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SPARC

Stratospheric Processes And their Role in Climate

Core project of the World Climate Research Programme

www.sparc-climate.org

40 SPARC scientists from the Brewer-Dobson Circulation workshop (see summary this issue) held in Grindelwald, Switzerland, June 2012, visited the Sphinx observatory on the Jungfraujoch (3571m) in the Swiss Alps, a UNESCO World Heritage site. The Sphinx is a high-altitude, international research station and hosts scientists from more than 20 different research institutions every year, investigating topics in astronomy, meteorology, atmospheric chemistry, and medicine. Photo courtesy Michaela Hegglin.

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WMO
IOC
ICSU International Council for Science

Report on the 33rd Session of the Joint Scientific Committe of the World Climate Research Programme 17-20 July 2012, Beijing, China

Johannes Staehelin[1], Greg Bodeker[2], Ted Shepherd[3]

[1]SPARC Office, Zurich, Switzerland, johannes.staehelin@env.ethz.ch, [2]Bodeker Scientific, New Zealand, greg@bodekerscientific.com, [3]University of Reading, UK, theodore.shepherd@reading.ac.uk

A. Busalacchi (chair of the JSC (Joint Scientific Committee), which coordinates research within the WCRP) opened the meeting, welcoming all participants and thanking the local organisers. He thanked the Projects and Working Groups (WGs) for their continued efforts, particularly the project and WG chairs that are rotating off at the end of the year.

H.-J. Wang gave a brief overview of the work of the Chinese Academy of Sciences, of which the Institute of Atmospheric Physics contributes significantly to the objectives of the WCRP. **H. Liao** thanked all participants of the joint **China-WCRP Symposium** that took place the day prior to the JSC meeting, and she reported on the main findings that the Chinese scientists presented at this symposium.

G. Asrar, Director of the WCRP Joint Planning Staff, presented an overview of recent high-profil WCRP activities. He also pointed out that the WCRP and its core projects strongly support students and early career scientists in their activities, *e.g.*, by supporting participation at workshops and conferences. The budget of the JSC is secured for the next few years, as are those of the International Project Office of the individual core projects. A. Busalacchi thanked G. Asrar and his team for their important work for the WCRP.

At the extraordinary session of the JSC after the OSC (Open Science Conference) in Boulder, Colorado, USA (October 2011), the JSC made its final decision regarding the new structure of the WCRP (**Figure 1**). The four core projects obtained new mandates and two new councils were created. Three working groups are in place, and a new Working Group on Regional Climate (WGRC) is planned. The six Grand Challenges (GCs) are important elements of the new structure.

New WCRP advisory councils

J. Mitchell discussed the outcome of the first **WMAC** (WCRP Modelling Advisory Council) meeting, which took place prior to the JSC meeting. The role of the WMAC is to regularly assess modelling capabilities within the WCRP, to identify gaps, overlaps and opportunities for synergies, to advise on modelling priorities across the WCRP, to support communication on modelling within the WCRP and the broader community, as well as to promote model development, evaluation and applications. It was decided that the WMAC should collaborate with IGBP to form a task team on Earth system prediction.

O. Brown presented the outcomes of the first **WDAC** (WCRP Data Advisory Council) meeting, which took place in parallel to the WMAC meeting. WDAC is tasked with serving as a focal point for observations and data within the WCRP, and is to advise the JSC and to coordinate between WCRP projects and WGs. WDAC is not intended to be directly involved with the activities of the core projects. The Council also discussed the inventory of Essential Climate Variables (ECVs) proposed at a recent meeting in Frascati, Italy, which was sponsored by the WCRP and GCOS (see below).

WCRP Grand Challenges

The main characteristics of a WCRP Grand Challenge (GC) were define as:

- A Grand Challenge is both **highly specifi** and **highly focused**, identifying a specifi barrier preventing progress in a critical area of climate science.
- This focus enables the development of **targeted research efforts** with the likelihood of significant progress over 5-10 years, even if its ultimate success is uncertain.
- It should thus enable the implementation of effective and **measurable performance metrics.**
- By being transformative, a Grand Challenge should bring the **best minds** to the table voluntarily, building and **strengthening communities of innovators that are collaborative**, perhaps also extending beyond

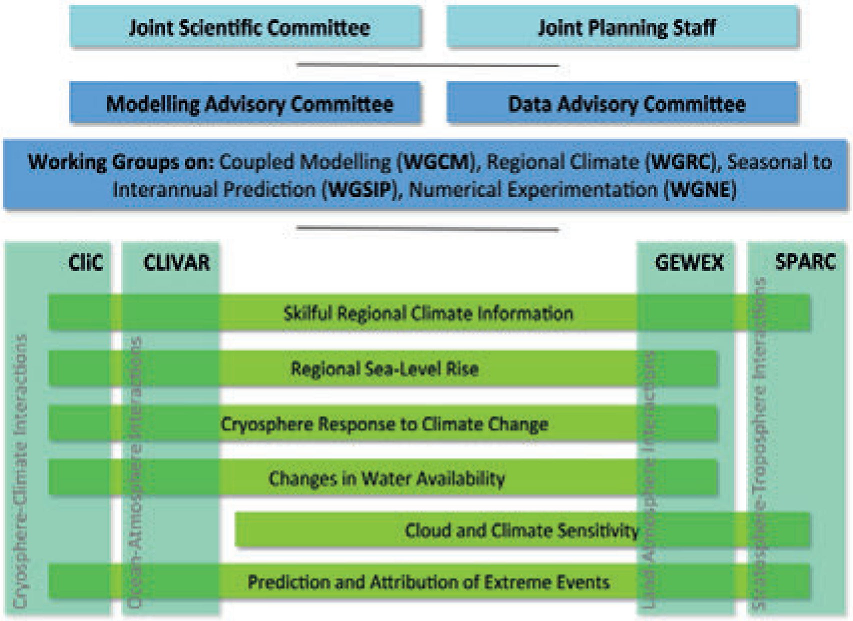


Figure 1: New organisational structure of the WCRP (including updated names of the Grand Challenges (horizontal green bars)).

"in-house expertise".

- It can **capture the public's imagination**: teams of world-leading scientists working to solve pressing challenges can offer compelling story-lines to capture the interest of the media and public.

F. Giorgi presented the GC on "Provision of Skilful Future Climate Information on Regional Scales", which included decadal and polar predictability. Five scientific obstacles were identified

1. Intraseasonal and seasonal predictability and prediction,
2. Decadal variability, predictability and prediction,
3. Reliability and value of long-term regional climate projections,
4. Interactions across the multiplicity of drivers and feedbacks at the regional scale,
5. Definition of usefulness when informing risk management and decision makers.

The scientific challenges include: creating and using observational data sets at regional and local scales; extracting predictable signals from the data; assessing global *vs.* local forcings; combining multi-model, multi-method information to characterize uncertainties; developing information relevant to societal sectors and co-exploration with stakeholders; and capacity development.

Four examples of focused research themes presented were polar climate predictability, monsoon systems, development of techniques to extract regional information from multi-model ensembles, and extremes. In the discussion it was recommended that the main scientifi challenges be separated into sub-tasks to support climate services. Four such initiatives are: intraseasonal to seasonal to interannual prediction, decadal prediction, long-term regional climate information, and polar climate predictability.

The involvement of stakeholders as well as the necessity of being interdisciplinary was emphasised. It was decided that CLIVAR will lead the first two initiatives (intraseasonal to seasonal to interannual prediction and decadal prediction), and long-term regional climate information would be supported in the initial phase by the WGRC. SPARC will continue to lead the development of polar climate predictability and this initiative will be moved to the GC on "Cryosphere". "**Skilful regional climate information**" was recommended as a new name for this GC.

K. Steffen presented the GC on "**Regional Sea-Level Rise**". Recent projections of global sea-level rise for 2100 span 20cm to 2m, and sea level is expected to rise further in the following centuries. Satellite data measurements indicate that global average sea level has risen by 2.5mm/yr since 1993. Current numerical models largely disagree in their projections of the regional pattern of sea-level changes. The causes for such inter-model discrepancies include:

- Regional sea-level rise is influenced to a large degree by the redistribution of temperature and salinity in response to changing winds,
- Local effects (*e.g.*, from shelf dynamics) can confound the interpretation of the data in certain areas,
- Atlantic meridional overturning and gyre circulations are important in some regions,
- Cryospheric contributions to global sea-level rise could be masked by several local effects.

The following scientific priorities were identified

- Reduce uncertainties in solid-Earth and gravity models used for predictions/projections,
- Improve estimates of the relative contributions of climate modes to sea-level variability,

- Assess climate modes in climate models and observations, and separate climate modes from long-term trends,
- Investigate the degree of decadal variability in sea-surface height observations and forecasts,
- Determine the contribution of wind relative to other factors affecting regional sea-level variability and long-term changes.

In the discussion it became clear that this GC necessarily includes global as well as regional aspects. CLIVAR will lead the GC in close collaboration with CliC and GEWEX. Activities of the WCRP-IOC (Intergovernmental Oceanographic Commission) sea-level cross-cut should also be integrated into this GC.

V. Kattsov began his presentation on the GC on "**Cryosphere Response to Climate Change**" by introducing its motivations, *i.e.*, to understand the prospect of an ice-free Arctic Ocean, changes in the seasonality of water supply for large populations due to melting glaciers, the feedback between climate warming and the release of greenhouse gases from permafrost thawing, and the role of ice-sheet dynamics in contributing to global sea-level rise.

The overall goal would be to promote targeted research for improving understanding of cryospheric processes and related feedbacks. Several areas for research were mentioned, including:

- Confidence in model predictions of cryospheric changes, including regional aspects,
- Improvement of information for decision-makers relevant to impact assessment and adaptation (*e.g.*, timing of the Arctic multi-year sea ice disappearance, more comprehensive observations, better quantificatio of feedbacks).

Focused science topics might cover:

- Seasonal, interannual and long-term predictions and projections of polar climate, with particular focus on the role of the cryosphere in climate predictability,
- Analysis of model inter-comparison results to better understand and attribute model biases related to the cryosphere,
- Permafrost representation and high-latitude land surface (*e.g.*, wetlands) in model descriptions, particularly looking at their role in the global carbon cycle,
- Development of ice sheet models, with specific emphasis on the role of ice sheet dynamics in the rate of sea-level rise.

It was recommended that focused research topics with goals that could be reached within a time horizon of about five years be identified. "**Cryosphere in a Changing Climate**" was suggested as a new name. The polar climate predictability part of this GC is to be co-ordinated by SPARC (moved from the regional climate GC). Co-ordination with communities not directly involved with the WCRP was also recommended.

T. Nakajima presented the GC on "**Improved Understanding of the Interactions of Clouds, Aerosols, Precipitation and Radiation and their Contributions to Climate Sensitivity**", pointing out the important role of aerosols in climate and climate change, as well as related uncertainties. These uncertainties include interactions between aerosols and hydrometeors, direct and indirect effects on radiative forcing, and interactions with clouds; all of which contribute to uncertainty in climate sensitivity. There was a consensus that the WCRP should focus on aerosol-cloud interactions. **J. Syvitski** pointed out that the IGBP is also interested in aerosol-climate interactions and suggested co-ordinating this GC with IGAC. K. Trenberth highlighted that studies relevant to aerosol-climate interactions are already being carried out in GEWEX. It was recommended that the title be changed to "**Clouds and Climate Sensitivity**". **S. Bony** was asked to lead a revision of the GC White Paper to focus on the role of clouds and the large-scale distribution of precipitation within climate, to better align this GC with the core competencies of the WCRP, with contributions from GEWEX, WGCM, WGNE and GEWEX/GASS. WGCM will coordinate the GC, with assistance from GEWEX for management. SPARC will take care of the aerosol aspects, in close co-ordination with GEWEX, IGAC, iLEAPS and AeroCom.

K. Trenberth introduced the GC on "**Past and Future Changes in Water Availability**" (with connections to water security and the hydrological cycle) by highlighting the key role of water in sustaining life. Several key science questions were identified

- What is the quality of precipitation data with respect to various observing systems and their measurement deficiencies, as well as model data (*e.g.*, deficiencies related to model parameterizations)?
- How will changes in climate affect the characteristics of precipitation, with particular emphasis on extreme events (droughts and floods)
- How can models be improved and how much confidence do we have in model performance (including predictions and projections)?

- How large is the influence of land-surface change on past and future water availability and security?
- How can new observations lead to improvements in water management?

He further discussed recent improvements in observational data sets, including precipitation and soil moisture measurements from current and planned satellite instruments as well as from in situ data. The effects of changes in land surface and hydrology on the past and future water cycle were also addressed, including questions regarding terrestrial water storage. The challenge is to provide information that can be used to better evaluate the vulnerability of water systems and to increase resilience to changes, particularly in extremes, through good management and governance. The title of the GC was changed to "**Changes in Water Availability**". The white paper was endorsed but it was recommended that more emphasis be put on regional aspects. GEWEX will coordinate this GC.

D. Karoly began his presentation of the GC on the "**Science Underpinning the Prediction and Attribution of Extreme Events**" by highlighting the large impact of extreme events on society. Extreme events occur on many temporal and spatial scales, and their frequency and intensity are affected by climate variability (through factors such as ENSO and the NAO), and climate change. The challenges cover availability and reliability of measurements, related modelling and attribution to climate change, as well as proper provision of information for decision makers. Targeted research is expected to improve our understanding and prediction capabilities.

In the discussion it was noted that several aspects of the proposed GC are covered by other GCs and it was suggested that more feedback be obtained from the individual WCRP projects to improve the focus of each initiative. The new title of the GC will be "**Prediction and Attribution of Extreme Events**" and it will be led by GEWEX. The Expert Team on Climate Change Detection and Indices will continue its work within CLIVAR and will possibly contribute by leading certain initiatives.

