available model studies of 20th century climate simulate a decrease. This includes models that explicitly simulate stratospheric ozone depletion, which also indicate that stratospheric ozone depletion should have driven a hemispheric total sea ice extent decrease.
- Observed changes in the Southern Ocean have been linked to changes in near surface winds. These changes include the subtropical super gyre, the meridional overturning circulation, and the ocean becoming a less effective sink of CO_2.
- Links to SAM: the mixed layer depth response to the SAM shows zonal asymmetry.

Future Research Questions

- What is the cause of the discrepancy in sea-ice trends between observations and models over the 20th century? Are differences due to model deficiencies or unknown processes affecting sea ice variability?
- What is the intrinsic model variability of ice and ice core properties? What are the implications when this variability is simulated?
- How will the ocean circulation and carbon uptake evolve as ozone recovers?
- Where is the heat derived to support ocean heat content changes associated with ocean circulation changes induced by wind stress?
- How will the ocean circulation and wind changes affect carbon uptake?

Session IV: Modelling and predictions

State of Knowledge

- Models show that the relative role of ozone and GHGs in forcing past climate trends, particularly of the SAM, varies seasonally, while being comparable in the annual mean.
- A bias remains in the simulation of the mid-latitude jet position when compared to reanalysis data. The bias in jet latitude appears to be positively correlated with the size of the simulated jet shift in response to ozone and GHG depletion. The future evolution of jet trends remains unclear, and depends on the relative role of ozone *vs* GHG forcing.
- A well-resolved stratosphere and a high upper boundary are required to simulate a proper tropospheric response. The response to prescribed ozone depletion is significantly larger in models with high vertical resolution in the lower stratosphere compared to models with low-top and low vertical resolution in the stratosphere. This may be related to a lack of momentum conservation at the top of the model, leading to an unrealistic dynamical response in the stratosphere. Many CMIP5 models probably have high enough stratospheric resolution to resolve this response.
- Zonal mean ozone is usually prescribed in models, but ozone exhibits zonal asymmetry in spring when the ozone hole is often centred off the pole. The use of zonal mean ozone distributions underestimates the climatic response, leading to a weaker and warmer vortex in austral spring, an overall reduction in the stratospheric response, and an underestimation of the SAM changes. At present, most CMIP5 models likely underestimate the tropospheric impacts of ozone changes.
- The stratospheric temperature response varies by a factor of two or more over the pole for a given ozone forcing, adding to the spread of model responses in the troposphere.
- Climate models consistently fail to reproduce Antarctic

sea-ice trends. This is probably caused by the insufficient representation of processes related to sea-ice formation and ocean-atmosphere interactions. Furthermore, the contribution of Antarctic ozone depletion to the recent Antarctic sea ice trends is unclear, even if several recent model studies regarding ocean-atmosphere coupling seem to indicate that this may not be the case.

Future Research Questions

- How important is the representation of natural variability in models? How do we improve tropospheric variability in models?
- What are the mechanisms for stratosphere-troposphere coupling? Which mechanisms need to be included in models?
- What is the cause of the bias in mid-latitude jet latitude?
- How important is simulated natural variability and what is its contribution compared to ozone and GHG forcing? Do we need to better differentiate long-term trends from seasonal to interannual variability when analysing model outputs?
- How well do the models represent the change in the Hadley Cell? Why, while reanalyses suggest the trend in the Hadley Cell extension is larger in austral summer than in austral autumn, do models fail to reproduce this seasonality?
- Do current GCMs underestimate the tropospheric response to ozone due to a lack of vertical resolution or momentum conservation? Do they overestimate the tropospheric response to ozone due to the jet bias?
- How important a shortcoming is the use of zonal mean ozone for the interpretation of CMIP5 results? What is the best design for future GCM experiments without coupled chemistry to account for the effects of the zonal asymmetry of ozone?
- What are the heat sources causing the surface warming pattern and do models capture them?
- Models disagree with sea-ice observations. Why has total Antarctic sea-ice extent increased and why don't current models capture this? What should we do to solve this major issue? For example, does freshwater input play a major role? How important is stratospheric resolution and ocean-atmosphere coupling for sea-ice modelling?
- How important is stratospheric resolution for sea-ice modelling?
- The coupling between the important Earth systems (atmosphere, ocean, land and cryosphere) remains a major modelling challenge.

Early Career Scientists and PhD Students Special Session

The young scientists attending the workshop met to discuss what, in their view, were the most relevant topics driving research development. Their foremost concern was how they, as early career scientists, could progress their careers while continuing interesting and relevant science. Major concerns in this area were model and instrument development, and the lack of high-impact publications that come with this area of research. The broad issues raised by the early career scientists were as follows:

Observations

They recognized the need for a robust global observational network, which has research-relevant measurements (not only ozone, but also precipitation and other variables). Particular care should be taken regarding the timescales on which these observations are made, for instance, surface wind observations over the ocean do not capture many high frequency variations - ideally these observations need to be made on sub-daily timescales. They also noted that more reanalysis data sets could be output at higher frequency, and more intercomparison of such reanalyses could be implemented so that issues such as trends in reanalyses can be better constrained.

There was a general consensus that a reduction in the observational uncertainty associated with ozone measurements is needed, and that this would lead to a better and more consistent implementation of ozone fields in model comparison projects. Specifically, the use of a zonally symmetric stratospheric ozone data set may not be sufficient for the detection and attribution of surface climate change and variability.

Physical Understanding

It was recognized that there was a need to revisit the fundamental dynamics of some models (*i.e.* the dynamical cores) instead of continuously adding and expanding on current models. This may allow for less 'tuning', and a better understanding of currently parameterized processes.

As a community, the early career scientists felt that to further research on ozone-related topics, a zonally asymmetric view must be adopted, both in terms of the evolution of stratospheric ozone and the corresponding surface response. This may involve employing new (or less frequently used) diagnostics other than the SAM. They also noted that the use of the SAM can be misleading, both in terms of its trend and variability. The need to focus on the seasonal response is of particular importance, especially over the March-May period.

Finally, the issue of coupling in models was raised. They noted that testing coupling mechanisms at all scales, from the large-scale, such as between the stratosphere and troposphere, down to the small-scale, is important. They concluded by noting that the co-variability between different climate systems is key to understanding the tropospheric circulation response to stratospheric ozone changes.

On Communication and Interdisciplinary Research

The importance of framing relevant scientific issues was raised, not just to policy makers, but also to us as an atmospheric community. This will help focus research, as well as improve chances of obtaining funding.

Of particular importance was the necessity of networking, in terms of developing cross-disciplinary research (*i.e.* oceanographers talking with atmospheric scientists, or modellers talking with observational scientists). This will also help make the community aware of older or less well-known studies, and prevent unnecessary duplication of such studies. They also mentioned it may also help to have a central location with relevant links to different observational or reanalysis data sets.

Concluding Remarks

This workshop provided a space for solid scientific discussion and exchange of ideas. It permitted a thorough analysis of our current understanding of the coupling between ozone depletion and SH surface climate. The discussions resulted in a large number of issues that need to be addressed, both from the analysis of observations and from modelling, preferably in a joint approach. The issues at hand require strong interdisciplinary interaction to provide appropriate answers.

One issue that came up frequently refers to reanalyses - their quality and applicability to climate studies. The community is concerned about their use, given the differences observed between the various versions, which can lead to widely different results depending on the aim of the study. This is a particularly crucial issue that needs to be discussed beyond the sphere of issue-oriented workshops.

Regarding models, there was an overall view that much work needs to be carried out to improve models, including the coupling between sub-models that represent the various Earth sub-systems involved. This is crucial to improving the relationship between model outputs and observations so that we can better understand the coupling and physics involved, for example, in understanding the effect of ozone-related atmospheric processes on ocean circulation and, in particular, carbon uptake.

Given the climate system's intrinsic variability, the workshop emphasized that using models to establish causal links between stratospheric ozone changes and tropospheric climate changes (*e.g.* trends) must be based on the use of ensemble simulations. Though such an approach is now standard practice, there is further scope for work with larger numbers of ensemble members, as well as multi-model ensembles, to ensure that results are indeed robust.

The workshop structure, by returning to the roots of scientific debate and discussion following the concept of the original Solvay Conferences, provided an optimal environment for the exchange of views and debate about future research directions. Furthermore, the active participation of early career scientists and PhD students - thanks to the support received from the WCRP, NSF and NASA - provided new perspectives, views, and concerns to this debate. In addition, the poster session provided both an opportunity for the presentation of current research and an informal atmosphere for sustained exchanges during coffee, lunch breaks, and even at the end of the day - exchanges that made an essential contribution to the aims, spirit and outcomes of the workshop.

Report on the WCRP Regional Workshop on Stratosphere-Troposphere Processes And their Role in Climate 1-3 April 2013, Kyoto, Japan

Shigeo Yoden[1], Masato Shiotani[2], Negar Banan[3], Subrata Kumar Das[4], Young-Ha Kim[5], and Vinay Kumar[6]

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A three-day World Climate Research Programme (WCRP) regional workshop on stratosphere-troposphere processes and their role in climate was held from 1-3 April 2013 at the Maskawa Hall of Kyoto University, Japan. There were 80 participants, including 24 from abroad (**Figure 16**). The "regional" workshop successfully promoted the participation of early career scientists and PhD students from Asian countries, including China, India, Indonesia, Iran, Japan, Korea, Malaysia, Pakistan, and Taiwan. Travel support grants from the WCRP were awarded to four participants who contributed to this report as co-authors. The program and other relevant information can be found on the workshop homepage: **http://www-mete.kugi.kyoto-u.ac.jp/Kyoto2013/.**

This WCRP/SPARC sponsored regional workshop addressed the following topics:

1. Global observations and modelling of the stratosphere and troposphere
2. Tropical and extra-tropical upper troposphere/lower stratosphere processes
3. Trends and variability in the stratosphere and troposphere
4. Special session: Climate research in service to society.

The main purpose of the workshop was to enrich the exchange of information between communities involved in scientific research of stratosphere-troposphere interactions and related processes using observations, data analysis, modelling and numerical studies, and theoretical studies. The workshop program consisted of three sessions of invited talks and two poster sessions on the first two days, and then a special fourth session open to wider research communities and the public on the third day. The invited talks and poster sessions focused on the principal scientific findings and uncertainties in the current knowledge of the indicated subjects.

Global observations and modelling of the stratosphere and troposphere

The workshop was opened by **Masato Shiotani**, who provided an overview of the WCRP and SPARC, including their current activities, and presented the main aims of the workshop. The first session was composed of five oral presentations that highlighted research covering stratospheric and tropospheric chemical and dynamical processes on a global scale. **John Gille** used high-resolution data from the HIRDLS (High Resolution Dynamics Limb Sounder) instrument to

Figure 16: Group photo of the participants at the WCRP Regional Workshop held in Kyoto.

examine how the Brewer-Dobson Circulation (BDC) affects the meridional distribution of ozone in the stratosphere, and controls its seasonal variation through interactions between the BDC overturning motion and isentropic mixing in the lower and lowermost stratosphere (330-450K). Seasonal variation of the transport and mixing processes was discussed, and a comparison between HIRDLS and OMI (Ozone Monitoring Instrument) ozone observations was also shown. **Shigeyuki Ishidoya** reported on the gravitational separation of minor atmospheric constituents in the stratosphere using high-precision measurements of the isotopic ratios of N_2, O_2, and Ar ($\delta^{15}N$ of N_2, $\delta^{18}O$ of O_2, and $\delta^{40}Ar$) and the concentration of Ar ($\delta(Ar/N_2)$) from air samples collected over Japan on 4 June 2007. He suggested the possibility of using gravitational separation as a new indicator of changes in stratospheric circulation. **Takatoshi Sakazaki** focused on the diurnal variation of ozone in the stratosphere as observed by the SMILES (Superconducting Submillimeter-Wave Limb-Emission Sounder) instrument, attached to the Japanese Experiment Module (JEM) onboard the International Space Station. He explored the role of dynamics and photochemistry in the global structure and the seasonal variability of the diurnal variations of dynamical fields (*i.e.*, tides) and ozone fields by analysing datasets from satellite observations, global reanalyses and chemical transport models.