To implement the GCs, the lead organisations have been tasked with running focused workshops within the next year in order to collate input from the wider community and to identify specific work packages

Core project reports

G. Bodeker, co-chair of SPARC, started his presentation (made jointly with **T. Shepherd**, also co-chair) by noting the SPARC imperatives:

- Improve models through comparison with measurements,
- Improve the use of model information through model assessment and diagnostic analysis,
- Improve reanalyses,
- Improve observational records through assessment of data products and development of climate records,
- Serve user needs.

He presented an overview of current and emerging SPARC activities, one of which is a collaborative project with IGBP/IGAC: the IGAC-SPARC Chemistry Climate Modelling Initiative (CCMI) that focuses on both stratospheric and tropospheric chemistry modelling (this is also in line with the new SPARC mandate, extending focus to tropospheric processes that link to the stratosphere). This new initiative replaces the Atmospheric Chemistry and Climate (AC&C) activity. SPARC has also taken the lead in planning the WCRP Polar Climate Predictability Initiative, for which an implementation plan is in preparation. A workshop regarding this initiative was held in Toronto in April 2012. While the discussion at this workshop was much broader than just polar climate predictability, the JSC felt that polar climate predictability should be the main WCRP contribution. It was suggested that the relationship with the WMO-WWRP (World Weather Research Programme) Polar Prediction Project be more clearly define upon completion of the strategy for the climate component by the WCRP-sponsored task team, before a scientific steering committee be selected. Finally, G. Bodeker indicated that the SPARC community did not support a change of the SPARC acronym, but recommended rather a change in the name, namely Stratosphere-troposphere Processes And their Role in Climate, while maintaining the existing acronym. A new logo that highlights the extension of SPARC's interests into the troposphere is also planned.

M. Visbeck, co-chair of CLIVAR (Climate Variability and Predictability), pointed out that CLIVAR is a very large project and noted that regional aspects have been important to CLIVAR from the beginning. Scientific co-ordination within the project is achieved by several panels and working groups. He presented an overview of some recent progress regarding anthropogenic climate change, intra-seasonal, seasonal and decadal climate variability and predictability, improved atmosphere and ocean components of climate models, data synthesis and analysis, ocean observing systems, and education and capacity development. The JSC suggested that CLIVAR should critically reevaluate its research agenda taking into account the GCs and the new WCRP structure. The new mandate of CLIVAR is the "interface between ocean and atmosphere". At its recent SSG meeting, CLIVAR started the construction of a "new" CLIVAR focusing on the following key topics:

- Intra-seasonal, seasonal and interannual variability and predictability of monsoon systems,
- Decadal variability and predictability of ocean and climate variability,
- Trends, extreme events and nonlinearities,
- Marine biophysical interactions and upwelling systems,
- Dynamics of regional sea-level variability.

These themes are presently being discussed within the panels and working groups. A proposed new "matrix" structure is planned to be fully implemented (in consultation with the wider community) in 2014. M. Visbeck also mentioned that CLIVAR's current procedure for openly asking for new SSG nominations through the newsletter and website was very successful.

K. Steffen, chair of CliC (Climate and Cryosphere), reviewed CliC's past mission statements and research themes. He also presented the priorities of CliC:

- Changes of ice sheets and glaciers with respect to climate variability and climate change – impacts on global sea level,
- Polar climate predictability,
- Cryospheric inputs to the Arctic and Southern Ocean freshwater budgets,
- The role of carbon and permafrost in climate systems,
- Sea-level rise, including observations, modelling and data products,
- Changes in mountain cryosphere and water resources (through the Asian and South American branches of CliC),
- Global snow cover.

These topics fit very well into the GC on "Cryosphere in a Changing Climate". It was suggested that CliC should also include more modelling activities, and that the role of its SSG should primarily be advisory, whereas working groups should be formed to carry out the scientifi activities.

K. Trenberth, chair of GEWEX (Global Energy and Water Exchange), began his presentation by reviewing the post-2013 GEWEX mission statements as well as GEWEX's imperatives:

- Data: development of relevant climate data records (atmosphere, water, land, and energy related quantities),
- Analysis: studies of observed variations, trends and extremes in water- and energy-related data sets,
- Processes: improve scientifi understanding of processes in water and energy cycles particularly regarding land and atmosphere models,
- Modelling: improve simulations on global as well as regional scales, and predictions of precipitation, clouds, and land hydrology,
- Applications: study the causes of variability, trends and extremes (in collaboration with the wider WCRP community),
- Technology transfer,
- Capacity development.

He reviewed the current activities of the GEWEX panels: GEWEX Data and Assessment Panel (GDAP), GEWEX Hydro-climatology Panel (GHP), GASS (Global Atmosphere System Study) and GLASS (Global Land Atmosphere System Study). The latter two panels have strong collaboration with NWP (Numerical Weather Prediction) via WGNE.

GEWEX identified the following critical questions:

- How to improve understanding and prediction of precipitation variability and changes?
- How do changes in land surface and hydrology influenc changes in water availability and security?
- How does global warming affecting climate extremes (droughts, floods and heat waves), and how do land processes contribute to the expected changes?
- How can the understanding of these effects be improved, and how can uncertainties be reduced in current and future climate models?

K. Trenberth pointed out that new data sets and synthesis activities are expected to provide significant opportunities for improving our understanding of the water and energy cycles.

Working groups

S. Bony (co-chair) noted that in its recent work, the WGCM has focused on CMIP5 (Coupled Model Intercomparison Project 5), in which 26 modelling groups are participating. Analyses presented at a recent CMIP5 workshop in Hawaii (March 2012) included results from 22 AOGCMs (Atmosphere-Ocean General Circulation Model), 4-8 decadal prediction simulation sets, about 6 high-top models, and 3-8 Earth System Models (ESMs) with coupled carbon cycles. The spread of future projections appears not to be larger than that from the CMIP3 AOGCMs, despite the greater complexity of the new generation of AOGCMs. Most of the ESMs showed results comparable to the AOGCMs. Compared to earlier studies, some quantities are represented considerably better (*e.g.*, rate of sea ice loss in the Arctic), and others exhibit a decrease in the model spread (*e.g.*, for the Atlantic Meridional Overturning Circulation), whereas for some quantities no significant improvement has been found (*e.g.*, double ITCZ, Arctic clouds and atmospheric circulation, Antarctic sea ice loss, etc.). S. Bony indicated that the community is at the point where significant progress in the prediction of the distribution of clouds, precipitation and related large-scale circulation patterns can be made. She also pointed out that CMIP5, in combination with new observations and Global Cloud Resolving Models, would provide an opportunity for the WCRP to take the lead in this important research area through the implementation of the GC on "Clouds and Climate Sensitivity".

F.J. Doblas-Reyes explained that one of the main objectives of WGSIP (Working Group on Seasonal to Interannual Prediction) is to make predictions and projections at scales from short-term weather forecasts through to multi-decadal and centennial time scales in a "seamless" way. The WGSIP terms of reference were updated since the group no longer reports to CLIVAR but rather to the JSC directly. F.J. Doblas-Reyes reported that WGSIP has contributed to the planning of the WWRP Polar Prediction Project and the WCRP Polar Climate Predictability Initiative. WGSIP has also been involved in many IPCC-related meetings. The following topics will be discussed at a workshop planned jointly with WGCM for early 2013:

- A review of climate prediction in general and in particular the results of the Climate Historical Forecast Project (CHFP, "flagship" of WGSIP) and the Decadal Prediction component of CMIP5,
- Bringing seasonal forecasting and climate modelling communities together to discuss formulation of models, assessments of forecast, initialisation, etc.

Planned experiments of the CHFP include (i) land surface (GLACE2 experiment), (ii) stratosphere (Stratospheric Historical Forecast Project), and (iii) Sea ice (Ice Historical Forecast Project). WGSIP has experience using current ocean observations and climate models to produce regional climate predictions on different time scales (seasonal, intra-seasonal and decadal) and is prepared to make an important contribution to the GC on "Skilful Regional Climate Information". WGSIP will also provide input for the GCs dealing with the cryosphere, water availability and extremes.

C. Jakob began his presentation with a short review of the WGNE (Working Group on Numerical Experimentation, a joint working group of WMO's CAS and WCRP) terms of reference. He mentioned that WGNE liaises with numerous groups including operational NWP centres, the WCRP, WWRP and other WMO groups. He listed on-going and planned projects, including the Transpose-AMIP (Atmospheric Modelling Intercomparison Project, part of CMIP), which is testing climate models in NWP mode. Another WGNE project is the "Grey zone project" in which the range of model features that are neither fully-resolved nor parameterised are analysed. Results from a recent workshop on systematic errors suggested that errors in weather models are not that different from those of climate models. This workshop successfully found much common ground between the two communities. Key conclusions from another recent workshop held in Pasadena, USA, on model physics include: (i) funding for model physics development needs to be improved, (ii) long-standing issues (some of the old and well-known model biases) need to be focused on, (iii) working conditions for model development through links with academia should be improved (since operational and academic communities have different strengths) and recognition of this type of work should be enhanced, and (iv) better communication of outcomes and more positivity about this field are needed

F. Semazzi discussed the status of the WGRC (Working Group on Regional Climate). He and P. Yanda were tasked with producing a white paper summarizing and prioritizing the situation in Africa at the extraordinary JSC session in Boulder, October 2011. CLIVAR VACS (Variability of the African Climate System) is proposing a pan-Africa climate conference together with the African Climate Policy Centre (ACPC) to be held in Addis Ababa in October 2013. K. Trenberth presented a brief overview of regional aspects of GEWEX, while J. Hurell covered particular aspects of regional climate related to CLIVAR. A single monsoon panel was proposed. It was decided that regional aspects of the respective GCs should be put forward within the individual core projects wherever feasible, whereas WGRC should act as the interface with GFCS (see below). JSC plans to name the WGRC co-chairs shortly.

Other projects

F. Giorgi reported on **CORDEX** (COordinated Regional climate

Downscaling EXperiment), which will be integrated into the new WGRC. CORDEX aims to evaluate and improve RCD (regional climate downscaling) models and techniques to provide a co-ordinated set of RCD-based projections and predictions for different regions, as well as to facilitate dialogue and communication, particularly with the research community from developing countries. CORDEX has been very successful over the past year, with groups engaged in work in many regions. CORDEX has grown very fast and better mechanisms are needed to co-ordinate the activities between different parts of the project as well as across the wider CORDEX community. CORDEX data are also used for impact studies and the question was raised as to whether and how these activities should be supervised by CORDEX.

M. Manton explained that **START** promotes capacity building via support of regional research and assessments, as well as by providing education and improving knowledge for appropriate action. START has a regional structure with nodes in Africa, South-East Asia, Temperate East Asia, South Asia, and Oceania. START is also engaged with CORDEX and supports institutional capacity building. **G. Jia** presented an overview of activities of the START Temperate East Asia Regional Centre (TEA), which is located at the CAS Institute for Atmospheric Physics in Beijing. TEA pursues research foci such as integrated studies of the East Asian monsoon system and global change, and carries out comprehensive field studies. TEA research facilities include observation sites and a regional data system. M. Manton reported on MAIRS (Monsoon Asia Integrated Regional Study), which focuses on cross-disciplinary, regional-scale research involving stakeholder interests. He presented an illustrative example of drought impacts in Inner Mongolia, where the interaction with social scientists has been vital to understanding the overall situation. He also highlighted the important role of scientific papers that include authors from different countries. MAIRS aims to connect with the Future Earth initiative on the regional level.

B. Goswami summarized recent progress in **monsoon prediction**, much of which was highlighted at a conference on Opportunities and Challenges of Monsoon in a Changing Climate (OCHAMP-2012). This conference took place as part of the Golden Jubilee Year (1962-2012) celebrations of the Indian Institute of Tropical Meteorology (IITM) in Pune, India. Conclusions from the conference include: coupled models for monsoon prediction show measureable progress but still require further improvement; new observations are needed to improve cloud parameterisation schemes, one of the largest sources of model bias; and the influence of aerosol on the monsoon remains highly uncertain.

WCRP capacity development, communications and outreach plans

G. Asrar's presentation covered the building of research capacity in developing regions and communication of science to the public. He emphasized the important role of training and educating students and early career scientists, particularly from developing countries, in a sustainable way. He mentioned the many capacity development efforts carried out by the WCRP, providing examples such as CORDEX and START. He added that the WCRP will continue to actively search for new financial resources to support capacity building, for example through discussions with the WMO. He also reported that the JSC urged the secretariat to improve WCRP communication with the public and to improve outreach. It was suggested that experts of the core projects should join the JSC to discuss the endorsed document.

Planet Under Pressure Conference

J. Syvitski, chair of the IGBP (International Geosphere-Biosphere Programme), reported on the "Planet Under Pressure" (PUP) conference, the first international conference supported by all four Global Environment Change (GEC) programmes. A major outcome of PUP was the State of the Planet Declaration and 9 policy briefs, which were presented at the RIO+20 Conference. One of the main aims was to facilitate and promote longer-term discussions between GEC science and industry. Despite considerable partipication from industry, J. Syvitski observed that challenges in engaging GEC scientists and industry remained. It was mentioned that very little inter-disciplinary research was presented at PUP; and this is believed to be a real challenge for the Future Earth initiative.

Agency updates

R. Rosen reported on recent steps taken to better co-ordinate climate activities within NOAA (National Oceanic and Atmospheric Administration, USA). He described the new strategic plan of the US Global Change Research Program (USGCRP), of which NOAA makes up one of the 13 involved federal agencies. He reported that in its most recent review, the US National Academy of Science found that good progress had been made in science, but less so in societal issues, in comparison with earlier USGCRPs.

K. Sawyer gave a brief overview of CEOS (Committee on Earth Observation Satellites), which is a co-ordinating body of 30 members (including national space agencies) and 22 associate members (including WCRP and GCOS). CEOS co-ordinates space-borne Earth observations through co-operation of its members in mission planning and development of compatible data products, data policies, etc. CEOS also acts as focal point for international co-ordination. The mission of the Working Group Climate (WGClimate) aims to facilitate the implementation and exploitation of Essential Climate Variables (ECVs).

J. Schultz reported on the activities of EUMETSAT, aimed at generating climate data records from satellites. EUMETSAT contributes to climate monitoring through geostationary Meteosat data, as well as observations from the polar orbiting Metop satellites. EUMETSAT member states committed to the Third Generation of Meteosat, providing extensions of some observational records to more than 50 years by 2040. He also pointed out the important initiatives necessary for the proper processing of raw data, so that long-term satellite data are of climate quality.

Partner presentations

A. Simmons presented an overview of GCOS's (Global Climate Observing System, a joint undertaking of WMO, the United Nations Educational Scientific and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU)) activities. These include the designation of Essential Climate Variables (ECVs), the assessment of observing system adequacy and the identification of data requirements. GCOS works with many operational agencies, in particular meteorological services and related panels, including the Atmospheric Observation Panel for Climate (AOPC) - sponsored by GCOS and WCRP (participation through SPARC), the Terrestrial Observation Panel for Climate (TOPC) - sponsored by GCOS, WCRP (link through K. Steffen) and GTOS, and the Ocean Observing Panel (OOPC) – sponsored by GCOS and WCRP (representation by ex-officio member of CLIVAR). Recent GCOS activities include, amongst others, publication of a satellite supplement to the 2010 update of the implementation plan, liaising with CEOS, and contribution to the observational component of GFSC. A new implementation plan (due in 2015-2016) is presently being prepared.

J. Syvitski (IGBP chair) emphasised the key role of cooperation between the IGBP and WCRP within the Future Earth initiative. The present pillars of the IGBP include research and synthesis, the research-policy interface, as well as communication and outreach. Research foci were strongly related to the anthropocene concept and a new series of synthesis reports will be completed in 2013 (*e.g.*, Earth system impacts from changes in the cryosphere, Megacities in coastal zones, Geoengineering impacts, Nitrogen and climate, Air pollution and climate). A new focus of the IGBP is the planetary leadership for policy makers, however, he also highlighted the continued need for research in related natural sciences. He agreed that further integration is needed within the International Human Dimensions Program on Global Environmental Change (IHDP GEC), funded by ICSU and the ISSC (International Social Science Council). The most difficult part is the human dimension, since the social science agenda is not common with other GEC agendas. He also pointed out the importance of fundable science contributions. A closer collaboration between IGBP and WCRP was suggested, particularly concerning certain IGBP synthesis activities. Many interactions between the two programmes do, however, already exist at the project level. The JSC agreed to charge WMAC with the establishment of a task team to explore closer collaboration with the IGBP.

G. Brunet explained that the main aim of the WWRP (World Weather Research Programme of WMO) is to improve weather prediction. WWRP interacts with many partners, including WCRP, IGBP and GCOS. The joint sub-seasonal to seasonal prediction project aims to improve the collaboration and co-ordination between operational centres and to support certain international research activities. A few case studies are under consideration, *e.g.*, the Pakistan floods and concurrent heat wave in Russia (2010), or the Australian floods (2011). These studies should demonstrate the benefits of sub-seasonal prediction for society. He also provided an overview of the WWRP Polar Prediction Project. Plans are made for a "Year of Polar Prediction", tentatively scheduled for 2017-2018.

Sponsor initiatives

In his overview of the GFCS (Global Framework for Climate Services), **J. Lengoasa** (WMO) noted the need to translate scientific data into information that is understandable to users. A co-ordinated and integrated approach is important so as to enable user feedback. The main aims of the GFCS are to better manage the risks related to climate variability and change, and to promote adaptation to climate change based on scientific information. Pillars of the GFCS include a user interface platform, a climate service and information system, and capacity building. An implementation plan is in preparation and the assistance of the WCRP in this regard is appreciated. The initial foci are: food security and agriculture, water resource management, disaster risk reduction, and human health. These priorities are in agreement with the ICSU visioning process. J. Lengoasa noted that the WCRP GCs would provide key contributions to the GFCS. WCRP can also contribute through assistance with the user-interface by providing access to science-based climate information and by ensuring that research results are made readily available. The WCRP's contribution to capacity building is also welcome.

S. Wilson (ICSU) spoke about the Future Earth Initiative, which will play a vital role in addressing part of ICSU's mission statement, namely to strengthen international science for the benefit of society. He clarified that he was speaking on behalf of the Global Alliance for Future Earth, which includes ICSU, ISSC, funders including the Belmont Forum and several UN Organisations, as well as the WMO, which is engaged as an active observer. He recognised the potential of greater synergies between Future Earth and the GFCS. The purpose of the Global Alliance for Future Earth is to provide the knowledge necessary for societies to manage the risks originating from global change, and to find opportunities in realising global sustainability. New approaches, which are more international, inter-disciplinary and collaborative in nature, are required. Users, funders and scientists should also be involved in the design of the project. For this task a Transition Team was formed, with representatives from many different disciplines, sectors, regions and organisations. The transition team is also responsible for the development of an initial research framework, institutional design, as well as a strategy for outreach, education and stakeholder engagement. S. Wilson noted that the existence of the Alliance had already generated interest from the World Bank, which may open new funding avenues. Several concerns were expressed, however, including the fact that the process is very top-down in nature, there seemed to be a lack of sufficient engagement by the community, and there may be potential overlaps with GEC initiatives. The initiative is planned to start by 2014, since funding agencies would like to move ahead quickly.

W. Watson-Wright noted that the IOC (Intergovernmental Oceanographic Commission) of UNESCO is the focal point for ocean observations, science, services and data exchange within the UN system. The OceanObs'09 conference called for a framework for planning an enhanced and sustained global ocean observing system in which 'essential ocean variables' are key elements. This concept should lead to an "Integrated Observing System". She also highlighted the interaction between the IOC and the WCRP, mainly through CLIVAR, and urged the WCRP regional activities to participate more with the IOC regional sub-commissions and programmes in order to better connect with users.

Nomination process for SSG and WG members, closing of the meeting

A. Busalacchi presented the new procedure for the nomination of SSG and WG memberships: projects are asked to identify potential new members several months prior to the JSC meeting, so that discussion with the WCRP membership team would be possible. He then thanked all participants, particularly the JSC members rotating off, before closing the meeting.

The full WCRP meeting report is available at **http://www.wcrp-climate.org/documents/JSC33_Report_Final.pdf**.

SPARC Workshop on the Brewer–Dobson Circulation

25–29 June 2012, Grindelwald, Switzerland

Clara Orbe[1], Hella Garny[2], William Seviour[3]

[1]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA, clara.orbe@gmail.com, [2]Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany, hellagarny@gmail.com, [3]Department of Physics, University of Oxford, UK, seviour@atm.ox.ac.uk

The Brewer–Dobson circulation (BDC) has become a topic of increased importance in climate science as we develop a better understanding of its role in natural climate variability and potential response to climate change. Many fundamental questions about the BDC remain and it is still poorly constrained by observations. To re-examine our knowledge of the BDC, in terms theory and observations, the mechanisms driving it, and the potential chemical and dynamical impacts of changes in the BDC, a SPARC workshop was held in Grindelwald, Switzerland, from 25-29 June 2012.

The workshop was opened by **N. Butchart**, who reminded participants of the previous BDC workshop held in 1999 in Oxford, and reviewed developments since then. At the time of the last workshop only one general circulation model (GCM) had been used to study the effect of climate change on the BDC (Rind *et al.*, 1990), while today a large number of GCMs and chemistry climate models (CCMs) have been used for this purpose. Furthermore, he listed some of the outstanding questions to be addressed, including: How well is the BDC represented in reanalyses? How well do models reproduce interannual variability of the BDC? What role do gravity waves play in driving the BDC? How well do we understand the mechanisms behind changes in the BDC that are consistently simulated by state-of-the-art global models? What evidence do we have from observations for changes in the BDC?

A. Plumb also presented an historical overview, reviewing several key studies that contributed significantly to our current understanding of the BDC. Dobson's study in 1929 (Dobson *et al.*, 1929) first suggested that poleward transport from the tropical stratosphere to higher latitudes existed, providing an explanation for the observed springtime maximum in Arctic ozone. However, it was not until further observational evidence accumulated in work by Brewer (1949) and subsequent studies, that the existence of such a circulation was accepted. Further work on the theoretical front provided a dynamical framework for understanding the key role played by eddies in forcing this circulation (Dunkerton, 1978). Specificall , the theory of downward control (Haynes *et al.*, 1991) contributed substantially to our understanding, as well as more recent research on the roles of both subtropical and high-latitude waves in driving stratospheric circulation. The current idealised picture of residual circulation is summarized in **Figure 2**, illustrating the branches of circulation associated with different wave breaking regions. A. Plumb concluded with a ques-

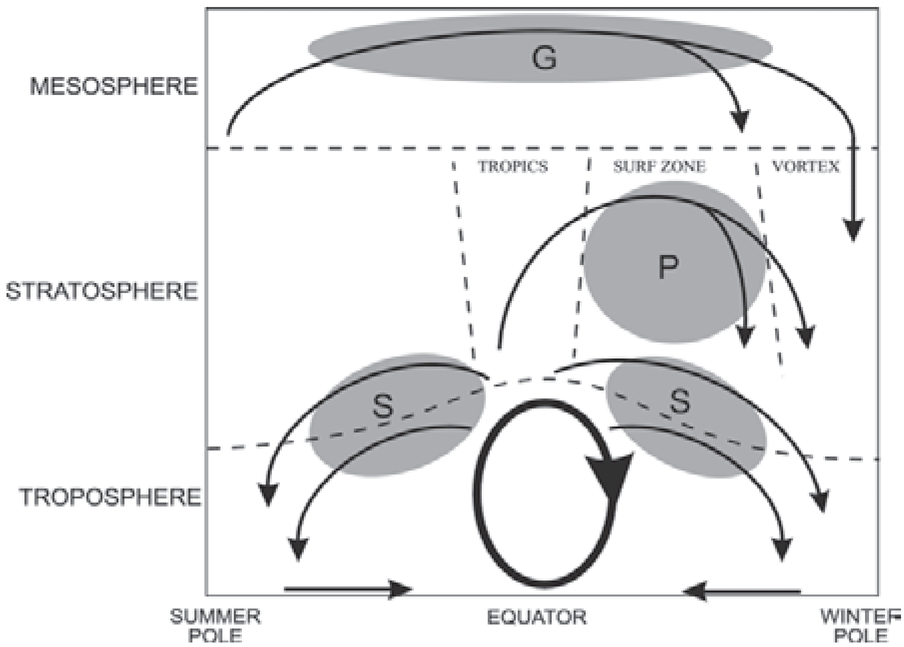


Figure 2: Schematic of the residual mean meridional circulation in the atmosphere. The heavy ellipse denotes the thermally-driven Hadley circulation in the troposphere. The shaded regions (labelled "S", "P", and "G") denote regions of breaking waves (synoptic-, planetary-scale and gravity waves, respectively), responsible for driving branches of the stratospheric and mesospheric circulation. After Plumb (2002).

tion that was frequently revisited throughout the workshop: "What do we really mean by the Brewer–Dobson Circulation? Is it the residual circulation, or the transport circulation, where the latter includes two-way mixing?"

M. Wallace complemented A. Plumb's review with a discussion on diagnosing different wave contributions to the BDC, namely tropical and high-latitude planetary waves and synoptic-scale waves associated with the tropospheric sub-tropical jet. He reviewed both "diagnostic" approaches, (*i.e.*, studies that explicitly calculate wave forcing using the downward control principle), and studies that use a more "empirical" approach. As an example of the latter, he illustrated new work by Grise and Thompson, (2012 submitted), which examines the correlations between tropical temperatures and upwelling, as well as wave fluxes and drag in different regions.

Drivers of BDC

While the troposphere is a source of wave driving for the stratosphere, background stratospheric winds control where these waves propagate and break. To address this issue, **E. Gerber** presented work on stratospheric versus tropospheric controls of the strength and vertical extent of residual and transport circulation in the context of an idealised GCM. Further work with a simplified model probed the interaction between gravity wave drag (GWD) and planetary waves, showing that the sum of the forcing is constrained, potentially explaining the fact that tropical upwelling estimates across models are similar despite large differences in the contribution of GWD versus resolved wave drag (as illustrated in **Figure 3**). Continuing on the role of gravity waves, **J. Alexander** gave an overview of how gravity wave (GW) fluxes are estimated from observations. She showed that observed climatological GWD is very well reproduced in both high-resolution GW-resolving models and lower resolution models with different GW parameterisations. There are exceptions, however, for example, the tendency for models to under-estimate sub-tropical wave drag. Trends can so far not be deduced from observations due to the limited temporal resolution of the data.

Independent studies by **R. Scott** and **R. Ueyama** suggested that, at least for planetary waves, the distinction between low- *vs*. high-latitude wave driving may be an artificial one. Specificall , R. Scott emphasised how the width of the surf zone distributes the effect of high-latitude planetary wave (PW) drag more equatorward than one might expect. In this sense, so-called "high-latitude" wave forcing can penetrate into the sub-tropics, with the extent modulated by factors such as the quasi-biennial oscillation (QBO). R. Ueyama continued on this theme with work from an idealised GCM and from the ERA40 reanalysis that further demonstrated the extension of planetary wave drag to lower latitudes (as illustrated in **Figure 4)**. Her presentation sparked an interesting discussion regarding the time scales on which we assess the circulation response to wave drag (*i.e.*, transient versus steady-state responses).