Kazuyuki Miyazaki assimilated multi-satellite data into the global chemical transport model CHASER (CHemical AGCM (Atmospheric Global Circulation Model) for Studies of atmospheric Environment and Radiative forcing) for chemical composition in the troposphere and stratosphere based on an ensemble Kalman-Filter technique. He also discussed future possible efforts to improve the estimation by introducing additional constraints from other chemically-related species. **Kengo Sudo** discussed the role of climate change and stratospheric ozone in tropospheric chemistry involving O_3 and CH_4, based on his simulations with the CHASER coupled chemistry-climate model from 1970-2009 with the EDGAR-HYDE emission data. He performed several sets of sensitivity simulations to isolate impacts of emission change, climate change, and stratospheric ozone depletion on tropospheric ozone evolution over the 40-year period. He found that long-term climate change (warming) and short-term variability (*e.g.*, ENSO, the Arctic Oscillation, and the Pacific North American pattern) play an important role in the trend and variability of tropospheric ozone. His simulations also showed that both the warming trend and stratospheric ozone depletion reduce the increasing CH_4 trend.

Tropical and extra-tropical upper troposphere/lower stratosphere processes

Upper Troposphere/Lower Stratosphere (UTLS) processes in the tropics and extra-tropics modulate climate forcing and impact not only the stratosphere but also the troposphere. **William Randel** presented the annual cycle of lower stratospheric ozone and other tracers in the tropics, and quantified the mechanisms controlling its variability. Lower stratospheric ozone varies by up to a factor of two near 17.5km, with the variability being in phase (out of phase) with temperature (carbon monoxide). He estimated ozone tendencies in the frame of the transformed-Eulerian mean (TEM) equation using observational data, and showed that transport by tropical upwelling is the predominant cause of the observed cycle. In addition, WACCM (Whole Atmosphere Community Climate Model) simulations were used to quantify the contribution of eddy forcing. These simulations also showed that in-mixing processes resulting from the Asian summer monsoon circulation is also an important factor in the upper tropospheric annual cycle, as suggested by previous modelling studies. **Masatomo Fujiwara** presented results from SOWER (Soundings of Ozone and Water in the Equatorial Region) campaigns, in which balloon-borne observations were made at various sites in the tropical Pacific. Most recently, they matched observed air parcels between the observation sites using isentropic trajectories calculated with reanalysis data to measure the difference in water vapour concentrations between the matched sites. This provided direct evidence of dehydration in the tropical tropopause layer (TTL) resulting from horizontal advection. In addition, a summary of the development and validation of various balloon-borne instruments focused on TTL processes was presented.

Andrew Gettelman reviewed tropical and extra-tropical UTLS processes, including their impacts on climate and climate trends seen in the UTLS region (**Figure 17**). For example, water vapour changes in the TTL affect radiative forcing in the UTLS and therefore the tropopause temperature and height. Also, cooling resulting from ozone depletion in the stratosphere accelerates the stratospheric jets by satisfying the thermal wind relationship. This jet acceleration then alters planetary wave propagation and momentum deposition in the lower stratosphere, which ultimately strengthens the BDC. Results from large-scale modelling studies indicate that the UTLS changes in temperature and stability caused by ozone and other greenhouse gases even affect tropospheric circulation by shifting the subtropical jets poleward. **Shigenori Otsuka** presented results from numerical simulations of the formation of the tropopause inversion layer (TIL) associated with an extra-tropical "bomb" cyclone. In the life-cycle simulation, a negative correlation between the strength of the TIL and relative vorticity at the tropopause is clear during the developing and mature stages of the cyclone. The three-dimensional structure of the TIL shows an arc-shaped wave packet of inertia-gravity waves propagating up- and northward from the jet streak associated with the cyclone, implying that gravity waves may play an important role in producing the negative correlation.

Trends and variability in the stratosphere and troposphere

Trends and variability of temperature, water vapour, and ozone in the stratosphere and troposphere are important components of global change. This session was started by a talk by **Karen Rosenlof**, detailing what observations can be used to infer variations in the strength of the BDC, and its subsequent impact on stratospheric water vapour and ozone distributions. The distribution of water vapour is impacted by changes in meridional circulation, and can in turn alter the radiative budget and surface climate. A cost-effective trace gas measurement program using AirCore to monitor changes in strength of the BDC was introduced, as well as the Airborne Tropical Tropopause Experiment (ATTREX, see the article in this issue) using the Global Hawk, which is focused on water, aerosol and clouds in the TTL. **Satoshi Sugawara** reported on their high-precision analysis of various gas concentrations, such as CO_2, CH_4, N_2O, SF6, and their isotopes, in stratospheric air samples collected systematically over Japan since 1985. The estimated increasing trend in CO_2 is 1.55±0.03ppmv/year in the mid-stratosphere. He also discussed that stratospheric age-of-air can be estimated from the phase shift of interannual CO_2 variations. This talk also provided a discussion on a possible change of the vertical gradient of CO_2 in the mid-stratosphere. **Seok-Woo Son** reported that the Antarctic ozone hole has affected not only the long-term trend, but also the intra-seasonal variability of Southern Hemisphere (SH) surface climate. He showed a negative correlation between the September ozone concentration and October Southern Annular Mode index, and with systematic variations in precipitation and surface temperature throughout the SH. This talk provided an overview of ozone recovery that started around the year 2000.

Kaoru Sato presented the three-dimensional structure of the middle atmosphere circulation based on data from a high-resolution middle atmosphere GCM without gravity wave parameterizations. A new formulation of the unified three-dimensional wave activity flux of inertia-gravity waves and Rossby waves was also introduced to diagnose the three dimensional structure. The role of sudden stratospheric warming (SSW) events in dynamical coupling between the stratosphere and troposphere was also discussed in this session. **Hitoshi Mukougawa** examined the predictability of stratosphere-troposphere dynamical coupling using the Japan Meteorological Agency (JMA) operational one-month ensemble forecast data set and a series of hindcast experiments from the JMA/MRI (Meteorological Research Institute) AGCM. He showed prolonged predictability of an SSW event and its relation to the persistence of a blocking event over the Atlantic. He also described downward propagation of stratospheric planetary waves and blocking formation over the North Pacific during several SSW events. **Masakazu Taguchi** investigated the ENSO-induced changes in the

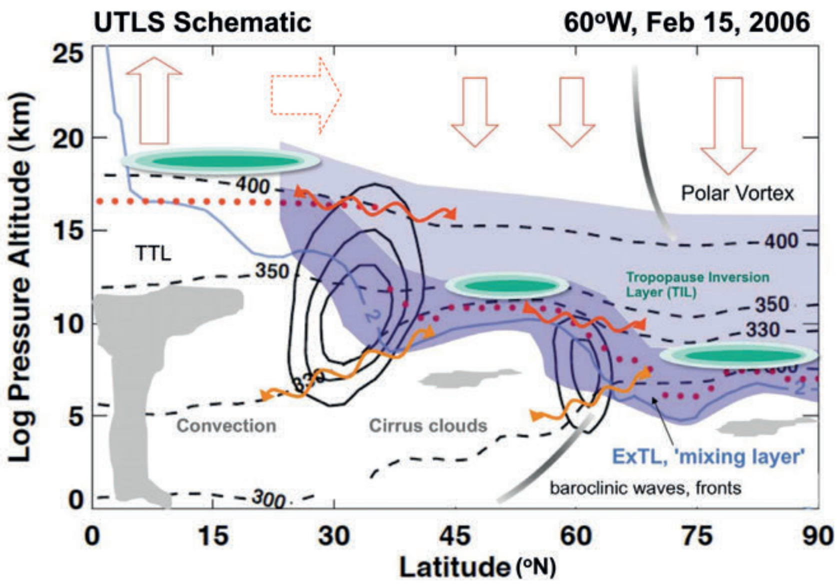

Figure 17: Schematic snapshot of dominant processes in the upper troposphere and lower stratosphere region using data from a Northern Hemisphere section along 60°W on February 15, 2006 (Gettelman *et al.*, 2011).

Northern winter stratosphere using the JRA-25/JCDAS reanalysis and JMA hindcast datasets. He showed that the frequent occurrence of disturbed vortex conditions during cold ENSO years was mainly the result of a couple of SSWs (*e.g.*, those in the 1984/85 and 2005/06 winters). These SSWs occurred with moderate upward and marked poleward propagation of wave activity under easterly QBO conditions.

Special session: Climate research in service to society

The special session, open to the wider research communities and the public, was intended to provide a unique opportunity to discuss the roles of climate research in service to society.

Guy Brasseur, director of the German Climate Service Centre, could not attend the workshop but sent his video message and recorded slide show. He opened the presentation by stating that we are entering a new period of geological history dominated by human impacts on the Earth system, called the Anthropocene. He highlighted four grand challenges that have been posed to the scientific community in the last century: (1) numerical weather prediction, (2) understanding the role of chemical species, (3) projecting climate change, (4) understanding the Earth as a complex non-linear interactive system, and a new grand challenge (5) responding to global change, *i.e.* planetary stewardship. He concluded that planetary stewardship requires new interdisciplinary approaches, two-way communication between scientists and stakeholders, and that science will play a fundamental role in addressing these issues. Also, that traditional climate and environmental research must be complemented by a well-designed approach to adaptation to planetary changes.

Tetsuzo Yasunari, new director of the Kyoto-based Research Institute for Humanity and Nature, talked mainly about the "Future Earth" Program (**Figure 18**). Future Earth is a new 10-year international research initiative aimed at developing the knowledge needed to effectively respond to the risks and opportunities of global environmental change, and to support transformation towards global sustainability over the coming decades. Future Earth will mobilise thousands of scientists while strengthening partnerships with policy-makers and other stakeholders, so as to provide options and solutions for sustainability in the wake of Rio+20. Future Earth aims to integrate four international global environmental change programmes (GECs), including WCRP, to facilitate collaboration and transdisciplinary research through co-designing and co-producing scientific programs with stakeholders to promote protection of global and regional environments, and to help construct a sustainable society.

After a break, **Matthew Hitchman**, **Hiroshi Kanzawa**, and **Karen Rosenlof** commented on the two keynote lectures from the viewpoint of a university professor in the US, Japan, and as a researcher of a governmental research institute, respectively. **Tetsuzo Yasunari** joined these panellists for discussion on multi-disciplinary aspects of climate research and its near-future directions. A USTREAM webcast of the whole special session is available at **http://www.ustream.tv/channel/wcrp-sparcwskyoto2013.**

Poster sessions

Takuki Sano and **Koji Imai** reported on the product improvements and validation, respectively, of the newest version of JEM/SMILES products. These products provide global measurements of trace gases in the middle atmosphere from October 2009 to April 2010. **Makoto Suzuki** presented JEM/SMILES observations of O_3, ClO, HO_2, HOCl and BrO, and their photochemical diurnal variations. CloudSat-CALIPSO data were used to investigate cloud properties over five different summer monsoon regions (**Subrata Kumar Das**), and for the study of the simultaneous occurrence of polar stratospheric clouds and upper tropospheric clouds caused by blocking anticyclones in the SH (**Masashi Kohma**). **Gwenael Berthet** introduced a new LOAC (light optical aerosol counter), capable of characterising particles for tropospheric and stratospheric aerosol measurements, and **Fabrice Jegou** reported on Arctic stratospheric aerosol observations made using the LOAC and other instruments during the 2009 summer in the framework of the International Polar Year. Several presentations related to obser-

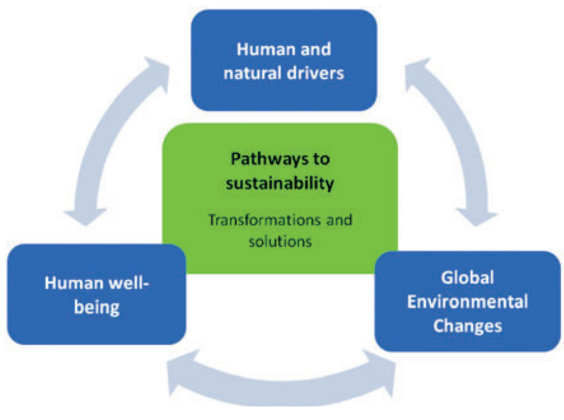

Figure 18: Schematic of the conceptual framework for Future Earth. Available at **http://www.icsu.org/future-earth/whats-new/relevant_publications/future-earth-research-framework**

vational studies on ozone and other trace gases in Asia were also made: multi-year ozonesonde observations in Hanoi (**Shin-Ya Ogino**); Car-MAX-DOAS observations along a national highway in Pakistan (**Fahim Khokhar**); and diurnal and seasonal variations of surface ozone over nine years in three cities in Malaysia (**Negar Banan**).