The role of natural variability in modulating the BDC was the subject of presentations at the end of the first day of the workshop. Sources of variability that were highlighted included the QBO (**S. Yoden**), the solar cycle (**E. Rozanov**), orbital precession (**B. Winter**), and volcanic eruptions (**G. Pitari**). For example, in assessing changes in tropical upwelling it was shown that decreased tropical age-of-air tends to immediately follow volcanic eruptions. Finally, different approaches for diagnosing the residual circulation were presented: **K. Sato** proposed decomposing the zonal mean residual circulation into two components, an ageostrophic Eulerian mean flow and the Stokes drift, while **D. Demirhan-Bari** and **A. Gabriel** analysed the 3D structure of residual circulation and how it is reflected in tracer distributions

Reanalyses

Reanalysis data sets have proven to be very useful tools for studying the stratosphere, however, discrepancies between these data sets remain large - a matter which prompted the initiation of the SPARC Reanalysis Intercomparison Project (S-RIP). **M. Fujiwara** presented preliminary results from this intercomparison of eight reanalysis data sets, and identified four outstanding issues in the representation of the middle atmosphere: (1) forecast model and satellite biases in stratospheric temperatures, (2) the need for improved representation of the QBO and semi-annual oscillation (SAO), (3) the structure of the BDC, and (4) the scarcity of ozone observations. In particular, he emphasised that the BDC is not well constrained by observational data fed into the reanalyses, and that the reanalyses do not necessarily capture the long-term balance between wave drag and circulation correctly.

K. Okamoto compared the residual circulation inferred from five reanalysis data sets within a Transformed Eulerian Mean (TEM) framework. By isolating the contribution of gravity waves using downward control analysis, K. Okamoto suggested that differences in gravity wave drag may help to

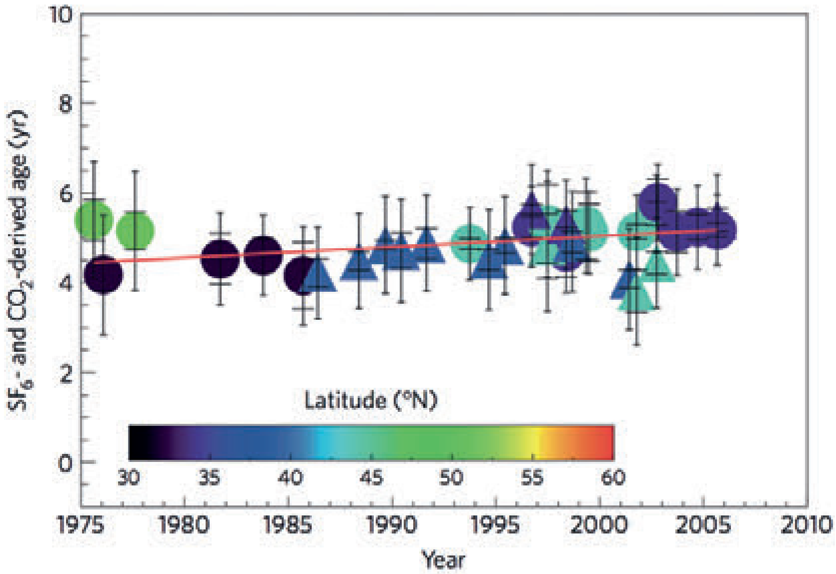
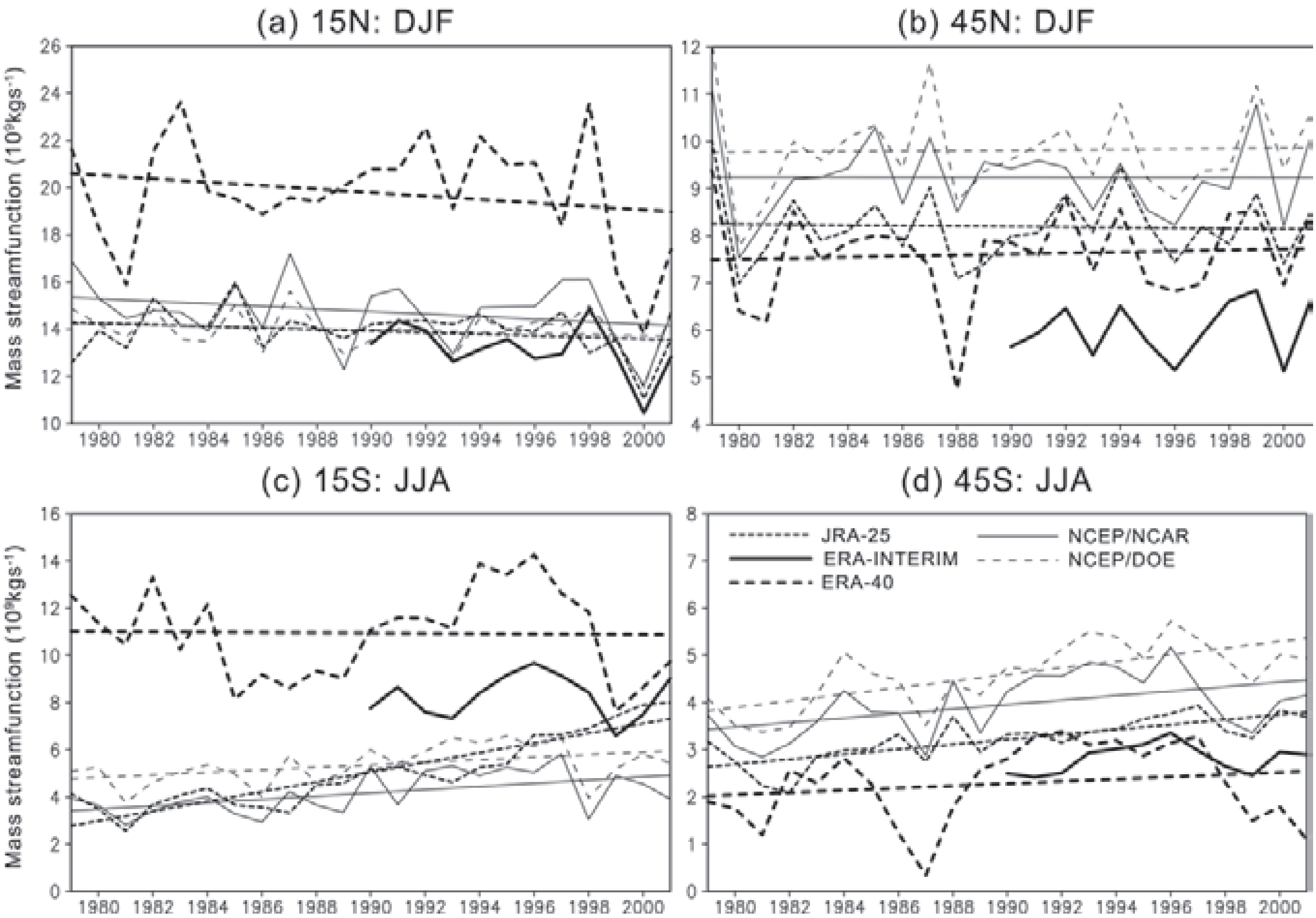


Figure 3: Measures of the BDC from observational data. **Left**: mean age-of-air derived from SF_6 and CO_2 in-situ measurements at latitudes indicated by the colour bar and heights between 25 and 35km; after Engel *et al.* (2009). **Bottom four panels**: time series' of residual mass flux at 100hPa at different locations and seasons from different reanalysis data sets; after Iwasaki *et al.* (2009).



explain why the reanalyses differ in their overall representation of residual circulation. W. Seviour analysed the residual circulation in ERA-Interim in more detail, emphasising that 6-hourly data is needed due to a semi-diurnal oscillation in tropical upwelling, however, it was suggested that this oscillation is likely unphysical. A local minimum in tropical upwelling was found at the equator; a feature that persists throughout the year. With regards to trends, ERA-Interim shows a decrease in tropical upwelling over the 30-year period 1979-2009, and **T. Iwasaki** showed that this trend is consistent with the other reanalysis data sets (see **Figure 5**). **M. Diallo** and **B. Legras** presented estimates of age-of-air derived from ERA-Interim using a chemistry transport model (CTM). The age-of-air estimates show positive trends in the middle stratosphere, in agreement with negative upwelling trends, but in the lower stratosphere the air becomes younger, despite weaker upwelling. This decrease in age-of-air is attributed to trends in mixing, as

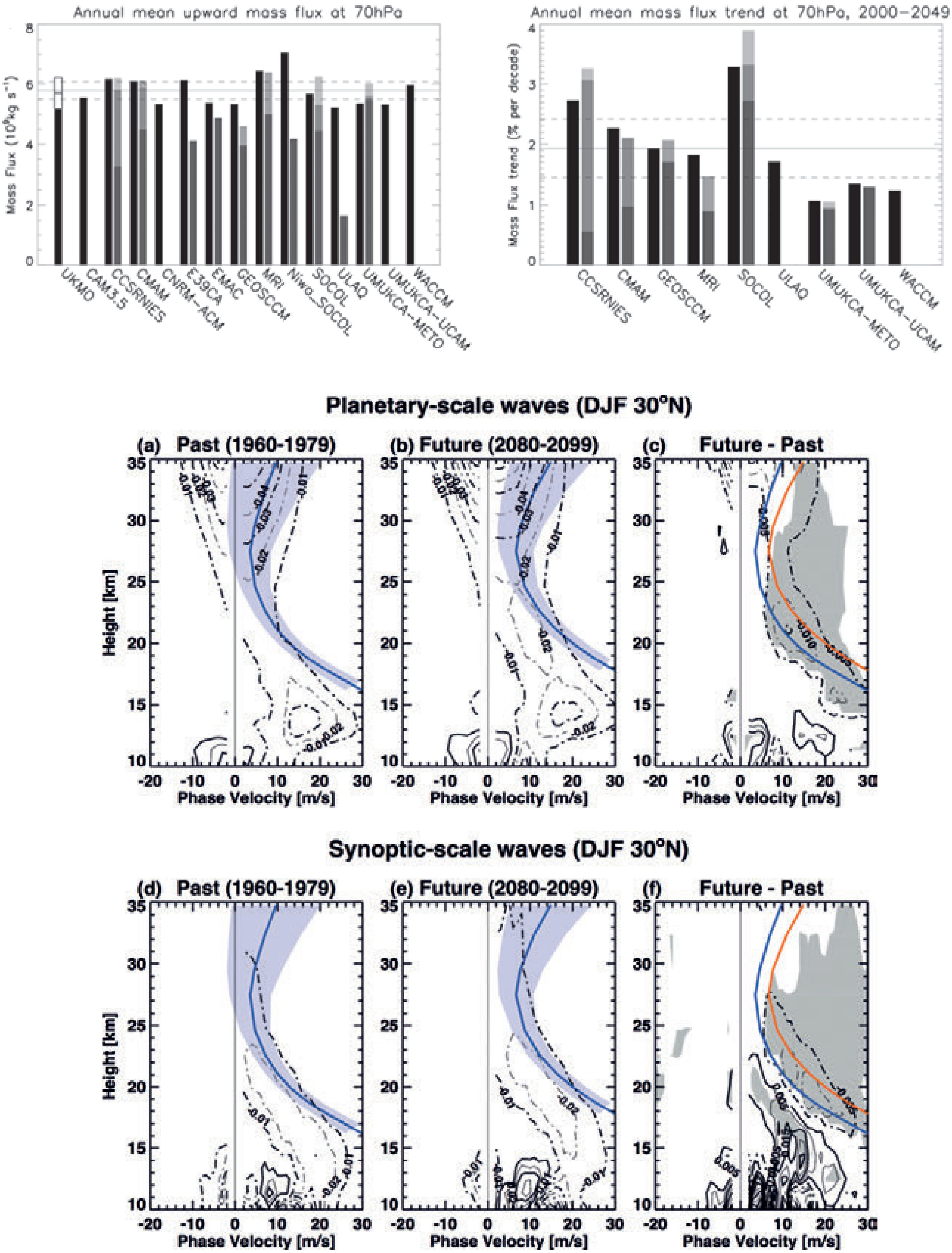


Figure 4: Mechanism for BDC changes in CCMs. **Top**: Climatologies (left) and trends (right) of 70hPa tropical upwelling for various CCMs (black), together with the wave driving by resolved waves (dark grey), OGWD (grey) and NOGWD (light grey). From SPARC CCMVal (2010). **Bottom**: EP flux divergence co-spectra *vs*. altitude from transient waves for zonal wavenumbers 1-3 at 30°N for DJF averages of (a) the past, (b) the future, and (c) the difference between the future and the past. Superimposed on (a) and (b) are the zonal-mean zonal wind (blue lines) and standard deviation of the daily zonal-mean zonal wind about the mean (blue shading). Zonal-wind profiles for the past (blue line) and future (red line) are shown in (c), together with regions where differences in EPFD are statistically significant at the 99.9% confidence level (grey shading). (d)-(f) as in (a)-(c), but for zonal wave numbers 4-16. After Shepherd and McLandress (2011).

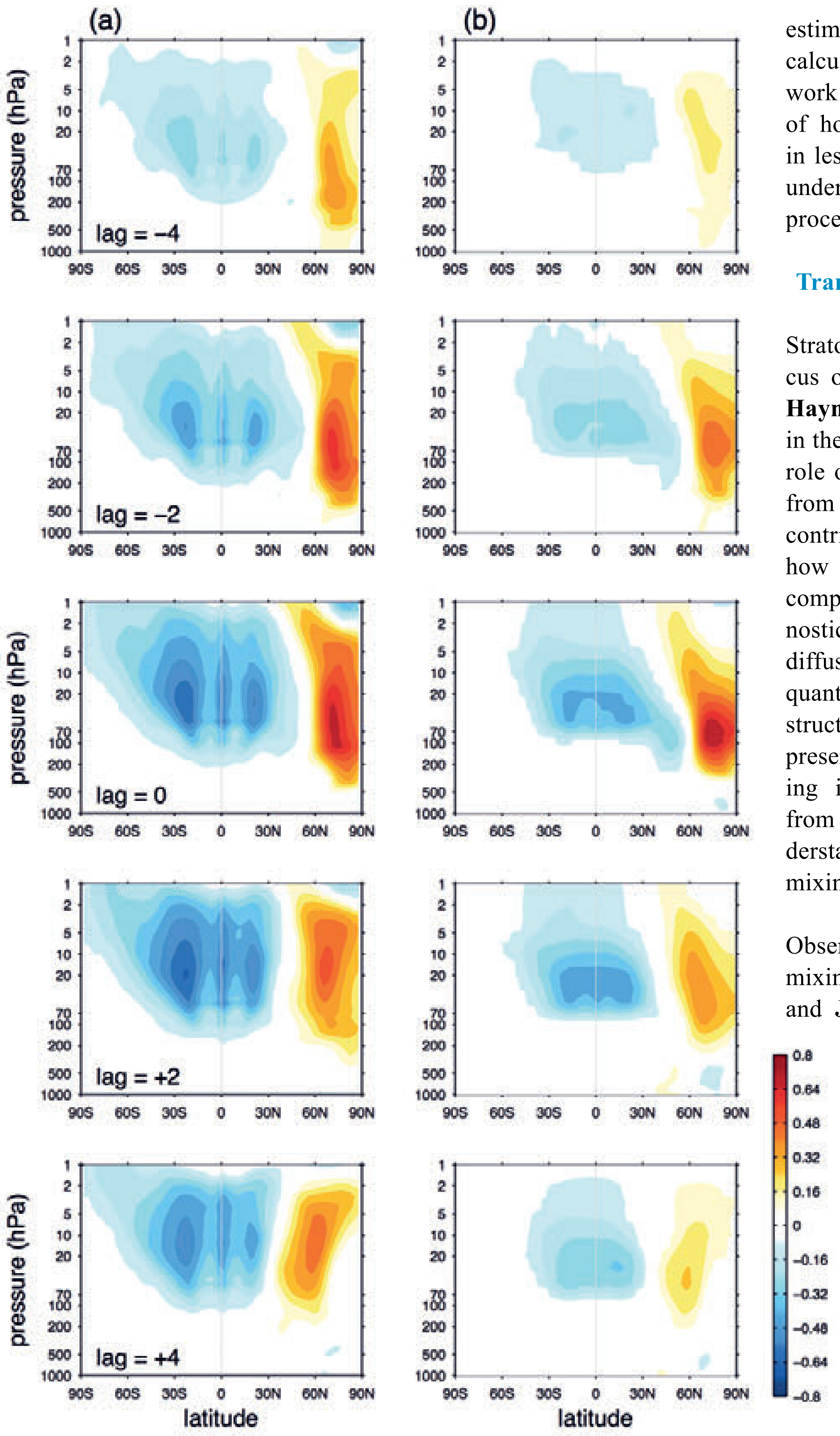


Figure 5: The 2-day time rate of change of the zonally-averaged temperature ∂[T]/∂t fiel correlated with the daily time series of the 100hPa level eddy heat fluxes [v′T′] averaged from 45-90°N at −4, −2, 0, +2 and +4 day lags based on 3-day Lanczos low-pass filtered (a) model and (b) ERA40 November-March data. Positive (negative) lags indicate the ∂[T]/∂t field lagging (leading) the high-latitude [v′T′] index. Correlation coefficients are significan at the 99% level. Figure courtesy R. Ueyama.

estimated by effective diffusivity calculations. It was noted that this work represented just one example of how reanalyses could be used in less conventional ways to better understand and describe transport processes.

Transport: Methods and theory

Stratospheric transport was the focus of a session introduced by **P. Haynes**. He reviewed past progress in the field, including the important role of transport barriers and ideas from chaotic advection that have contributed to our understanding of how simple flows can give rise to complex tracer geometries. Diagnostics, including Nakamura's eddy diffusivity, which have aided in the quantification of mixing and the structure of transport barriers, were presented. He listed as outstanding issues problems with trends from reanalysis data sets, and understanding the role of small-scale mixing processes.

Observationally-based measures of mixing were discussed by **P. Hoor** and **J. Gille**, who also suggested that the modal age-of-air may be a more physically meaningful diagnostic for transport than the mean age-of-air. P. Hoor described a new method to infer transient times in the lowermost stratosphere using CO_2 and N_2O measurements, while J. Gille used high resolution HIRDLS (High Resolution Dynamics Limb Sounder) ozone data to infer high-latitude descent, mixing regions and transport barriers.

Ozone

M. Weber introduced a session on the impact of the BDC on ozone variability from seasonal to decadal time scales. One useful metric introduced in this talk, and referenced by several others, was the correlation between extra-tropical winter mean eddy heat fluxes and spring-to-fall ozone ratios. Applications of this metric to CCM model output were used to separate the effects of recovery versus interannual variability in determining long-term ozone changes. **M. Kozubek** found that the strong correlation between winter eddy heat flux and spring-to-fall ozone ratio persists throughout the year and is well reproduced in the ERA-Interim data. **I. Wohltmann** used a passive tracer in a CTM to highlight different transport pathways.

Upwelling

Estimates of upwelling from models and observations

The upwelling branch of the residual circulation is considered the main entry point into the stratosphere, determining to a large extent its chemical properties. **N. Calvo** presented an overview of tropical upwelling, with an emphasis on deducing its main drivers through climatologies and trends of PW versus GW drag. She showed that upwelling trends from CCMs are quantitatively consistent, show an increase of about 3% per decade, and tend to agree that there is a strong contribution of PWs to tropical lower stratospheric upwelling. The consistent trends in upwelling from different models and the contributions of wave driving are shown in **Figure 3** (top panels).

As the session on reanalyses showed, residual circulation estimates, and in particular trends from reanalyses, are not entirely reliable. Independent measures of upwelling from observations such as upwelling derived from ozone profiles based on satellite (**B.-M. Sinnhuber**) or ozonesonde data (**R. Lehmann**), are thus required. As discussed by R. Lehmann, however, one difficulty arises from the potential role of mixing in the ozone budget.

K. Krueger proposed an alternative approach to quantifying BDC that avoids uncertainties associated with noisy vertical velocities from observational assimilations. She used Lagrangian backward trajectories, driven by reanalysis-derived diabatic heating rates, to calculate residence times in the tropical tropopause layer (TTL). She found strong correlations between residence times and extra-tropical and sub-tropical wave drag. The strength of the correlation between high-latitude heat fluxes and tropical temperature tendencies in reanalyses was found by **L. Hood** to depend on different phases of the QBO and solar cycle. In particular, he found the largest correlations during solar minimum when the QBO was in its westerly phase.

The use of high resolution GPS data presents a relatively new approach for the direct assessment of variability in tropical temperatures. After systematically removing the annual cycle, QBO and ENSO, **W. Randel** showed that there are two primary modes of temperature variability: (1) a “deep“ stratospheric mode, feasibly linked to stratospheric sudden warmings, and (2) a mode explaining most of the variance about the tropopause, which exhibits similar behaviour to the response to ENSO.

Coupling to tracers

Vertical advection of trace gases is strongly controlled by tropical upwelling, thus a strong correlation of both CO and ozone with upwelling is found in the tropical lower stratosphere on seasonal and sub-seasonal time scales. Through a budget analysis of zonal mean ozone, M. Abalos found that upward mixing into the stratosphere is important for the total amount of ozone in the lower stratosphere, but that the seasonal cycle in lower stratospheric ozone is determined by the seasonal cycle in upwelling. This result contrasts to that of F. Ploeger who argued that at least 30% of the seasonal amplitude in ozone variability in the tropical lower stratosphere is due to upward mixing, which is strongest in summer when the monsoon anticyclone mixes extra-tropical air equatorward.

S. Fueglistaler’s presentation on annual mean lower stratospheric temperature and ozone variability highlighted the fact that the tropical lower stratosphere is a region of strong coupling between trace species, upwelling and temperature. He demonstrated that in order to explain the seasonal cycle in tropical temperatures, the variation of static stability with latitude as well as the seasonality in ozone (discussed above), which feeds back radiatively on temperatures, needs to be taken into account.

The downwelling branch of the BDC

The downwelling branch of the residual circulation was the focus of several presentations, the first of which was given by **S. Tegtmeier**. Using diabatic circulation to approximate the Lagrangian circulation, she reviewed ways to quantify the downwelling branch of the BDC via observed changes in tracer isopleths and radiative transfer model calculations. Interannual variability in the northern hemisphere wintertime downwelling was found to correlate strongly with Eliassen-Palm flux anomalies. In addition, the

Figure 6: Participants of the SPARC Brewer-Dobson Circulation workshop held in Grindelwald, Switzerland, June 2012.

meridional structure was found to vary over the course of the winter, as well as between the southern and northern hemisphere, with strongest descent either at the vortex edge or core.

H. Roscoe posed the question "Where does the BDC return?", and concluded from a literature review that tropopause folds in the mid-latitudes seem to account for most of the downward mass flux As commented by a member of the audience, the return flux to the troposphere by tropopause folds or additional cross-tropopause mixing must equal the downward residual circulation mass flux

Residual circulation trends: Models and mechanisms

C. McLandress presented an overview of the mechanisms driving trends in residual circulation, as understood in the TEM framework. He stressed that the contribution of GWD versus resolved wave drag depends strongly on latitude. Although models consistently show a future increase in orographic GWD deposition at higher levels, he warned that this trend may simply reflect the fact that they all use similar GW parameterisations. Regarding the mechanism for resolved wave drag changes, **T. Shepherd** referred to the classic paper on critical lines and wave propagation by Randel and Held (1991). He showed how changes in the background winds in response to upper tropospheric tropical warming affect wave propagation and therefore deposition of resolved wave drag in the tropical lower stratosphere, as shown in **Figure 3** (bottom panels). The tropospheric warming that drives the changes in background winds and thus enhanced wave propagation is induced in CCMs by the prescription or simulation of sea surface temperatures (SSTs). Both **M. Taguchi** and **S. Oberlaender** showed that increases in mean tropical SSTs drive the strengthening of the lower branch of the BDC. M. Taguchi further demonstrated that increases in upwelling in the lower stratosphere scale approximately linearly with SST changes, while S. Oberlaender showed that changes in the deep branch are driven by a combination of both tropospheric warming and stratospheric cooling (*i.e.*, direct radiative effects of greenhouse gas changes).

Overall, the mechanism for an enhancement of the shallow branch as outlined above is commonly accepted, but changes in the deep branch, and in particular those associated with GWD changes, are less well understood. When dealing with models, it should be noted that model configuration potentially plays a large role in the representation of the circulation. **F. Bunzel** and **S. Hardiman** examined the sensitivity of transport to model configuration in terms of vertical extent and resolution. Simulations with a single model under different configurations showed that the climatological residual circulation and age-of-air is affected by the vertical resolution and by the model lid height. Relative trends in upwelling were found to be similar by F. Bunzel, however, S. Hardiman found that the upwelling trends are stronger when grouping high-top models among CMIP5 simulations compared to low-top models.

Transport trends

Observations

H. Boenisch opened the session on age-of-air observations by stressing the point that from an observational point of view the BDC includes transport by both the residual circulation and two-way mixing. Residual circulation transit-time calculations were introduced to isolate the contribution of residual circulation to the time air parcels spend in the stratosphere. Trend estimates using the JRA-25 reanalysis show decreasing transit times in the lower tropical stratosphere (*i.e.*, shallow branch) but no trends in the middle extra-tropical stratosphere (upper branch). On the theme of future changes in transport, H. Boenisch also reviewed the apparent discrepancy between modelled and observed mean age-of-air trends.

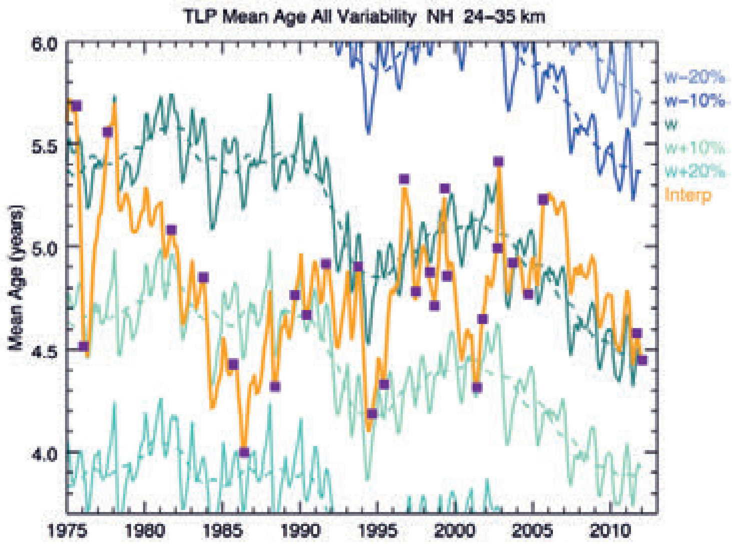


Figure 7: Several time series of the northern hemisphere mid-latitude mean age-of-air averaged over the 24-35km altitude range from Tropical Leaky Pipe (TLP) model particle trajectory runs. The TLP model runs used residual circulation and effective diffusivity calculated from MERRA reanalysis as input. The green and blue lines show mean age sensitivity to scaling the strength of the residual circulation by -20% to +20%. The purple squares are observationally derived mean ages using SF_6 and CO_2 measurements from Engel *et al.* (2009) and recent AirCore balloon flights, interpolated between TLP model runs based on comparing observed and modelled tracer profiles. The orange line represents the mean age-of-air time series from the TLP model runs that best fit the observations. Note the significant variability on seasonal to decadal time scales. Figure courtesy E. Ray.

While models consistently predict a decrease in mean age-of-air in concert with an accelerated residual circulation, the results of observed mean age from Engel *et al.* (2009) suggest a weak positive trend (see **Figure 3**).

Several talks regarding how transport trends are assessed using data sets of long-lived trace species followed. **T. von Clarmann** highlighted that MIPAS CO observations could be used to infer subsidence in the upper stratosphere, while **J. Urban** showed how satellite-derived water vapour anomalies and N_2O are useful proxies of tropical ascent rates and high-latitude descent respectively. **G. Stiller** presented age-of-air estimates inferred from high-resolution MIPAS measurements of SF_6.