Several numerical modelling studies focused on chemical processes: a meso-scale air quality study of climate change scenarios in Taiwan (**Jiun-Horng Tsai**); a global chemistry-transport model simulation of greenhouse gases and ozone depleting substances from 1980-present (**Prabir Patra**); an idealized model study of the role of well-mixed greenhouse gases in stratospheric cooling (**Shinji Goto**); and comprehensive chemistry-climate model simulations of the SH stationary wave response and seasonal dependence of future stratospheric temperature trends on ozone and greenhouse gas changes (**Lei Wang**). Using reanalysis data sets, **Tetsu Nakamura** analysed the long-term Boreal summer trend during the ozone-depletion period, and **Masatomo Fujiwara** studied the global temperature responses to the El Chichón and Pinatubo volcanic eruptions.

A small number of poster presentations focused on the dynamics of mesospheric circulation during potential vorticity increasing events (**Akihiro Masuda**) and SSW events (**Toshihiko Hirooka**). Several posters presented new research related to stratosphere-troposphere interactions: winter predictability in JMA one-month ensemble predictions (**Shunsuke Noguchi**); intensification of planetary wave activity in the troposphere prior to SSW events (**Patrick Martineau**); influence of the vertical and zonal propagation of stratospheric planetary waves on tropospheric blocking after SSW events (**Kunihiko Kodera**); and dynamical-core model experiments looking at the role of tropospheric synoptic eddies in stratosphere-troposphere coupling during SSW events (**Daniela Domeisen**). **Ryo Mizuta** reported on the projected change in extra-tropical cyclones in CMIP5 models associated with changes in the UTLS region. **Chikara Tsuchiya** investigated the climatology and trend of fronts as a gravity wave source in reanalysis data.

Several posters were presented in relation to tropics-extra-tropical interactions, with emphasis on the role of the stratosphere: ENSO influence of tropical convection on the SH high latitudes during the winter to spring transition (**Matthew Hitchman**); downward coupling processes through the TTL during an SSW event (**Nawo Eguchi**); and intraseasonal to seasonal variability of tropical upwelling in the BDC influenced by high-latitude planetary waves (**Rei Ueyama**). Some posters focused on the vertical dynamical coupling in the tropics using observational data: influence of the QBO on the interannual variability of tropopause temperature and height using COSMIC/FORMOSAT-3 data (**Vinay Kumar**); distinct stronger warming in the TTL associated with minor volcanic eruptions during the 2000s as revealed by GPS radio occultations (**Sanjay Kumar Mehta**); variability in the temperature structure around the TTL and its relationship with convective activity analysed with reanalysis and OLR datasets (**Eriko Nishimoto**); upper tropospheric cloud top height over the tropical Pacific observed with geostationary satellites (**Noriyuki Nishi**); and the occurrence of cirrus clouds associated with equatorial waves over the tropical Indian Ocean in November 2011 during the CINDY2011/DYNAMO campaign (**Junko Suzuki**). Further posters using model simulations were focused on: the roles of parameterized convective gravity waves in tropical stratospheric variability (QBO and SAO) in a climate model (**Young-Ha Kim**), and the climatology, seasonality, and intra-seasonal to interannual variability of the TTL temperature in CMIP5 models (**Joowan Kim**). Ryosuke Shibuya presented a poster about the latitudinal dependence of inertial oscillation in the atmospheric boundary layer revealed by large eddy simulations.

Acknowledgments

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Report on the 3rd SPARC DynVar Workshop on Modelling the Dynamics and Variability of the Stratosphere-Troposphere System

Elisa Manzini[1], Andrew Charlton-Perez[2], Edwin Gerber[3], Thomas Birner[4], Amy Butler[5], Steven Hardiman[6], Alexey Karpechko[7], François Lott[8], Amanda Maycock[9], Scott Osprey[10], Om P. Tripathi[11], Tiffany Shaw[12], Michael Sigmond[13]

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The third Workshop of SPARC's (Stratosphere-troposphere Processes and their Role in Climate) DynVar activity took place in Reading from 22-24 April 2013, jointly with the first SPARC SNAP Activity workshop, held from 24-26 April 2013. Both workshops were kindly hosted by the Department of Meteorology, University of Reading. We would like to acknowledge the great hospitality of the University of Reading and the excellent organization by the local committee. Synergy between the DynVar and SNAP themes provided a vibrant environment for the whole week. A total of ~100 participants from 16 countries attended both workshops.

The DynVar workshop was structured around the DynVar Research Topics (**http://www.sparcdynvar.org/research-topics-groups-folder/**), with invited oral and contributed poster presentations spread over the week (see report this issue) and two keynote presentations by **Ted Shepherd** (22 April) and **Joan Alexander** (23 April). Results from many CMIP5 analyses were discussed in the nine invited oral and 24 contributed poster presentations of the first two days. This outcome is a recognition of the unique opportunity that the CMIP5 archive presented to assess the stratosphere and its impacts on the climate system, which DynVar decided it would focus on during its second workshop held in 2010 (Gerber *et al.,* 2012; Manzini *et al.*, 2010, 2011; Charlton-Perez *et al.*, 2013). Discussions in Reading demonstrated that the stratosphere-troposphere dynamical coupling community was highly interested in being informed and participating in the broader activities of the World Climate Research Programme (WCRP), specifically in the development of the next phase of the Coupled Model Intercomparison Project Phase 6 (CMIP6).

In his keynote presentation, **Ted Shepherd** focused on the challenges of understanding and modelling the mechanisms of stratosphere-troposphere coupling on various timescales. On long time scales, the causes, extent and magnitude of a strengthened Brewer-Dobson Circulation (BDC) in response to climate change are current topics of investigation: Which dynamical processes (wave breaking, critical layer filtering, dissipation) and which spatial and temporal scales are dominant? Proposed mechanisms need to be examined systematically. Ted also pointed out that while there is strong consensus among climate models on the energetics of climate change, there is less consensus on the dynamical aspects of climate change, and that simulations suggest considerable multi-decadal variability in the stratosphere, whose origin still needs to be identified. Improving climate models by incorporating realistic stratosphere-troposphere coupling, might reduce uncertainty related to atmospheric circulation variability and change, with implications for regional climate change. Ted also called for a systematic assessment of model sensitivity and biases arising from gravity wave parameterizations, the topic of the keynote presentation by **Joan Alexander**. In her presentation, Joan emphasized the importance of the indirect role that gravity waves play in shaping the mean stratospheric flow, and consequently in affecting the behaviour of planetary and synoptic waves, both crucial elements of stratosphere-troposphere coupling. She questioned the current use of gravity wave parameterizations and their limitations in correcting model biases. Future directions in gravity wave parameterization development, such as climate sensitive gravity wave sources and lateral propagation, are underway and may provide the needed realism and coupling between the lower and upper atmosphere, although their benefits still need to be demonstrated.

A common theme of the DynVar presentations was the need for a renewed appreciation of the definition of a "well-resolved" stratosphere. There is a clear tendency to raise the lid of climate models - almost all CMIP5 models have tops at pressures <10hPa, and a substantial fraction of the CMIP5 models have tops at pressures <1hPa. However, drawing from our expertise in constructing and analysing models, it is clear that raising a model's lid to include the stratosphere in a climate model domain is a necessary but not a sufficient condition for a fully satisfactory representation of stratospheric dynamical processes, such as the Quasi-Biennial Oscillation (QBO), stratospheric sudden warming events, extreme wave events, variations in the wave forcing of the BDC, tropopause variability, water vapour variability, and vortex variability and change.

Nevertheless, the high-/low-top subdivision (top pressure <1hPa for high-top models) grouping of the CMIP5 model set has proven to be useful in demonstrating that stratospheric variability at all scales is better represented in the high-top models (**Andrew Charlton-Perez**). Further insights of high-/low-top differences emerged in presentations reporting inter-comparisons of: (1) tropopause characteristics: the CCMVal2 models with anomalously cold tropopause cold points tend to be anomalously cold throughout the stratosphere, but this behaviour is not exactly true for all CMIP5 models, due to high-/low-top differences in mean temperature (**Thomas Birner**); (2) ENSO teleconnections: Eastern Pacific ENSO events in high-top CMIP5 models generate anomalous signals in the polar stratosphere in the Northern Hemisphere, while low-top models do not show such a coherent signal. A negative Arctic Oscillation-like pattern in sea level pressure and surface temperature is stronger in the high-top than low-top models (**Natalie Calvo, Margaret Hurwitz**); (3) upper troposphere-lower stratosphere water vapour: clear differences between high- and low-top models arise only in the representation of the water vapour tape recorder (**Chiara Cagnazzo**); and (4) planetary wave coupling: most low-top models underestimate negative and extreme positive heat flux events. The bias in the negative events has implications for the downward dynamical coupling during strong vortex events, manifested by low pressure and eastward near-surface winds in the North Atlantic basin, impacts consistent with the positive phase of the North Atlantic Oscillation (**Tiffany Shaw**).

The high-/low-top distinction was not found to be a predictor for the climate change signal in the stratosphere in CMIP5 models (**Alexey Karperchko**), a sign that other model features other than stratospheric variability, such as parameterized gravity wave processes, or tropospheric and ocean responses to climate change, play a more dominant role in shaping the simulated response of the stratospheric circulation to climate change. A similar difficulty is found in identifying a signature of the high-/low-top model distinction in simulating the connection between the stratosphere and the North Atlantic Ocean, in spite of a stronger air-sea coupling in the high-top model set (**Thomas Reichler**).

The regular program of the workshop was followed by discussion sections focused on three main topics: (1) QBO, (2) circulation and climate change, and (3) mechanisms of stratosphere-troposphere coupling. This discussion time was the first step toward the construction of a new DynVar implementation plan. A second discussion session is planned as a side event at the SPARC General Assembly, to be held from 12-17 January 2014 in Queenstown, New Zealand. In Reading, the goal of the discussions focused on how DynVar can best participate and take advantage of the next phase of climate model inter-comparisons (CMIP6), expected to start in 2015. One important common outcome of the three discussion sessions was the need to provide justification for diagnostics focused on stratospheric dynamics, such as Transformed Eulerian Mean (TEM) variables, gravity wave parameterization tendencies, as well as all physical tendencies to assess the momentum and heat budgets.

Quasi-biennial oscillation

Simulation of the QBO in climate models remains challenging, with only a small minority of CMIP5 models reporting successful simulation of the QBO (**Thomas Krismer** and **Scott Osprey**). New developments based on stochastic and/or convection-driven gravity wave sources (**François Lott**) have the potential to increase the number of climate models with a QBO in the next phase of CMIP. However, given the competition of resources in climate modelling centres, it is expected that there will be the need to justify the application of atmospheric model components with proper resolution and parameterizations to be able to simulate the QBO. We assessed several robust reasons why the QBO is important: the QBO is a dominant mode of stratospheric inter-annual variability; the QBO and solar cycle variability interact in their modulation of the propagation of planetary waves in the stratosphere; the residual circulation driven by the QBO affects the BDC; and the QBO affects tropopause temperature in the tropics, and hence water vapour in the stratosphere. Tropospheric QBO impacts such as the effects on the Monsoon, Madden Julian Oscillation, NAO and ENSO are much less robust and are just starting to be investigated. In addition, the impact of the QBO on the mid-latitude stratosphere, through the Holton and Tan effect, needs to be re-assessed since this effect does not appear much in the CMIP5 models (**Bo Christiansen**), with consequences on the representation of the QBO-NAO relationship. An open question is whether improvements in the simulation of precipitation variability may facilitate the simulation of the QBO, given that convection generates the tropical waves (at planetary and gravity scales) that drive the QBO. Specific issues to be addressed are:

- What makes equatorial waves dissipate so fast in the lower stratosphere?
- Lower level penetration of the QBO is underestimated in current models, why? This affects water vapour entry and stratosphere-troposphere coupling.
- Radiative ozone feedback.

Recommendations for further analysis of the CMIP5 runs include:

- Equatorial waves and QBO structure (Lott *et al.*, in preparation)
- Relations with tropical tropospheric variability
- The QBO-NAO relationship (Hardiman *et al.*, in planning; Christiansen, in preparation).

To progress further, more data will be need to be output in CMIP6, including tendencies from the physics at all levels. The extraction of more diagnostics may possibly be restricted to dedicated experiments, such as AMIP-type runs. Note, however, that ocean coupling may degenerate the QBO performance. We agreed that the QBO initiative presented by Osprey *et al*., aimed at designing a set of experiments to address the limitation of current models in simulating the QBO, could possibly be initiated by involving a core group of modelling centres and by reporting what progress has been made in modelling the QBO so far.

Circulation and climate change

To reduce the uncertainty in climate projections of atmospheric circulation and its implications for surface and regional climate, the assessment of tropospheric and stratospheric dynamical processes in climate models is crucial. Fundamental questions that need to be addressed are:

- What are the causes of tropospheric and stratospheric circulation changes?
- What are the impacts of tropospheric changes on the stratosphere, and *vice versa*? For which changes do we understand the mechanisms?
- Which atmospheric circulation changes are robust across models?
- What are the dominant sources of uncertainty in projections of atmospheric circulation changes?

Robust changes include a poleward shift of the subtropical jets, BDC strengthening, tropopause rise, and Antarctic vortex change (this latter also driven by ozone depletion). Less robust are shifts of the Arctic polar vortex and northern mid-latitude tropospheric jet, and the QBO response. The Arctic vortex and QBO response to climate change may be critical because both involve indirect responses of the tropospheric circulation and depend on the response of gravity wave parameterizations, sources of large uncertainty in stratospheric modelling.

For CMIP6, questions were posed about the availability of raw data versus more derived quantities (*e.g.*, EP flux divergence), the possibility of having more levels near the tropopause, all physical tendencies from parameterisations to close momentum and thermodynamical budgets, more flexibility in getting the model outputs, and observation datasets prepared for straightforward comparison with models. Concerning the availability of derived quantities, the question of developing a DynVar data archive was posed. Regarding the CMIP6 experiments, we felt that for characterizing the relative role of interannual versus inter-model variance, fewer scenarios and more ensemble members would be a valuable option, and that we might wish to focus on more idealized experiments (*e.g.*, AMIP4K) or reduced complexity models, including experiments with dynamical cores. However, concrete plans still need to be made, calling for a dedicated small workshop, as concluded during discussions about the following topics.

Mechanisms of stratosphere-troposphere coupling

A number of mechanisms have been proposed: downward control; hydrostatic and geostrophic (fast and slow) adjustments, as for instance inferred by PV inversion; eddy feedbacks (baroclinic, planetary, *etc.*); wave coupling; resonance; and linear versus non-linear (index of refraction). There are questions about how independent the mechanisms are? How can we create tests that can falsify some mechanisms? Whether different mechanisms matter on different time scales? Whether the mechanism can accurately capture the region where impacts are observed (*e.g.,* Pacific versus Atlantic)? What signal would we expect at the surface? And, under what conditions do events couple to the troposphere? Given the rapid growth of literature on stratosphere-troposphere coupling mechanisms, it would be timely to write a review paper, and two such efforts are currently underway (Kidston *et al.*, in preparation; Baldwin *et al.*, in planning). Note also that previous comprehensive reviews happened eight or more years ago (Haynes, 2005; Shepherd, 2002; Holton *et al.*, 1995).

Independently from these efforts, and based on our developing experience in analysing CMIP5 runs, a proposal was made to write a new position paper to help focus and clarify a set of diagnostic and possibly idealized experiments for CMIP6 (timeframe: one year from now). A major question emerged regarding which model experiments should be designed to test stratosphere-troposphere coupling mechanisms: Are there differences in how stratosphere-troposphere dynamical coupling operates if the coupling originates in the stratosphere from radiative perturbations (water vapour, ozone, solar, GHG) or via a dynamical source in the troposphere (*e.g.*, acting as a stratospheric pathway in tropospheric teleconnections)? Further questions are: What are the implications of distinguishing types of coupling? Could DynVar propose an idealized experiment to be carried out in models of varying complexities? These questions would need careful thought about goals and suitable approaches, and could be addressed in a dedicated small workshop.

Summary and future plans

The DynVar workshop was a successful event thanks to the dedicated participation of all attendees, to whom we would like to express our gratitude. The current focus of the DynVar Activity is on exploiting the unique opportunity offered by the CMIP5 and SHFP (Stratosphere-resolving Historical Forecast Project) archives. In terms of its future scientific direction, the emerging vision is to embrace the "one-atmosphere" concept, and address tropospheric dynamical issues as well. This is a natural evolution of DynVar since stratosphere-troposphere dynamical coupling is an essential process in extra-tropical climate variability and change, and is consistent across timescales. A further important emerging item of discussion is what research opportunities the WCRP Grand Challenges (GC) (**http://www.wcrp-climate.org/index.php/grand-challenges**) may open to DynVar, and how we can best contribute to them. DynVar appears to be well positioned to contribute to GC1 on Regional Climate information (given that the atmospheric circulation is a major source of uncertainty in regional climate) and GC5 on Cloud, Circulation and Climate Sensitivity (through the "changing patterns" initiative lead by Sobel and Shepherd). The ideas regarding the future scientific direction of the activity, its contribution to the GCs, and participation in CMIP6 will be the subject of discussion at a DynVar side event planned during the SPARC General Assembly. Revision of the DynVar Research Topics and Groups will follow, as well as the activity implementation plan requested by SPARC. DynVar will also maintain links with the seasonal forecasting community, the SHFP project (Butler and Scaife, leads), and the Polar Climate Predictability Initiative (Bitz and Shepherd, leads).

Given the common scientific interest of stratosphere-troposphere coupling (although different time scales are addressed) and that a joint DynVar and SNAP workshop has proven very successful, we are evaluating the possibility of reconvening with a second joint DynVar-SNAP workshop to be held in early 2015.

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Report on the 1st SPARC Stratospheric Network for the Assessment of Predictability (SNAP) 24-26 April 2013, Reading, UK

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The first SPARC Stratospheric Network for the Assessment of Predictability (SNAP) workshop was organized at the Department of Meteorology, University of Reading, UK, from 24-26 April 2013. This was a joint workshop with the 3rd SPARC Dynamical Variability (SPARC-DynVar) workshop held from 22-24 April, with 24 April as a joint day (see report this issue). The joint workshop was well attended and had around 100 participants (**http://www.met.reading.ac.uk/~pn904784/DynVar_SNAP_Workshop/participant.html**) from 16 countries in Europe, Asia, Africa, Australia, North America, and South America.

The SNAP workshop was formally opened by **Simon Chandler-Wide**, Head of the School of Mathematical and Physical Sciences, University of Reading. Simon gave a short speech about the history of the University and Department of Meteorology, and formally welcomed the participants. The welcome address was followed by an introduction to SNAP by **Andrew Charlton-Perez** (see also Charlton-Perez and Jackson, 2012). During the workshop, participants presented their work, underlining current understanding of stratospheric dynamical variability, its predictability, and its impact on surface weather and climate. On 26 April an extensive discussion was held, focusing on future plans for SNAP, including an experimental protocol for the SNAP predictability experiment, which will take place during 2013 and 2014, and links to other related activities including the seasonal to sub-seasonal prediction initiative (S2S, **http://www.wmo.int/pages/prog/arep/wwrp/new/S2S_project_main_page.html**).

Thomas Jung gave the keynote talk, presenting a detailed overview of the role of the stratosphere in extended range weather forecasting, with case studies including the stratospheric sudden warming (SSW) of 2009 and the extremely cold European winters of 2005/06 and 2009/10. His studies used the ECMWF Integrated Forecast System (IFS). He described a study of the generic tropospheric circulation response to an optimized stratospheric forcing that changes the strength of the wintertime Northern Hemisphere stratospheric polar vortex. Results of the experiment showed that the response of the tropospheric circulation to stratospheric forcing was significant, and had the expected strong projection onto the surface Northern Annular Mode (NAM). The response was found to be linear with respect to the forcing and delayed by around 10 days from forcing onset. His case study experiments used a different but related technique, attempting to quantify the role the stratosphere played in recent cold winters by damping the stratospheric state toward a reanalysis. In these experiments, small reductions in tropospheric forecast error were found in the stratospheric damping experiments. He also emphasized the potential tropical source of stratospheric variability by showing that, in some cases, reduction in extra-tropical forecast error is similar for cases when either stratospheric damping or an equivalent tropical tropospheric damping is used.

Martin Charron gave an introduction to the Canadian Global Weather Forecasting System that includes the stratosphere, and discussed the additional skill in surface weather forecasting gained from raising the model lid. The new Environment Canada NWP (numerical weather prediction) global model has a lid at 0.1hPa and 80 vertical levels. The model includes a non-orographic wave drag scheme, methane oxidation scheme, and a new ozone climatology. In addition to comparing the forecast skill of the old and new models, he also showed results from a comprehensive set of experiments that attempted to systematically identify the source of the forecast skill improvements in the new model. One interesting result was that additional tropospheric forecast skill was obtained without any extra observations in the stratosphere, suggesting that improvements in the estimation of the initial state due to reduced stratospheric bias were important.

Greg Roff presented results from extended range forecasts using the Australian Community Climate and Earth System Simulator (ACCESS). ACCESS runs a global and regional short-range ensemble prediction system (AGREPS) in pre-operational research mode. He found that the AGREPS system performs comparably, to the operational ECMWF-EPS system, as shown for the forecasts of the Queensland, Australia, flooding of 27 January 2013 (**Figure 19**). He also presented an important challenge to SNAP, that is, to clearly identify where operational forecasting centres might see benefit in forecast skill from better representing stratospheric dynamical processes.

An introduction to the WCRP-WWRP S2S project was given by the S2S co-chair **Frédéric Vitart**. S2S is a new WWRP/THORPEX-WCRP joint research project whose main goal is to improve forecast skill and understanding on the sub-seasonal to seasonal timescale, promote its uptake by operational centres (**Table 3**), and exploitation by the applications community. The project is designed to pay specific attention to the risk of extreme weather, including tropical cyclones, droughts, floods, heat waves, and the waxing and waning of monsoon precipitation. S2S is in the process of establishing an extensive database of sub-seasonal to seasonal (up to 60 days) forecasts and re-forecasts. The database will, in part, be modelled on the THORPEX Interactive Grand Global Ensemble (TIGGE) database for medium range forecasts (up to 15 days). The impact of stratospheric variability on surface weather and climate will be a key topic of the S2S project.

Stratospheric variability and predictability

An invited talk on the predictability of the stratosphere and associated teleconnections was given by **Adam Scaife**. He presented a series of monthly forecasts of the January 2013 SSW. These forecasts showed that a SSW signal started appearing on 21 December 2013 in the operational forecast model, and that Met Office forecasts were modified to include the potential effects of this event. This was an example of the importance of what Adam called 'actionable information' for forecasters, which SNAP should bear in mind when considering the impact of stratospheric variability on sur-

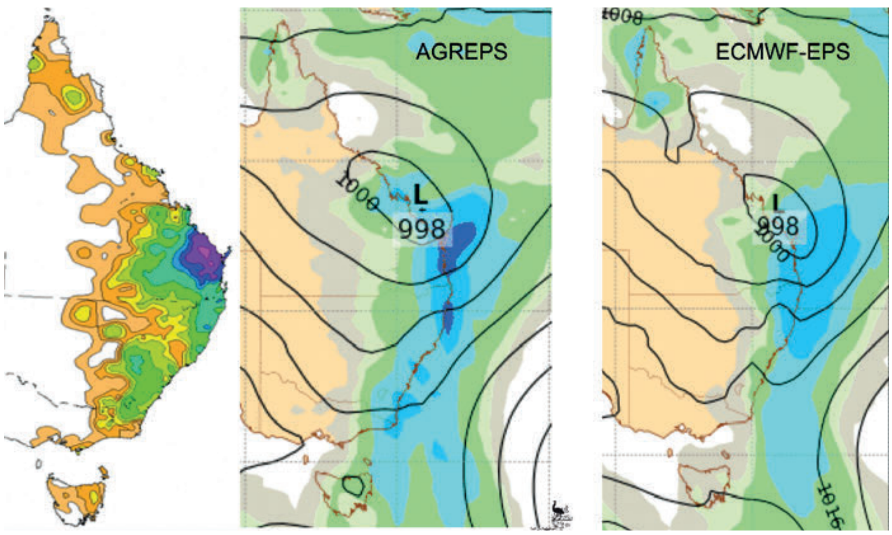

Figure 19: The flooding of Queensland, Australia as simulated by AGREPS and ECMWF-EPS.