Models

R. Garcia expanded on the discrepancy between modelled and observed trends in end-of-20th century mean age-of-air, suggesting that uneven sampling and breakdowns in the assumptions regarding the linearity of SF_6 can help us to understand, but not entirely reconcile, these differences. The assumption of linearity was directly addressed by **T. Reddman** who found that SF_6-derived mean age-of-air for models with and without mesospheric decay led to significantl different mean ages. **E. Ray** also focused on this issue through the use of a tropical leaky-pipe model driven by MERRA-derived winds and mixing fields. The model was able to produce mean age-of-air estimates that agreed quite well with the estimates of Engel *et al.* (2009), and, as shown in **Figure 7**, in particular that decadal-scale natural variability can likely mask long-term trends, potentially providing an explanation for the current mismatch between observations and models. A similar point was made by **L. Wang**, who used a lower stratospheric temperature time series from a CCM to argue that a statistically meaningful response to BDC changes in temperatures is detectable only for time scales of about one century.

Mixing

H. Garny investigated the relative contributions of the residual circulation and the effects of two-way mixing in determining age-of-air and its changes. Age-of-air is determined by transport in the residual circulation at low and high latitudes, while effects of mixing can lead to additional aging in the mid-latitudes. Only at high latitudes in the lowermost stratosphere do the effects of mixing lead to younger air. Using trajectory calculations driven only by the residual circulation, she found that mixing plays a substantial role in future age-of-air changes. The accuracy of model representations of mixing was explored by **E. Becker** who used a spectral model to show that age-of-air can be quite sensitive to changes in horizontal and vertical diffusion.

Focusing on transport near the tropopause, **C. Orbe** presented a new methodology for diagnosing stratosphere–troposphere exchange (STE) in terms of one-way flu distributions conditional on stratospheric residence time. Results with an idealised model suggest that increased strength of the BDC does not necessarily imply decreased mean residence times, emphasising yet again that changes in transport depend strongly on changes in mixing.

Tropopause and stratosphere-troposphere coupling

Influence on the tropopaus and troposphere

Tropopause height is strongly linked to residual circulation, as shown by **T. Birner**. When removing stratospheric dynamics in a CCM by relaxing the stratosphere to radiative equilibrium, tropopause height shows large perturbations. In particular, the equator-to-pole difference in tropopause height is strongly linked to stratospheric dynamics.

A. Karpechko explored how the stratosphere modulates the tropospheric response to increased greenhouse gases using results from ECHAM5. He found that in winter the Arctic sea level pressure response to doubled CO_2 depends largely on model lid top, with implications for the representation of precipitation responses over Europe. An alternative formulation of the circulation was introduced by **A. van Delden**, who used extratropical potential vorticity (PV) anomalies to illustrate the coupling between the lower stratosphere and upper troposphere.

Coupling to the Troposphere

In an appeal for a more physically-based measure of stratosphere-troposphere coupling, **M. Baldwin** advocated the use of 600K daily mean PV averages over Northern Hemisphere high latitudes. He showed that anomalous wave drag in the stratosphere is associated with anomalies in downwelling that extend into the upper troposphere over the pole. Since tropopause variability is tightly coupled to variations in the strength of the vortex this might be a more physical proxy of stratosphere-troposphere coupling than more conventional measures such as the Northern Annular Mode. **A. Orr** also suggested that wave-mean flow feedbacks were a possible mechanism behind the surface response over Antarctica to changes in the ozone hole.

Stratospheric water vapour

The final session of the workshop was dedicated to stratospheric water vapour, with an emphasis on the water vapour "tape recorder" signal and its link with tropical upwelling. **S. Lossow** identified a pronounced tape recorder signal in MIPAS-derived observations of water vapour, HDO and the isotopic ratio δD. Attempting to resolve apparent discrepancies between MIPAS and ACE-FTS tape recorder measurements, as first discussed by Randel *et al.* (2012), he showed how offsets in the vertical resolution of H_2O and HDO fields can introduce an artificial tape recorder effect. After the correction of these offsets, both MIPAS and ACE-FTS indicate the existence of a tape recorder in δD, but the signal is rather weak. Motivated by the finding that the ERA-Interim H_2O tape recorder is about twice as fast compared to independent Aura MLS observations, **S. Liu** reconstructed a more realistic tape recorder signal using a Lagrangian advection-condensation model driven by ERA-Interim wind and temperature fields. By incorporating the large-scale temperature and circulation in this manner, she demonstrated that while ERA-Interim winds might yield realistic upwelling, additional diffusion in the model's internal transport scheme leads to an overestimate of the tape recorder as simulated in the reanalysis water vapour fields. Linking back to earlier talks on the kinematic versus diabatic approaches for driving trajectory calculations, she suggested that both are comparable for ERA-Interim data. Such was not the case with ERA40 data, where the kinematic approach yielded saturation mixing ratios that were too high. The dynamical controls on stratospheric water vapour were further discussed by **M. Jucker**, who emphasised the crucial role of lower stratospheric temperatures.

Summary

The presentations and discussions over the course of the week revealed a number of common themes that served as bases for the summary discussion on Friday afternoon. Several key points were highlighted as being crucial to current understanding of the BDC and its drivers. One point addressed the fact that the BDC is a transport circulation, consisting of both residual circulation and the effects of two-way mixing. It was stressed, therefore, that the differences between these circulations need to be more clearly defined. In particular, it was generally agreed that more care be taken in distinguishing between net mass overturning, deep tropical upwelling, and polar downwelling, despite how intimately these processes are related. For example, one paradigm for studying these processes may be through the evaluation of how they depend on different types of waves. While this distinction has proven useful in understanding projected changes in the structure of the BDC, several presentations questioned how physically meaningful the distinction between high *vs.* low latitude wave driving is, showing instead that planetary waves that enter the stratosphere at mid- to high latitudes can propagate and break far equatorward from their entry point. In this sense, high *vs.* low latitude wave driving may not be the ideal lens through which we identify different aspects of stratospheric circulation.

Participants in the discussion identified several major gaps in our understanding that can be synthesised into six key questions:

(i) **What is the relationship between the residual/diabatic circulation and the transport circulation (*i.e.*, including two-way mixing)?**
While it is well established that the BDC consists of both residual circulation and transport by two-way mixing, it is not yet clear what the relative importance of the two factors in determining age-of-air and tracer distributions is. In fact, the relationship will likely be different for different tracers, depending on their sources/sinks, chemical lifetimes, and wave driving (*i.e.*, Rossby waves versus GWs). While for Rossby waves there are physical arguments that relate wave drag to implied horizontal PV mixing it remains to be explored how we can better constrain the effects of mixing and residual transport on tracer distributions.

(ii) **What is the role of gravity-wave drag in the BDC?**
It is well known that both orographic (OGW) and non-orographic (NOGW) gravity wave drag are important for dynamical balance in the middle atmosphere and need to be included in middle atmosphere models in an appropriate manner. There are, however, still many issues concerning gravity wave drag parameterisations. For example, different GW parameterisations may simulate similar climatologies but for very different reasons (*e.g.*, due to trade-off effects between OGWs and NOGWs). An inter-comparison of GW drag parameterisations could help to identify where and why these discrepancies arise. Another major problem is the fact that there are few observations of GW drag. A future challenge will be to get more and better measurements of GW drag that can be used with gravity-resolving models to help identify weaknesses in model parameterisations. Another possible approach is to use reanalysis data to better constrain GW drag. However, it is not clear how well the reanalysis increments can be trusted.

(iii) **What do we need from the reanalyses, and do we trust them?**
Many observational constraints, not just those applied to GW drag, could be obtained by using reanalysis products, including increments. However, it first needs to be clarifie how we can use this information as it is still not apparent which analysis increments will be needed for which observed quantities. Furthermore, the momentum and thermodynamic budgets in the reanalysis products need to be better understood so that we can determine how much trust we should place in the reanalyses' representations of the BDC and its recent changes. This might require analysing additional output variables such as idealised tracers for both the troposphere and the stratosphere; something which the community should advise all reanalysis centres to provide. Finally, another approach that would be useful in assessing climatologies and trends in reanalysis data involves comparing observed tracer fields with those simulated by CTMs driven by reanalysis winds.

(iv) **How consistent are models and observations over the historical record, and on different time scales?**
There are still large differences between observational records and model results. For example, the newly retrieved SSU middle atmospheric temperature data set shows major differences with CCM simulations. This example is, unfortunately, not an exception, and large discrepancies between modelled and observed temperature and water vapour trends are common. This poses a major impediment to progress in understanding and our ability to accurately model these trends. Furthermore, it has recently been emphasised that when inferring trends, low-frequency variability can introduce large uncertainties in the estimates, therefore prompting an overall need to better understand variability on small time scales.

(v) **What kind of observational network is needed to detect long-term changes?**
The need for long-term observational records for the detection of changes in the BDC was strongly emphasised in several presentations during the workshop. Finding cheaper alternatives to, for example, balloon-borne measurements, is crucial, as well as establishing links to operational networks to ensure the continuity of such measurements. Models will need to be utilised to press for long-term measurements and it should be emphasised that limb viewers are valuable for relevant tracer measurements. Ultimately, these priorities will need to be communicated to scientific agencies in order to ensure the continuation of existing measurement programmes.

(vi) **What are the mechanisms for, and impact of, long-term changes in polar downwelling, and how consistent are models with the observational record?**
While models consistently predict increases in the strength of the BDC in the tropical to mid-latitude lower stratosphere, predictions in downwelling at higher latitudes are much less consistent. While polar downwelling changes potentially have large impacts on high latitude ozone distributions, it remains difficult to diagnose high-latitude trends due to the high dynamical variability in

this region. It is therefore imperative that probabilistic approaches be used to avoid confusing trends with low-frequency variability. In particular, the impact of decadal-scale variability on the interpretation of observational records needs to be better understood. Finally, the full depth of the vortex should also be considered when inferring trends in downwelling.

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Report on the 9th SPARC Data Assimilation Workshop in Socorro, NW, USA

David Jackson[1], Gloria Manney[2], Ken Minschwaner[3]

[1]UK Meteorological Office, UK, david.jackson@metoffice.gov.uk, [2]NASA Jet Propulsion Laboratory, Pasadena, USA, manney@nwra.com, [3]Department of Physics, Socorro, USA, krm@kestrel.nmt.edu

The Ninth Stratospheric Processes And their Role in Climate (SPARC) Data Assimilation (SPARC-DA9) workshop was held in Socorro, New Mexico, USA, from 11-13 June 2012. This workshop was one of a regular series of meetings held since 2002, and had around 40 participants. The progress in the activities proposed for initiation at the last workshop in 2011 was summarized, and ideas for new activities were discussed.

Stratosphere / troposphere interactions and SNAP

SNAP (Stratospheric Network for the Assessment of Predictability) is a SPARC-supported project aimed at better understanding how the representation of the stratosphere can affect tropospheric predictions via an intercomparison of model results from a number of forecast centres. Further details appear in Charlton-Perez and Jackson (2012). A num-

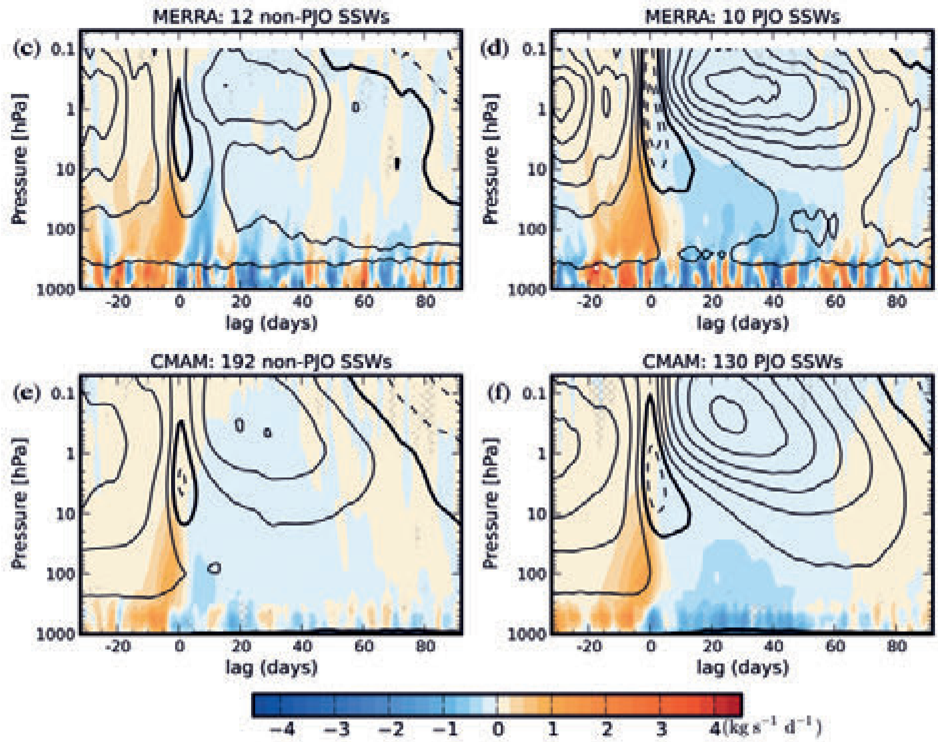


Figure 8: Pressure-time section of vertical EP flux (shaded) and zonal wind (contours) before and after non-PJO SSWs (left column) and PJO SSWs (right column). The values are composites taken from MERRA reanalyses (**top row**) and the CMAM model (**bottom row**). The x-axis shows the lag in days from the onset of the SSW. Regions not significant at the 95% level are hashed out. The zonal wind contour interval is 10m/s and the zero wind line is in bold. Figure courtesy Peter Hitchcock, University of Cambridge.

ber of speakers presented results that promise to be highly relevant to determining the scientific direction of SNAP.

An invited talk by **P. Hitchcock** reviewed recent work showing that links between the state of the stratosphere and tropospheric predictability (*e.g.,* after a sudden stratospheric warming (SSW)) are sometimes seen, but sometimes not. He focused his talk on understanding why this happens, and in particular on the role of the Polar night Jet Oscillation (PJO). Around 50% of SSWs are followed by PJO events, and they are more likely to follow split warmings. Both model and reanalysis results show that wave driving is more strongly suppressed during the SSW recovery phase if a PJO event is occurring (**Figure 8**). This suppression means that radiative damping plays a dominant role in enhancing the persistence of the lower stratospheric anomaly, and there is an associated enhancement of predictability.