Table 3: Major operational forecasting systems and their configuration for the S2S initiative:

	Time Range	Resol.	Ens. Size	Freq.	Hcsts	Hcst Length	Hcst Freq	Hcst Size
ECMWF	D 0-32	T639/319L62	51	2/week	On the fly	Past 18y	weekly	5
UKMO	D 0-60	N96L85	4	daily	On the fly	1989-2003	4/month	3
NCEP	D 0-60	N126L64	16	daily	Fix	1999-2010	daily	4
EC	D 0-35	0.6x0.6L40	21	weekly	On the Fly	Past 15y	weekly	4
CAWCR	D 0-120	T47L17	33	weekly	Fix	1989-2010	3/month	33
JMA	D 0-34	T159L60	50	weekly	Fix	1979-2009	3/month	5
KMA	D 0-30	T106L21	20	3/month	Fix	1979-2010	3/month	10
CMA	D 0-45	T63L16	40	6/month	Fix	1982-now	monthly	48
Met. Fr.	D 0-60	T127L31	41	monthly	Fix	1981-2010	monthly	11
SAWS	D 0-60	T42L19	6	monthly	Fix	1981-2001	monthly	6
HMCR	D 0-60	1.1x1.4L28	20	weekly	Fix	1981-2010	weekly	10

face weather. Adam also discussed a number of case studies of recent cold winter events and discussed experiments that highlighted the role of stratospheric variability in the predictability of these events. He estimated that the mean time on which the current version of the Met Office model could predict SSW events was around 12 days. He also showed experiments highlighting the role of drivers of variability in the extra-tropical stratosphere including ENSO, the QBO, and the solar cycle. Finally, he presented results from the most recent version of the Met Office seasonal forecasting model, GloSea5. Excitingly, these results show much greater skill than previous models in predicting the wintertime NAO, with a correlation between DJF mean NAO and November forecasts of around 0.6 over a series of hindcasts. **Alberto Arribas** discussed this result in further detail, highlighting some of the improvements made to the Met Office systems, including enhancements of both vertical and horizontal resolution, which led to this step change in forecast skill.

The role of SSWs in producing skilful seasonal forecasts was also discussed by **Michael Sigmond**, using the Canadian Middle Atmosphere Model. He showed the enhanced potential predictability that can be achieved in sea level pressure, surface temperature, and precipitation for forecasts initialized during SSWs. This was contrasted with the lower levels of model skill for forecasts initialized during periods in which the stratospheric state was close to the climatology. As a way of exploiting the additional skill, he suggested that forecasting centres run additional, special seasonal forecasts once an SSW appears in observations.

Daniella Domeisen gave a presentation about the ability of the MPI-ESM seasonal prediction system to reproduce stratospheric variability and predictability. The mean state of the stratosphere was shown to be well reproduced, but the model still struggles in the tropical upper stratosphere, where there appears to be a large positive bias in zonal mean zonal wind. In a composite of 67 SSWs the model appears to successfully reproduce downward coupling.

Masakazu Taguchi investigated basic characteristics of stratospheric predictability for the NH winter stratosphere by comparing the JRA-25/JCDAS reanalysis data with one-month ensemble hindcast (HC) experiment data using the Japan Meteorological Agency (JMA) numerical weather prediction model. The HC data exhibits a large spread and low skill when the polar night jet is in a weakening phase. The spread and skill are found to be correlated, as expected (large spread corresponds to low skill), but their distributions are also characterized by outliers, which have markedly low skill for a given spread.

Stratosphere-troposphere coupling, stratospheric warmings and surface weather

The tropopause connects the stratosphere and troposphere and plays a very important role in stratosphere-troposphere coupling. **Mark Baldwin** highlighted the role of the tropopause and suggested that the understanding of the variation of tropopause height may hold the key to understanding the stratospheric impact on surface weather. He described the large variability of tropopause height (upwelling/downwelling) at the polar cap as a mechanical plunger, influencing the entire troposphere. Because of the large signal to noise ratio in tropopause height, he suggested using new metrics for stratosphere-troposphere coupling, such as the variance of tropopause height and the e-folding timescale of tropopause height (**Figure 20**).

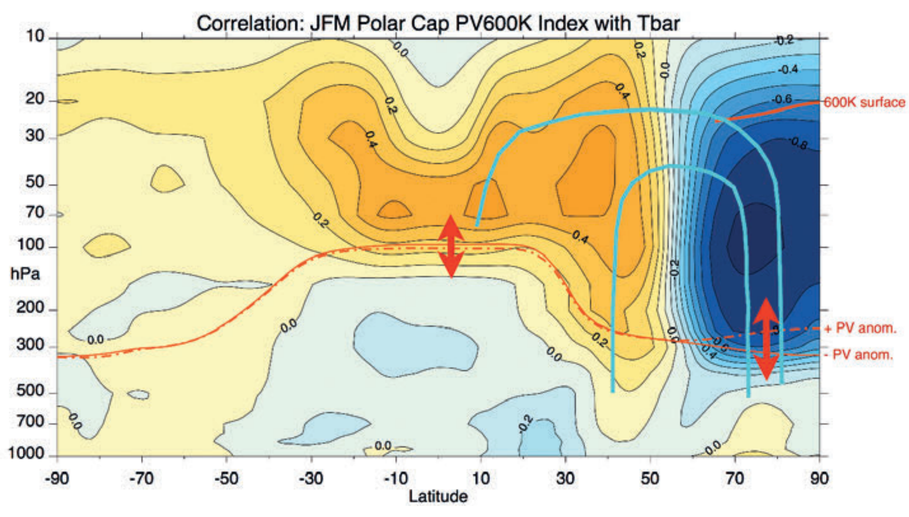

Figure 20: Large variation in PV anomaly at the tropopause.

Shigeo Yoden introduced a five-year Japanese research project looking at extreme weather variability in the coupled stratosphere-troposphere system. This project is a collaboration between groups working on data analysis, mechanistic circulation modelling, general circulation modelling, NWP modelling studies, and JMA/Meteorological Research Institute climate modelling studies. The project aims to perform comprehensive studies of extreme weather events in the coupled stratosphere-troposphere system, understanding their dynamical processes with a hierarchy of numerical models, and future projections with a state-of-art climate model. This research project may also contribute towards the promotion of international research collaboration, including WCRP/SPARC activities.

Miriam D'Errico presented the effects of stratosphere-troposphere coupling on decadal predictability of the climate system using a coupled ocean-atmosphere model. She showed results from climate projections using both the high- and low-top versions of the CMCC climate model.

The tropical stratospheric response to SSW events was presented by **Miguel Gomez-Escolar**. He found that the upper and middle tropical stratosphere is significantly coupled to the evolution of the polar cap. He discussed new ways of extracting composite temperature anomalies during SSW events, avoiding contamination from QBO-induced temperature changes. He showed that lower stratospheric responses to SSW events are only present during easterly QBO phases and are related to changes in sub-tropical wave breaking.

Beatriz Funatsu investigated the impact of SSWs on changes in the occurrence of tropical convection following two SSWs that occurred in January 2009 and January 2010, using satellite observations from the Advanced Microwave Sounding Unit. She found that following the onset of a SSW there was a subsequent overall increase in the occurrence of deep convection over South America, Africa, and the Maritime Continent.

Daniel Mitchell presented work that distinguished between the impact of vortex displacement and vortex splitting during SSWs on the surface weather using reanalysis data. He found that vortex splitting events are more strongly correlated with surface weather and lead to positive temperature anomalies of more than 1.5K over eastern North America, and negative anomalies of up to -3K over Eurasia. The signals from vortex displacement events were found to be weaker and generally associated with cold-air outbreaks over North America.

Toshihiko Hirooka presented a study of mesopause circulation changes during SSWs. He found that mesospheric easterlies do not always appear before SSW easterlies in the upper stratosphere. He also discussed dynamical reasons for the difficulty that models have in reproducing the mesopause changes associated with SSW events.

Quasi-biennial oscillation

Bo Christiansen made a presentation about the QBO influence on variability of the stratospheric winter vortex in CMIP5 and CCMVal2 models. He showed that while models show significant bimodality in the tropical stratosphere associated with the QBO, there is little bimodality in the polar vortex region despite models having realistic vortex variability. He also showed that the Holton-Tan (HT) relationship is significantly weaker in models than in the reanalysis (**Figure 21**).

Peter Watson gave a presentation considering the effect of the QBO on the stratospheric polar vortex. Using dynamical system theory, he argued that composite pictures of the vortex evolution during different QBO phases could be misleading, and instead advocated a detailed study of the transient response of the vortex to QBO forcing. Using results from the HadGEM2 model, he described how transient experiments of this type favour the standard HT mechanism over other explanations for the QBO-vortex link.

Another presentation on the HT mechanism was made by **Hua Lu**, who discussed changes in the HT effect on decadal time scales. Using ERA-40 and ERA-Interim reanalysis data she showed that more planetary waves break in the upper stratosphere in winter when the previous QBO phase transition occurred during NH winter, causing stronger meridional circulation and a warmer, more disturbed polar vortex. She also showed that from 1977-1997 the HT effect was weak due to more frequent winter transitions of the QBO phase during that period.

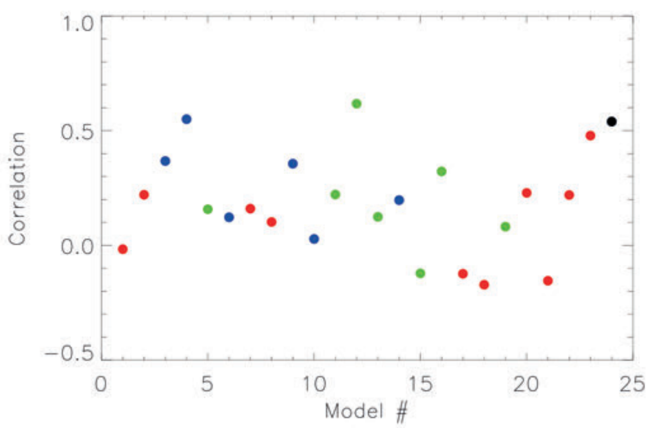

Figure 21: Correlations between winter mean vortex and QBO. The colours indicate the representation of the QBO in the models: No QBO (red), Prescribed QBO (blue), Spontaneous QBO (green), and NCEP (black).

Manfred Ern studied observed QBO forcing with ECMWF and satellite temperature data, using longitude-time 2D spectral analysis. The Kelvin wave contribution to momentum forcing of the QBO during the 2002-2006 period was found to be only 30% of the total.

Annular modes, ENSO and blockings

Torben Kunz presented a study of the effect of stratospheric variability on the NAM surface signal. He quantified the relative role of the downward effect of the zonal mean secondary circulation induced by quasi-geostrophic (QG) adjustment to stratospheric wave drag and radiative damping, and of wave drag local to the troposphere. The role of both contributions appeared to be quantitatively similar but differed qualitatively. QG adjustment was found to be responsible for the initiation of the surface NAM signal, while the wave drag maintains the persistence of the signal for several weeks.

The effect of SSWs on the predictability of the tropospheric NAM over nine winters from 2001/2002 to 2009/2010 was presented by **Yuhji Kuroda**, using the MRI climate model. Results showed that the stratosphere plays an important role for better medium-range prediction of the tropospheric NAM when stratospheric variability is very large during a SSW (as in 2004 and 2006). The predictability of the tropospheric NAM reaches a few months, as shown in **Figure 22**.

Robert Black presented a performance assessment of the CMIP5 model representation of the primary modes of boreal extra-tropical low-frequency variability, the vertical and temporal behaviour of the annular modes, and stratosphere-troposphere dynamical coupling. He showed that the high-top models represent stratospheric zonal wind anomalies better, however, little distinction was found in the magnitude and structure of zonal wind anomalies at tropospheric levels.

A study of the relationship between ENSO, blocking, and stratospheric sudden warmings was presented by **David Barriopedro** using reanalysis data for the 1958-2010 period. Results reveal that SSWs characterized by splits of the stratospheric polar vortex exhibit different regional blocking precursors, associated wave numbers, and vortex structure depending on the ENSO phase. This indicates some ENSO influence on the determination of different tropospheric SSW precursors. Splitting SSWs tend to be preceded by eastern Pacific blocks during La Niña, but by reduced eastern Pacific blocking activity and enhanced western Atlantic blocking frequency during El Niño.

James Anstey used the CMIP5 dataset in combination with CMAM runs to assess the blocking-SSW relationship. He showed that there was little observable difference in blocking between high- and low-top models, but that models with higher vertical resolution in the upper troposphere and lower stratosphere tend to show reduced blocking biases (**Figure 23**).

External Forcings

Edwin Gerber explored the im-

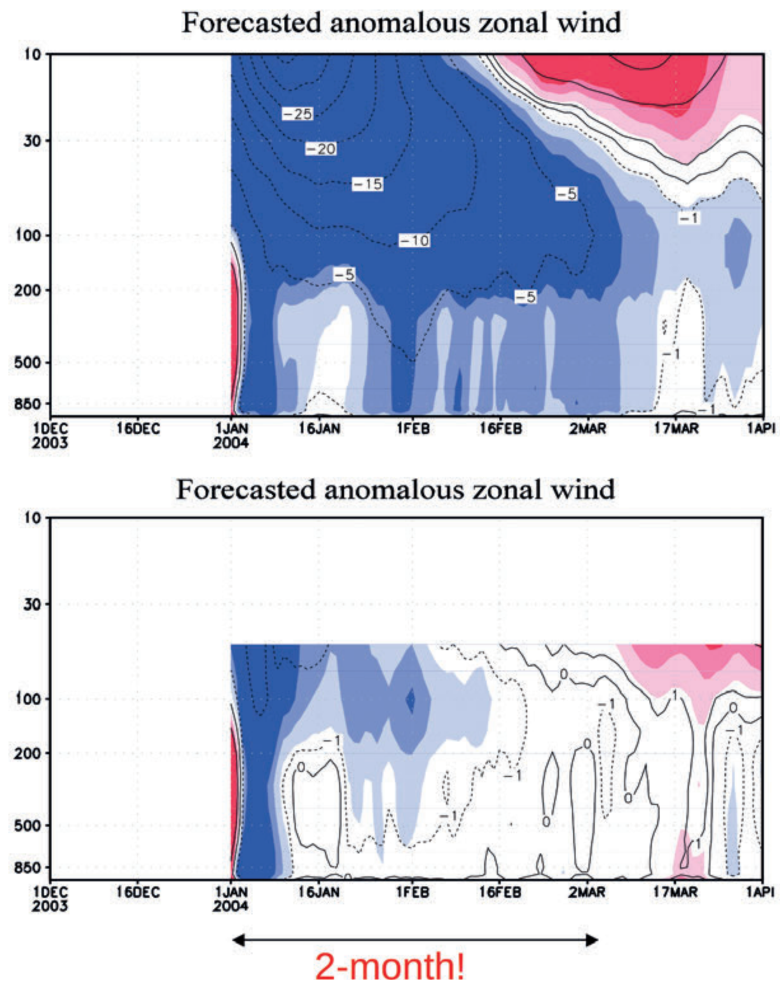

Figure 22: The effect of SSWs on the predictability of tropospheric NAM.

pact of anthropogenic forcing on the austral jet stream in CCMVal2, CMIP3, and CMIP5 models, focusing on summer, the period of the year when stratospheric ozone loss and recovery has been shown to impact the troposphere. He found that the multi-model mean response of the jet stream to greenhouse gases and ozone is fairly comparable, suggested that ozone changes have dominated the jet position in the recent past, and that the effects of ozone and greenhouse gases will largely offset each other in future.

The impact and the potential benefits of using ozone data from the Earth Observing System Microwave Limb Sounder (EOS MLS) in medium- to extended-range tropospheric forecasts in a current NWP system was examined by **Jacob Cheung**. In the extreme case (Arctic ozone hole, March 2011) where the EOS MLS ozone profile is superior to that of the control, tropospheric errors in the medium- to extended-range forecasts are dominated by the spread of ensemble members, and hence he found no significant reduction of root mean square errors due to an improved representation of ozone.

Laura Wilcox quantified the effect of external forcings on the Southern Hemisphere final warming date, and the sensitivity of projected changes to model representation of the stratosphere using high- and low-top CMIP5 model ensembles. The final warming date in the models was found to be generally too late in comparison with those from reanalyses - around two weeks too late in the low-top ensemble, and around one week too late in the high-top ensemble (**Figure 24**). She also examined this behaviour in response to changes in stratospheric ozone and greenhouse gases, finding that variability in the final warming date on timescales associated with changes in stratospheric ozone concentrations was only significant in the high-top ensemble.

Encarna Serrano evaluated the ability of the Whole-Atmosphere Community Climate Model (WACCM) to reproduce tracer transport processes through the tropical tropopause. Model results showed that the main features of vertical structure and seasonality of temperature, ozone and CO near the tropical tropopause in WACCM are very similar to satellite observations, and that WACCM is a valuable tool for evaluating ozone and CO transport near the tropical tropopause, although the cold point tropopause is slightly higher (~1km) in the model than in observations (**Figure 25**).

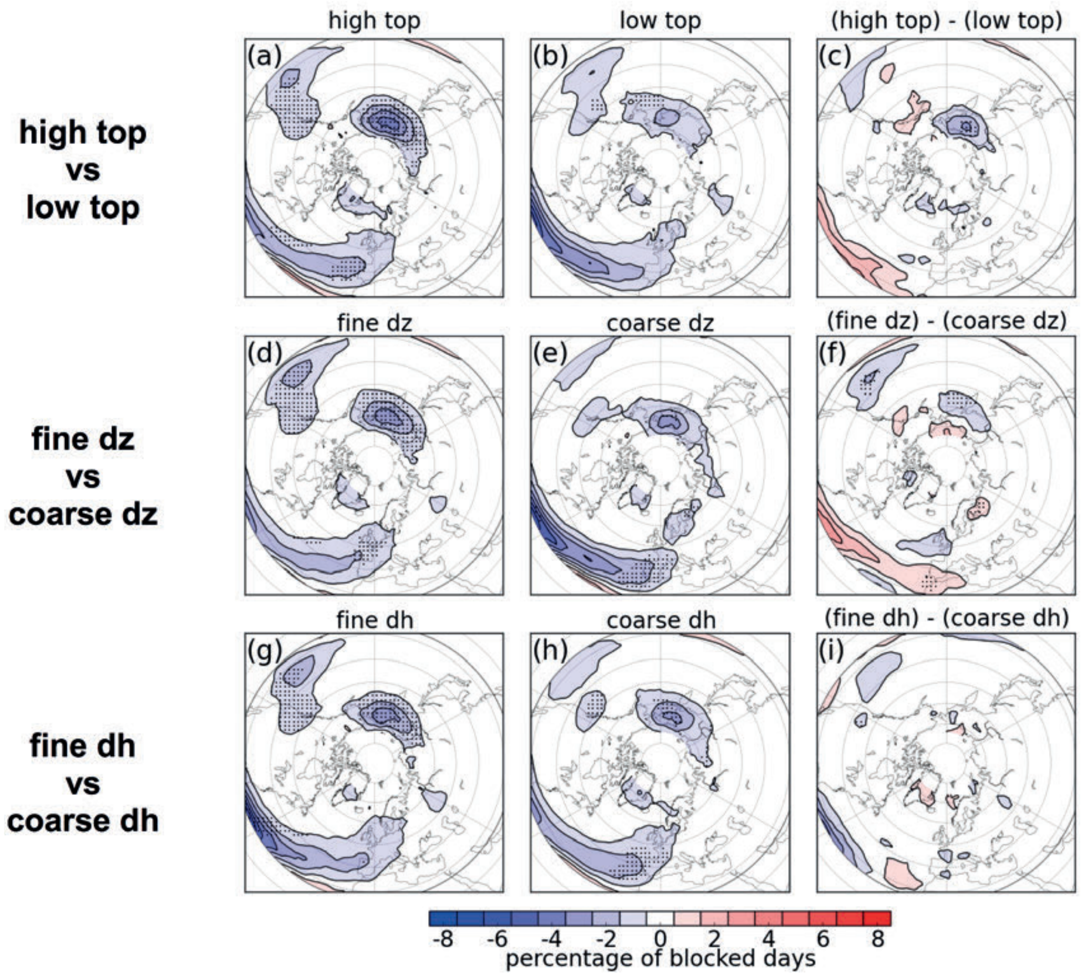

Figure 23: Effect of model resolution on blocking trends. Top Row: high-top vs. low-top models; Middle Row: fine vs. coarse vertical resolution model versions; Bottom Row: fine vs. coarse horizontal resolution model versions.

A model study of the tropospheric circulation changes in response to zonally asymmetric ozone anomalies was presented by **Dieter Peters**. He found significant changes in intra-seasonal and interannual variability in the stratosphere when comparing model runs with symmetric and asymmetric ozone distributions. These changes also have links to tropospheric circulation.

A possible impact of a future grand solar minimum on surface climate was presented by **Amanda Maycock**, who indicated that a large decrease in solar activity over the coming century would enhance the stratospheric cooling in response to increasing CO_2 concentrations. The cooling would weaken the stratospheric polar jet and consequently result in an equatorward movement of the mid-latitude jet, thus affecting the regional climate over Western Europe.

Summary and future plan

The first SNAP workshop concluded with an extensive and fruitful discussion session on Friday morning. The discussion focused on the future plans for the SNAP experiment and modifications of the originally planned activities in lieu of recent findings about the performance of low- and high-top operational models. Ideas presented by the participants will be used to draft an experiment protocol for the project, which will later be agreed upon by the project steering committee.

Next actions for SNAP are to complete the SNAP predictability experiment, which is to be carried out in two phases. Phase I will focus