S. Bancala analysed the preconditioning of SSWs in ECMWF analyses. Major warmings were classed as wavenumber 1 (W1) or wavenumber 2 (W2) based on the preconditioning of the polar vortex. More than 70% of all detected major warmings are W1 events. In addition, different W2/W1 and splitting/displacement ratios exist. Not all W1 major SSWs led to vortex displacements (about 1/3 caused splitting events), whereas all W2 events resulted in vortex splitting. **Y. Zyulyaeva** used reanalyses to examine the "stratospheric bridge" between North Pacific sea surface temperatures in December and the North Atlantic troposphere in January. Qualitatively, the reanalyses were able to adequately describe this phenomenon, but quantitatively there were large differences between reanalyses in the vertical component of Eliassen-Palm fluxe that play a key role in the stratospheric bridge concept.

M. Charron's invited presentation examined the improvements in forecast skill when the model lid was raised in the Canadian NWP (Numerical Weather Prediction) model. The improved stratospheric forecast skill is due to the higher lid of the new model, while an updated radiation scheme helps to improve tropospheric forecasts. He hypothesized that the cycling of a better model and assimilation provide more accurate initial conditions, resulting in improved forecasts.

D. Jackson presented a summary of models used in global operational NWP systems around the world. Currently only two centres (Germany, Russia) use models with an upper boundary below the stratopause. The benefit to tropospheric forecasts of including the whole of the stratosphere in models was demonstrated. Some models now have an upper boundary even higher, near the mesopause. However, the advantages of this can be offset by issues such as the lack of mesospheric observations and under-estimation of tidal amplitudes. Furthermore, future model developments that impact the middle atmosphere are likely to focus on improved parameterisations, model dynamical cores and data assimilation methods (*e.g.*, hybrid Kalman Filter / 4D-Var approaches), rather than a further raising of the model upper boundaries.

Gravity waves and their representation in models and analyses

J. Alexander presented an invited talk that included a thorough review of gravity wave observations, and the representation of these waves in models. An examination of two high-resolution models (Kanto – T213 with 300m vertical resolution, and CAM5, with 0.25° horizontal resolution and ~2km vertical resolution) showed that resolved gravity wave momentum fluxes appeared too weak compared to observations, because of numerical and explicit diffusion, and poor vertical resolution.

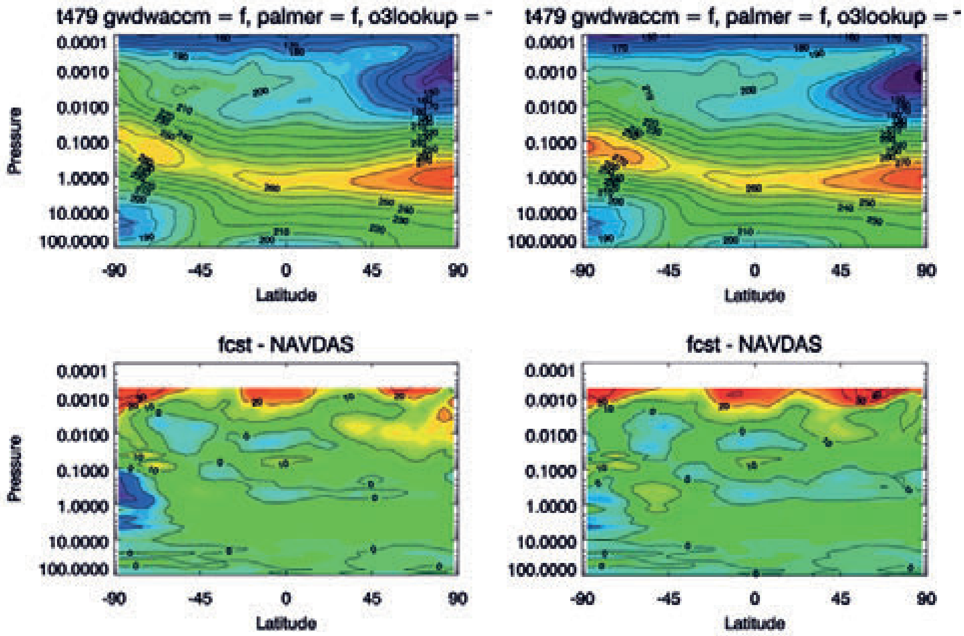


Figure 9: **Top Panels**: 10-day zonal mean temperature forecast from the NOGAPS ALPHA model initialised at 00UT, 10 June 2007 with strong high wave-number damping (time scale = 1.4hr) (**left**) and with weak damping (time scale = 5.6hr) (**right**). **Bottom panels**: differences between forecasts on the top panel and the NAVDAS temperature analysis at 00UT, 20 June 2007. Figure courtesy Dave Siskind, NRL.

The invited presentation by **D. Siskind** described experiments with the Naval Research Laboratory NOGAPS-ALPHA model at a range of horizontal resolutions (T79 to T479) and vertical resolutions (~1-2km). Model runs were performed with and without parameterised gravity waves in order to investigate the impact of resolved gravity waves. The winter stratopause and summer mesopause (two well observed features that are strongly impacted by gravity waves) were poorly represented, even at T479. Improved results were obtained only when the diffusion was tuned to an unrealistically low level (**Figure 9**).

Results from these presentations, and the subsequent discussion, underscore the fact that there is no fixed answer to the model resolution required to adequately represent gravity waves and their effects. Rather, appropriate resolution depends on the formulation of each model.

M. Pulido described efforts to estimate the missing forcing from gravity waves in models using 4D-Var. This process is quite straightforward, but estimating the parameters required to obtain the gravity wave parameterisation scheme is a very different matter. The parameterisations are highly non-linear, ill-conditioned, and thus variational methods are not well suited to estimating them. Instead, a genetic algorithm developed at NCAR was used. In this case, there was convergence towards realistic parameters in all experiments. For the case of inferring missing drag in a multiple-model inter-comparison, 4D-Var is not useful since a different adjoint has to be written for each model. Here, an ensemble Kalman Filter was developed that can infer missing drag for different models. This approach, with the inclusion of maximum likelihood error covariance estimation, worked well for offline estimation of gravity wave parameters. For online estimates, ensemble transform Kalman filtering performed better.

M. Pulido also presented complementary material from **G. Scheffle** on estimating the impact of gravity wave drag parameters using data assimilation.

R. Lieberman examined tidal variability in NOGAPS-ALPHA. The model output was initialized by meteorological analyses every 6 hours, but the forecast output was saved hourly. This data set is thus a useful resource for short-term tidal analysis at high latitudes and high altitudes (> 60km). Diurnal tides in NOGAPS-ALPHA agree well with SABER temperature and TIDI winds (u, v) observations, which is encouraging since SABER and EOS Microwave Limb Sounder (MLS) mesospheric temperatures are used in the analyses. However, semi-diurnal tides show more structure in the observations than in the model. There is substantial numerical evidence, but very little observational support, for tide-planetary wave (PW) coupling mechanisms. The NOGAPS hourly product makes it possible to explore the evolution of tides concurrently with PWs. She was able to show the utility of short-term tidal definitions during periods of PW and tidal enhancement. R. Lieberman also presented a proposal for a new instrument, the Doppler Wind and Temperature Sounder (DWTS). This would exploit a new approach for measuring high altitude winds and temperatures to produce profiles of daytime and night-time temperature and cross-track winds between altitudes of 25 and 250km with less than 2% uncertainty, at intervals of 10km along-track. Above 110km and below 50km, the along-track wind component is also determined, thus enabling recovery of the horizontal vector wind.

Assessment of middle atmosphere analyses and S-RIP (SPARC Reanalysis / analysis Inter-comparison Project)

Extensive discussion at the 2011 SPARC Data Assimilation Workshop resulted in the formation of the S-RIP project, which is focused on comparing and assessing the performance of reanalyses, with an emphasis on the stratosphere. S-RIP is led by **M. Fujiwara**, who summarized the aims of S-RIP. Further details also appear in Fujiwara *et al.* (2012).

M. Rex gave an invited talk about polar ozone loss and the tropical tropopause layer. All studies heavily rely on meteorological field from data assimilation systems. Key findings include the fact that Arctic ozone loss appears to be getting more severe during cold winters because of ozone/climate coupling, that processes at the tropical tropopause layer (particularly above the Western Pacific) play an important role for the global ozone layer, and that a tropospheric ozone and OH hole exists over the tropical West Pacific. His results showed a high level of sensitivity to uncertainties in temperature in the polar lower stratosphere and vertical velocity at the tropical tropopause.

S. Chabrillat assessed the fitness of ECMWF and CMC meteorological analyses to model tracer transport in the Arctic vortex during the 2010-2011 winter, for several chemical transport models. Since it is difficul to use vertical velocity from analyses, vortex averaged N_2O was used as a diagnostic of vertical transport. The GEM-BACH model driven by CMC analyses agreed much more closely with observations that any ECMWF-driven model.

K. Rosenlof presented an invited talk on diagnosing the stratospheric mean meridional circulation from reanalyses. This can be done in a number of ways: by using the transformed Eulerian Mean (TEM) residual velocities or equations, by deriving constituent distributions using reanalysis winds in a CTM, or by looking at the propagation of seasonal signals. With regard to S-RIP, she felt that we need to be able to assess both: (1) Differences between the various reanalyses, and (2) Effective accuracy. To assess accuracy, both absolute values and variations in quantities that are likely a function of the mean meridional circulation, such as the seasonal cycle in lower stratospheric mass flux or the stratospheric entry value of water vapour, could be used.

A. Dessler also focused on water vapour. He used a trajectory model driven by horizontal winds and heating rates from MERRA and ERA-Interim to advect millions of air parcels. The grid of parcels is initialized every day at 365K and run for the period of the reanalysis data set. The parcels are advected forward in time; most head into the stratosphere and are removed when they re-enter the troposphere or at age >10 years. Stratospheric H_2O can be accurately simulated over the last 25 years with this trajectory model using simple microphysical assumptions. There is no increase in stratospheric H_2O for either long-term warming or ENSO warming, and decadal variations of about 0.9ppmv arise from variations in the Brewer Dobson circulation.

S. Davis examined a variety of metrics using reanalyses, models and satellite data, and found a 0-1.5°/decade tropical widening. Tropical widening trends based on absolute thresholds (*e.g.*, OLR, and tropopause) are biased high. Trends based on reanalyses agree well for zonal-wind metrics, but not for others. S. Davis also talked about variability and trends in effective diffusivity from reanalysis. The effective diffusivity is a diagnostic for mixing, and changes in it could have implications for stratospheric circulation changes, since model and observations show Brewer-Dobson circulation increases that imply decreases in the mid-latitude age-of-air. However, balloon-based observations do not show such a decrease. Effective diffusivity from reanalyses reveals the possibility that mixing has increased between the tropics and mid-latitudes (**Figure 10**), with the caveats that trends from reanalyses should always be treated with caution, and that they are not consistent across all reanalyses. This may be the answer to the above-mentioned discrepancy between tropical widening in reanalyses and models, since mid-latitude mean age-of-air trends are sensitive to mixing trends, such that increased mixing would lead to increased recirculation and hence increased age-of-air.

G. Manney examined the clima-

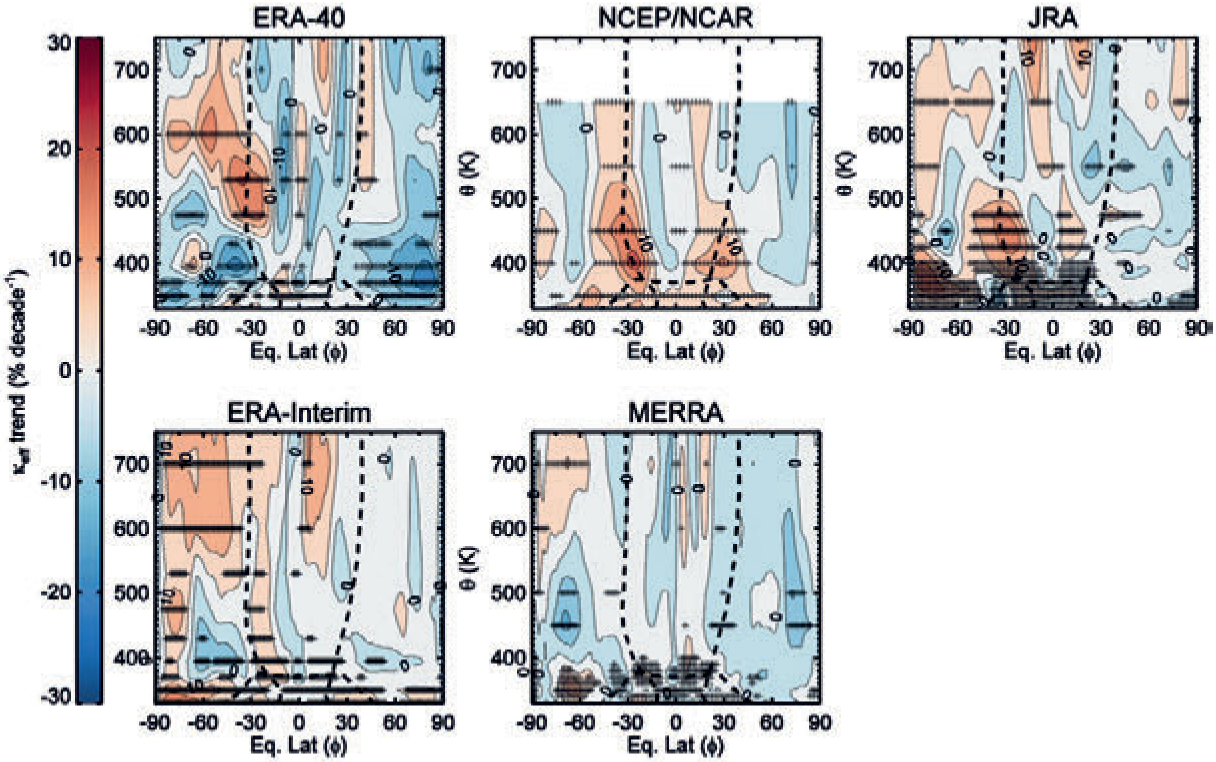


Figure 10: Potential temperature-equivalent latitude sections of the trend (%/decade, colours) in effective diffusivity (Keff) from 1979-2008 in reanalyses from ERA40 (**top left**), NCEP/NCAR (**top centre**), JRA (**top right**), ERA-Interim (**bottom left**) and MERRA (**bottom centre**). Dashed lines show the annual mean turnaround latitudes in the Transformed Eulerian Mean (TEM) streamfunction, with upwelling occurring equatorward of the turnaround latitudes. Overlaid crosses indicate areas that are significant at the 95% confidence level. Figure courtesy Sean Davis, NOAA.

tology and variability of Upper Tropospheric/Lower Stratospheric (UTLS) jets from MERRA reanalyses using a new identificatio scheme. A comparison between SSW and cold vortex years showed distinct differences in merged jet patterns and multiple tropopause frequency, as well as subtle differences in upper tropospheric jet patterns. Finding reasons for these differences is a subject of ongoing research. **W. Daffer** broadened the study to perform an inter-comparison of MERRA, ERA-Interim, NCEP and GEOS-5 reanalyses. The results show strong sensitivity of UTLS jets and the tropopause to the data assimilation system used to characterize them. In a related talk, **M. Schwartz** examined multiple tropopauses, and barriers and pathways that define UTLS transport. Results from MERRA, NCEP and ERA-Interim analyses are largely consistent with each other. MLS, HIRDLS and ACE-FTS observations were also used to derive tropopause diagnostics and a comparison between these and the diagnostics from the reanalyses is underway.