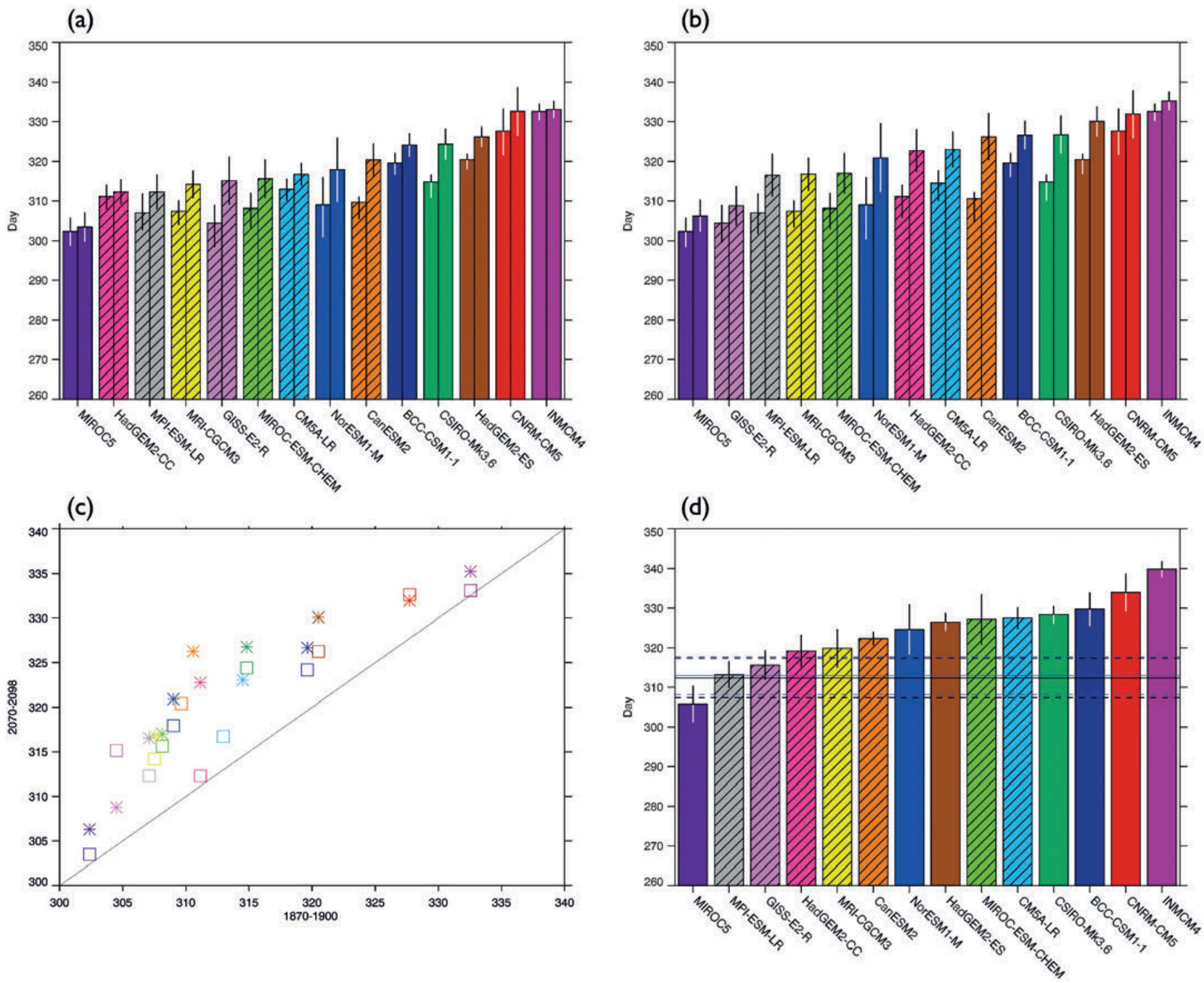

Figure 24: Mean final Southern Hemisphere warming dates for CMIP5 model for (a) 1870–1900 (left bars) and 2070–2098 (right bars) in RCP4.5, (b) 1870–1900 (left bars) and 2070–2098 (right bars) in RCP8.5, (d) 1979–2005. Whiskers show +/-2 standard errors. High-top models are indicated by hatching. In Figure 4d, the horizontal solid lines show the mean final warming date from ERA-Interim (black) and CFSR (blue), with dashed lines indicating ˙2 standard errors in each case. (c) The relationship between 1870–1900 and 2070–2098 final warming date is shown for RCP4.5 (squares) RCP8.5 (stars). Figure source: Wilcox and Charlton-Perez, 2013.

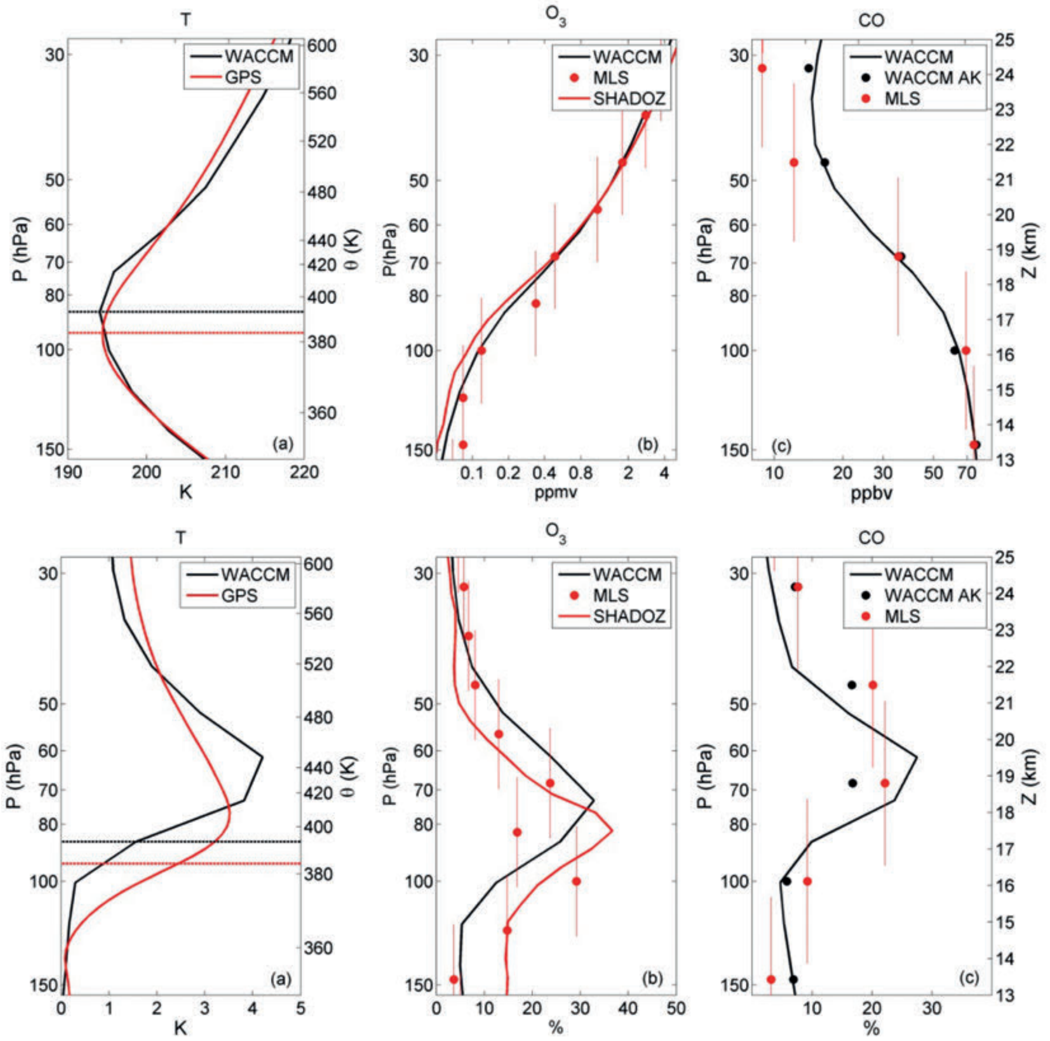

Figure 25: Top panel: Vertical structure of time mean (2004-2009) temperature (a), ozone (b), and CO (c) averaged over 18°S-18°N for WACCM and observations. The error bars represent the vertical thickness of the layers where MLS measures ozone and CO. The horizontal lines in panel (a) indicate the location of the annual mean cold point tropopause. The black dots in panel (c) indicate the WACCM values when using MLS averaging kernels for CO. Bottom panel: As in top panel but for the vertical structure of the annual cycle in temperature and tracers. The amplitude for the tracers is shown relative to the annual mean concentration. (Source: Abalos *et al.*, 2012).

on forecasts of two very recent test events, the NH January 2013 SSW, and the late SH final warming of October 2012. Once this test phase has been completed, the project will work to define additional dates for forecast comparisons to be added to the SNAP forecast archive. In addition, SNAP will begin to collect a set of operational forecasts from each of the modelling centres involved, to facilitate the comparison of forecast performance during periods in which extreme stratospheric events are not occurring.

A key part of the forecast protocol will be to specify, in detail, which stratospheric fields can be collected from the modelling centres to provide a detailed understanding of the dynamical background of stratospheric predictability.

SNAP furthermore agreed to play a role in the upcoming S2S project. SNAP will seek to encourage members of the network to make use of S2S to examine stratosphere-troposphere predictability on the subseasonal time range, using the large archive of data that S2S will collect.

Acknowledgments

The authors are grateful to the Natural Environment Research Council and WCR-SPARC for their financial support.

Reference

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SPARC Reanalysis Intercomparison Project (S-RIP) Planning Meeting

29 April – 1 May, 2013, Exeter, UK

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The SPARC community has been using reanalysis datasets to understand atmospheric processes and variability, and to validate chemistry-climate models. Currently, there are eight global atmospheric reanalysis datasets available and four more will be available soon (**Table 4**). The SPARC Reanalysis Intercomparison Project (S-RIP) is an emerging SPARC activity that was proposed last year (Fujiwara *et al.*, 2012). The goals of S-RIP are to create a communication platform between the SPARC community and reanalysis centres, to understand current reanalysis products, and to contribute to future reanalysis improvements. By August 2012, the working group (WG) with 11 members had been formed, and the reanalysis centre contacts for the project had been confirmed. The WG discussed chapter titles, co-leads, and initial contributors to the final SPARC report and planned a kick-off meeting. This article summarizes the discussions held during the S-RIP Planning Meeting hosted at the Met Office, Exeter, UK, from 29 April-1 May 2013. There were 39 participants, 20 oral presentations, and 21 poster presentations.

Meeting outline

The purposes of the meeting were to finalize the report outline, to determine the diagnostics list and observational data required for validation for each chapter, to agree on the general guidelines and protocols, and to define the project timetable. Based on past SPARC activities (*e.g.*, SPARC CCMVal, 2010), the WG initially proposed 11 chapters. The first four "basic" chapters are the Introduction, Description of the Reanalysis Systems, Climatology and Interannual Variability of Dynamical Variables, and Climatology and Interannual Variability of Ozone and Water Vapour. The following, "advanced" chapters were initially proposed to be: The Brewer-Dobson Circulation, Stratosphere-Troposphere Coupling, The Upper Troposphere and Lower Stratosphere (UTLS), Polar Processes, The Quasi-Biennial Oscillation (QBO), The Upper Stratosphere and Lower Mesosphere (USLM), and Gravity Waves. Prior to the meeting two co-leads were confirmed for most of the chapters. At the meeting, all chapters, except for the introduction, were given one hour for a presentation by the co-leads and discussion with the participants. The Brewer-Dobson Circulation session included short invited talks by some of the main contributors to the chapter (**Hella Garny, Gabriele Stiller, Bernard Legras**, and **Howard Roscoe**). For each chapter, the co-leads and two rapporteurs prepared a one-page summary slide for the wrap-up on the final day. The finalized chapter list with the co-leads' names is shown in **Table 5**. We decided to divide the UTLS chapter in two, one focusing on the extra-tropical UTLS (ExUTLS) and the other on the Tropical Tropopause Layer (TTL), with a section in the ExUTLS chapter summarizing overlapping issues between the two chapters. Also, issues related to transport processes and gravity waves will be distributed to various chapters (**Simon Chabrillat** and **Nedjeljka Žagar** led the discussion on these issues at the meeting). There were also a large number of poster presentations that stimulated discussion.

At the meeting it was also decided that the project would focus solely on reanalyses (although some chapters may include diagnostics from operational analyses). Therefore, we decided to slightly rename the

Table 4: Available global atmospheric reanalysis datasets:

Reanalysis Centre	Name of the Reanalysis Product
ECMWF	ERA-40, ERA-Interim, [ERA-20C], [ERA-SAT]
NOAA/NCEP	NCEP/NCAR (R-1), NCEP/DOE (R-2), NCEP-CFSR
JMA	JRA-25/JCDAS, [JRA-55]
NASA	MERRA, [MERRA-2]
NOAA – CIRES	20CR

project to the SPARC Reanalysis Intercomparison Project, (*i.e.*, "analysis" has been dropped from the name suggested in the original proposal). For most of the chapters, we will compare newer reanalyses, *i.e.*, MERRA, ERA-Interim, JRA-25/JCDAS, NCEP-CFSR, and 20CR. We also aim to include JRA-55, ERA-20C, ERA-SAT, MERRA-2, etc., when available. Some chapters may include older reanalyses such as R-1, R-2, and ERA-40, because they have been heavily used in the past and are still being used for certain studies, and to gain insight into potential shortcomings of past research results. At the beginning of each chapter an explanation will be given as to why specific reanalyses were included/excluded. The intercomparison period is 1979-2012, *i.e.*, "the satellite era," but some chapters will also consider the pre-satellite era before 1978.

On the first day of the meeting, before starting the chapter discussion, there were seven presentations by reanalysis centres. **David Tan** presented introductory comments on reanalyses and then talked about both the JMA's activities (JRA-25/JCDAS and JRA-55), on behalf of Yayoi Harada, and the ECMWF's activities (ERA-Interim, ERA-20C, ERA-SAT, etc.). **Craig Long** presented NOAA's activities (R-1, R-2, CFSR, and 20CR), while **Paul Berrisford** presented routine diagnostics activities for various reanalyses carried out at ECMWF. **Steven Pawson** presented NASA's activities (MERRA and MERRA-2) remotely. **Adrian Simmons** discussed detailed comparisons of MERRA and ERA-Interim temperatures and assimilated observations.

S-RIP Report outline

The chief outcome of the meeting was the drafting of plans for Chapters 2-11 of the S-RIP final report. These plans are briefly summarized as follows:

Chapter 2. Description of the reanalysis systems

This chapter shall include a detailed description of the forecast model, assimilation scheme and observational data assimilated for each reanalysis, together with information on each reanalysis "stream" and on what data are archived.

Chapter 3. Climatology and interannual variability of dynamical variables

A climatology of major dynamical variables, created from an ensemble of the newer reanalyses for the period 1979-2012 (1979-2001, allowing comparison with ERA-40, in the appendix) will be created on both standard pressure levels and potential temperature levels. Various key plots of the ensemble climatological means and individual reanalysis anomalies from these means will be created and presented in an online atlas. Inter-reanalysis variations will be quantified. Observations for validation include radiosondes, lidars, rocketsondes and various satellites, whose data were not assimilated in the reanalyses.

Chapter 4. Climatology and interannual variability of ozone and water vapour

This chapter will include a detailed evaluation of ozone and water vapour in the reanalyses using a range of observations obtained from sonde, aircraft, and satellite instruments. The diagnostics considered will include climatological evaluations, seasonal cycles, interannual variability, and trends. Other, more event-based diagnostics such as the tape recorder, QBO, and polar dehydration will be used to understand differences in the climatological evaluations, while detailed analysis of these processes will be covered in the "advanced" chapters.

Table 5: List of chapters and names of co-leads:

	Title	Co-leads
1	Introduction	Masatomo Fujiwara, David Jackson
2	Description of the Reanalysis System	Masatomo Fujiwara, David Tan, Craig Long
3	Climatology and Interannual Variability of Dynamical Variables	Craig Long, Masatomo Fujiwara
4	Climatology and Interannual Variability of Ozone and Water Vapour	Michaela Hegglin, Sean Davis
5	Brewer-Dobson Circulation	Thomas Birner, Beatriz Monge-Sanz
6	Stratosphere-Troposphere Coupling	Edwin Gerber, Yulia Zyulyaeva
7	ExUTLS	Cameron Homeyer, Gloria Manney
8	TTL	Susann Tegtmeier, Kristin Krüger
9	QBO and Tropical Variability	James Anstey, Lesley Gray
10	Polar Processes	Monica Santee, Alyn Lambert
11	USLM	Diane Pendlebury, Lynn Harvey
12	Synthesis Summary	Masatomo Fujiwara , David Jackson

In addition, relevant information on the assimilated ozone and water vapour, and the prognostic representation of these fields in the reanalyses will be summarized.

Chapter 5. Brewer-Dobson circulation

This chapter will evaluate stratospheric circulation using diagnostics such as the age-of-air (mean age and spectrum), metrics for the strength of mixing barriers, and residual circulation quantities. Tendencies for heat and momentum as well as analysis increments will be considered. Eulerian chemistry transport models and trajectory calculations will be used. Results will be validated against satellite, ground-based, balloon, and aircraft observations of SF_6, CO_2, and NO_2, including the recent MIPAS data sets. Both climatological results and trends in the main diagnostics will be examined.

Chapter 6. Stratosphere-troposphere coupling

This chapter covers two-way coupling between the troposphere and stratosphere, focusing in particular on extra-tropical coupling on daily to intraseasonal time scales, and how this shorter-term variability is modulated on interannual time scales (*e.g.*, by ENSO). The chapter will synthesize and compare established approaches with more recent metrics to characterize planetary wave coupling and blocking, coupling of the zonal mean flow (*e.g.* the annular modes), and the mechanism(s) connecting the stratosphere and troposphere (*e.g.*, changes in tropopause height). There has been recent discussion on how to best characterize Stratospheric Sudden Warmings (SSWs). The established and alternative definitions of SSWs and the resulting impact on diagnostics of stratosphere-troposphere coupling will be explored.

Chapter 7. Extra-tropical UTLS

The diagnostics to be produced will include various tropopause identification methods, multiple tropopauses, the tropopause inversion layer, UTLS jet characterization, estimates of horizontal boundaries between the ExUTLS and TTL, trajectories, and Rossby wave breaking. This chapter will also have a section that reviews common diagnostics for the ExUTLS and TTL.

Chapter 8. TTL

The diagnostics shall include the general TTL structure (cold point and lapse rate tropopause, *etc.*), clouds and convection (cloud fraction profiles, OLR, *etc.*), diabatic heat budget, transport (Lagrangian cold point, residence time based on vertical winds and heating rates, *etc.*), wave activity, and long-term changes (*e.g.*, tropical belt widening).

Chapter 9. QBO and tropical variability

Diagnostics for this chapter will include analysis of the tropical QBO, its extra-tropical teleconnections (as well as other relevant teleconnections such as with ENSO and the solar cycle), its zonal momentum budget, and spectral characteristics of tropical waves including modal analysis and equatorial wave energetics. Observations for validation include operational and campaign radiosondes, rocketsondes, and satellites such as HIRDLS and SABER. Information regarding non-orographic gravity wave parameterization (if present) and analysis increments may also be utilized.

Chapter 10. Polar processes

This chapter will cover the formation of polar stratospheric clouds, chlorine activation, denitrification and dehydration, and (possibly) chemical ozone loss in the lower stratospheric winter polar vortices. Focus will be on process-oriented and case studies. The chapter will also include a review of previous works showing significant biases in lower stratospheric temperature, winds, or vortex strength/structure/evolution rendering some reanalyses (*e.g.*, R-1, R-2, and ERA-40) unsuitable for polar process studies.

Chapter 11. USLM

This chapter will look at diagnostics including the Semi-Annual Oscillation, climatology of the winter polar vortex, SSWs focusing on stratopause evolution and mesospheric cooling, various waves (tides, two-day wave, and normal modes), inertial instability of the tropical stratopause, and Hadley circulation of the stratopause region. Observations including SABER, MLS, the NDACC database, and CMAM20 (a model nudged to reanalysis), will be used for validation purposes and to extend our knowledge of the state of the middle atmosphere. NOGAPS–ALPHA may also be considered for case studies.

Overview of the project schedule

We shall finalize the "basic" chapters (*i.e.*, Chapters 1-4) within 2 years. The "advanced" chapters (5-12) will evolve slightly more slowly, with an interim report every year. We will have dedicated S-RIP meetings every year and side-meetings at various occasions.

We welcome your contributions to this project. Please contact the authors of this article and/or the co-leads of the relevant chapters directly. Up-to-date information will be made available through the S-RIP website (temporally at **http://wwwoa.ees.hokudai.ac.jp/~fuji/s-rip/**).

Acknowledgments

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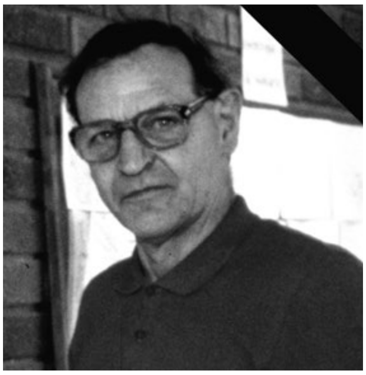
References

Fujiwara, M., S. Polavarapu, and D. Jackson, 2012: A proposal of the SPARC Reanalysis/Analysis Intercomparison Project. *SPARC Newsletter*, **38**, 14-17.

SPARC CCMVal, 2010: SPARC Report on the Evaluation of Chemistry-Climate Models. V. Eyring, T. G. Shepherd, D. W. Waugh (Eds.). SPARC Report No. 5, WCRP-132, WMO/TD-No. 1526.



Joe Farman
† 11 May 2013

Joe Farman, the leader of the team which first reported the existence of the Antarctic Ozone Hole, passed away on Saturday 11th May 2013. The publication of this finding in *Nature* was a truly seminal moment in atmospheric science, by the then almost unknown team of Joe, Brian Gardiner, and Jonathan Shanklin at the British Antarctic Survey (BAS). The immediate reaction of most active researchers was disbelief – even if the observations were right, the proposed link to the degradation products of chlorofluorocarbons (CFCs) seemed unlikely, to put it mildly. However, what was not immediately realised was the level of care that had been put into ensuring that the ozone measurements were correct, or that the simultaneous meteorological measurements (also started in 1957) showed no major dynamical change during the period when the Antarctic spring ozone values were declining so rapidly. Chemistry had to be the cause – and yet it surely couldn't be! Their careful analysis of the measurements was soon confirmed and within a remarkably short period the main chemical processes had been elucidated by the international community.

Joe's career seems very unorthodox from a modern perspective. Prior to the Nature paper, Joe had been working quietly with just two scientific publications in the 29 years since he had joined BAS, having been lured from de Havilland Propellors (where he worked on missile guidance systems) by the prospect of Antarctica. After the Nature paper, he immediately moved into a very prominent position, both scientifically and publically. His character did not change – working with Joe was always both rewarding and frustrating – but, for a private man, he showed a remarkable facility for dealing with the press, the political world and the public. His impact here was based on his scientific integrity. He did not like anyone making claims they could not back up. That included himself – while he was an excellent critic, he often struggled to come up with suggestions that he was happy with. Presumably this was one of the reasons that the Nature paper took a while to emerge. The brave and unambiguous link of ozone depletion to CFCs made in that paper could only be proposed because all other options had been considered and rejected.

After Joe retired from BAS in 1990, he joined us in the European Ozone Research Coordinating Unit. For the following 23 years he came in nearly every day, following the development of polar ozone loss in each Arctic and Antarctic winter. He made important contributions to the European Arctic Stratospheric Ozone Experiment and subsequent pan-European field campaigns exploring ozone loss. He also provided sage advice on all aspects of the stratospheric ozone research programme in Europe, which was often a valuable counterpoint when dealing with the European Commission and various national interests.

A service to mark Joe's passing was held in the chapel of his much-loved Corpus Christi College, Cambridge, where he studied as an undergraduate and was later a Fellow and Honorary Fellow. He is survived by his wife Paula, whom he met in 1959. He will be greatly missed by those who knew him, and his life will be honoured and remembered by many for years to come.

By Neil Harris and John Pyle

SPARC meetings

18-20 September 2013
Ozone Profile Trends (Si2N) Review Meeting, Helsinki, Finland

26-27 September 2013
Stratospheric Temperature Trends, Reading, UK

28-30 October 2013
Stratospheric Sulfur and it's role in Climate (SSiRC), Atlanta, Georgia, USA

12-17 January 2014
5th SPARC General Assembly, Queenstown, New Zealand

19-21 January 2014
SPARC Scientific Steering Group meeting, Queenstown, New Zealand

SPARC-related meetings

26-27 July 2013
ACCESS XII - Twelfth Atmospheric Chemistry Colloquium for Emerging Senior Scientists, Upton, NY, USA

28 July - 2 August 2013
Gordon Research Conference for Atmospheric Chemistry, West Dover, VT, USA

25-30 August 2013
Goldschmidt 2013, Florence, Italy

26-31 August 2013
IAGA 2013 Scientific Assembly, Mérida, Mexico

26-30 August 2013
International Technical Meeting (ITM) on Air Pollution Modelling and its Application, Miami, USA

8-20 September 2013
NCAS Climate Modelling Summer School 2013, Oxford, UK

9-13 September 2013
ESA Living Planet Symposium 2013, Edinburgh, UK

4-7 November 2013
International Conference on Regional Climate - CORDEX 2013, Brussels, Belgium

11-15 November 2013
First COSPAR Symposium, Bangkok, Thailand

9-13 December 2013
AGU Fall Meeting 2013, San Francisco, CA, USA

www.sparc-climate.org/meetings/

SPARC General Assembly 2014

12-17 January 2014
Queenstown, New Zealand

www.sparc2014.org

Important Dates

Registration opens: **1 July 2013**
Early-bird registration closes: **1 October 2013**
Standard registration close: **8 December 2013**