G. Manney and **J. France** presented results of studies on the high-altitude reformation of the stratopause after SSWs. Operational meteorological analyses cannot capture this feature well and show biases in stratopause altitude and temperature. Low model tops and crude gravity wave parameterisations are important factors leading to these deficiencies.

C. Long investigated the usefulness of reanalyses in providing indicators (via stratospheric cooling) of climate change. He discovered that since reanalyses have discrepancies with satellite data trends, they are not yet ready for use for analysis of climate trends in the stratosphere.

J. Xu evaluated temperature trends from using an ensemble of radiosondes, MSU and reanalyses. The results show that the magnitude of warming or cooling depends on the data sources, atmospheric heights and geophysical latitudes. For global mean temperature, the trend is approximately −0.8K/decade in the stratosphere, and the spread in the ensemble increases significantl with atmospheric height from approximately 0.1K/decade at 850hPa to 0.8K/decade at 30hPa.

C. Long also summarized current and future NCEP reanalysis plans. Two versions of the NCEP reanalyses have been run, initiated in 1995 and 1998 (named R1 and R2, respectively), and the latest reanalysis, the Coupled Forecast System Reanalysis (CFSR), was started in 2010. CSFR has many improvements over R1 and R2 (*e.g.*, use of satellite radiances, higher top/more layers and finer horizontal resolution). However, it has issues such as stream jumps being evident in many parameters (*e.g.*, stratospheric temperatures), a clear signature of a TOVS to ATOVS transition in 1998, and the need to use ERA40 equatorial winds in the early years, since it could not resolve a good QBO. Plans to resolve many of these issues using a lower resolution version of CFSR (called CFSR-Lite) are on hold until sufficien computer and manpower resources become available.

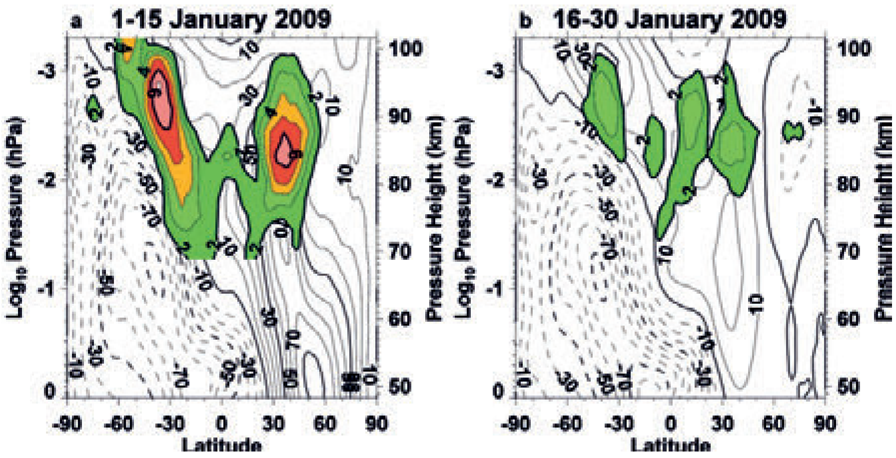


Figure 11: NOGAPS ALPHA zonal mean zonal winds (contours) and amplitude of migrating semi-diurnal tide in meridional wind (shading): (**a**) 1-15 January 2009, and (**b**) 16-30 January 2009. Figure courtesy John McCormack, NRL.

Data assimilation systems

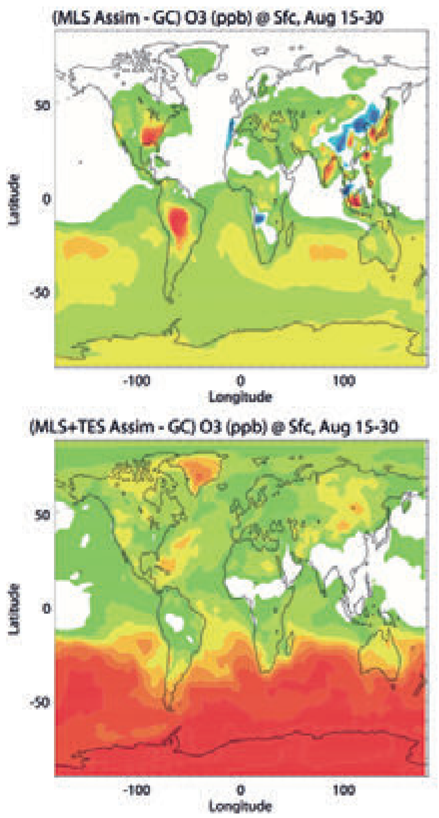
J. McCormack discussed the challenges of high altitude assimilation (up to 90km) with the NOGAPS-ALPHA system. A comparison between model and analysed field during the January 2009 SSW was made. **Figure 11** shows the striking changes in semi-diurnal tidal amplitude before and after the warming. Such changes in tides can feed through to changes in the ionosphere near the F-region peak. These changes can be investigated further using a version of WACCM-X (0-500km range) that is driven by NOGAPS-ALPHA analyses at the lower levels. The next generation assimilation system, NAVGEM, will use semi-Lagrangian advection and assimilate upper atmosphere observations from SSMIS. **K. Hoppel** compared SSMIS data with SABER mesospheric temperatures. The differences are small enough that we can expect a positive impact from UARS assimilation. Biases are generally less than 4K and can likely be dealt with by applying a radiance bias correction. A test SSMIS analysis was performed using NAVGEM with 4D-Var. Comparisons with MLS temperatures (not assimilated) show reasonably good agreement, although there is a large cold bias at pressures less than 0.01hPa.

L. Neef presented assimilations of Earth rotation parameters into the Community Atmosphere Model, the motivation being that Earth rotation varies in time. Observed changes reflect angular momentum of the fluid shell around the Earth, primarily in the atmosphere. Assimilation experiments with simulated observations were presented, and the results hold out the hope that Earth rotation analyses can be a new type of constraint on atmospheric models.

Q. Errera used a spectral representation of spatial correlations in background errors in experiments run with the Belgian Assimilation System of Chemical Observations (BASCOE). The experiments used 4D-Var and constituent data from MLS and MIPAS were assimilated. Ozone analysis increments were larger than in a control run where background error correlations were set to zero and agreement with independent observations were generally better for all analyses examined (ozone, NO_2 and HNO_3). These results were seen in a range of experiments, irrespective of whether model chemistry was switched off or on, and whether all constituent observations, or just ozone, were assimilated. An attempt to tune the error statistics by using the NMC method, however, did not seem to improve the analyses.

Chemical data assimilation

J. Neu presented results from a joint assimilation of Tropospheric Emission Spectrometer (TES) and MLS ozone measurements in the GEOS-Chem Chemistry Transport Model. TES is focused on tropospheric composition with broad averaging kernels, and an effective vertical resolution of ~6-7km for O_3, while MLS is focused on stratospheric composition with narrow averaging kernels, and an effective vertical resolution of ~2-3km for O_3. Joint assimilation of MLS and TES reduces the mean model bias with respect to North American ozonesondes over the entire troposphere from ~10-25% to 5-10%. Notably, assimilating only MLS ozone at pressures below 215hPa has a significant impact on surface ozone (**Figure 12**). There are, however, large regional differences and in some areas assimilation may exacerbate model biases. Further work is needed to understand what the assimilation is telling us about model vertical mixing, especially in the case of MLS alone. The next



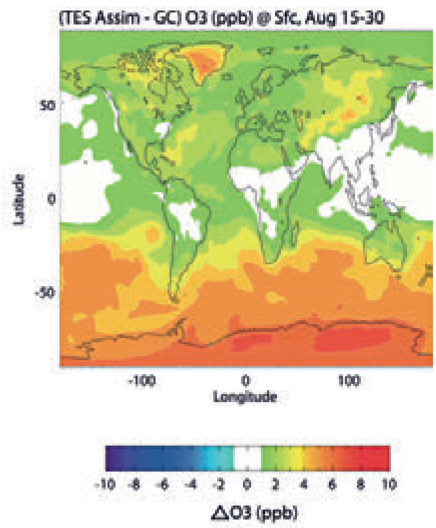


Figure 12: Changes in surface ozone from the free-running GEOS-CHEM model when assimilating MLS ozone at pressures less than 215hPa (**upper left**), TES ozone at pressures less than 908hPa (**upper right**), and both MLS and TES ozone (**lower left**). Figure courtesy Jessica Neu, JPL.

step is to examine the impact of assimilation on STE and better constrain its role in the tropospheric O_3 budget. The experiments were run using 3D-Var, but in future, 4D-Var assimilation with the GEOS-Chem adjoint model will allow analysis of the sensitivity to emissions and processes.

F. Kolonjari focused more on observations of ozone depleting substances from ACE-FTS. The ACE-FTS measurements of CFC-11, CFC-12 and HCFC-22 compare well with surface in situ measurements. The GMI model represents these species well in the troposphere, but not in the stratosphere. Such comparisons of ACE-FTS with models such as GMI can aid in the assessment of the quality of winds from data assimilation systems in both the troposphere and the stratosphere.

D. Jones showed assimilations of MOPITT CO observations in GEOS-CHEM using a weak-constraint 4D-Var algorithm. This approach allows the additional estimation of model errors within the context of 4D-Var. A particular problem is the vertical transport of trace gases associated with parameterised convection. It was shown that convection detrains at too low an altitude in GEOS-4, and even lower in GEOS-5, and that using the weak constraint reduces observation minus forecast differences. These differences can be varied by tuning the assumed model error covariance.

W. Lahoz presented results from the Observation System Simulation Experiments (OSSEs) in an attempt to determine the best design for a future tropospheric air quality observing system. **S. Skachko** described techniques for ensemble-based data assimilation for stratospheric chemistry, while **A. Lambert**'s presentation outlined the near-real time data processing stream from Aura MLS that can be used for data assimilation systems. **M. Santee** analysed trace gas measurements in the UTLS from Aura MLS, and examined their relationship with the strength of transport barriers diagnosed from meteorological analyses.

K. Wargan examined the issue of improving assimilated ozone from 500-50hPa. SBUV ozone data are important since they provide a continuous record through the reanalysis period, but they have poor vertical resolution in the above-mentioned layer. Transport using assimilated winds leads to more realistic ozone profile structures in the UTLS, but assimilation of SBUV in the GEOS-5/MERRA system does not show this vertical structure, since the assimilation process over-smooths it. Replacing background error covariances calculated by the NMC method with covariances that are proportional to the background ozone reduces this smoothing considerably, although the number of UTLS ozone laminae produced in the SBUV-only assimilation was still much less than when HRDLS or MLS ozone observations were assimilated.

J. de Grandpré studied the prognostic treatment of stratospheric ozone in the Environment Canada global NWP system. Ozone analyses are in good agreement with independent measurements, however, interactive ozone forecasts amplify an existing cold bias in the model in the lower stratosphere.

T. Verhoelst focused on observation operators and their application to atmospheric chemical fields Pragmatic observation operators allow quantification of vertical and horizontal spread and offset of remotely sensed data at a relatively "low cost". They can be used to improve co-location criteria, comparison strategies, and interpretation of the error budget in validation work. The next question is how to translate this into chemical data assimilation, and how to quantify the improvement that follows. Collaboration with the assimilation community is required to define diagnostics of improvement and appropriate case studies.

Discussion and future directions

Much of the discussion focused on the two projects that were set up and approved by SPARC in the past year, namely SNAP and S-RIP.

An outline of possible SNAP activities has already been written (see Charlton-Perez and Jackson, 2012). To date, much of the focus of SNAP has been on the interaction between SSWs and the troposphere. However, some concern was expressed that the scope of SNAP should be broader than this. For example, stratospheric connections to tropical cyclones and to the Southern Hemisphere troposphere may also be considered. It should be pointed out that SNAP activities are not yet fixed, and indeed there is further opportunity to discuss the inclusion of the above at a SNAP workshop that will take place at the University of Reading, UK, from 24-26 April 2013 (this workshop will follow on from the SPARC DynVar workshop, also to be held in Reading, 22-24 April 2013). Many scientists from a range of operational and academic centres have already volunteered for SNAP, but the project leader **A. Charlton-Perez** is very keen to hear from other scientists and extends an open invitation to attend the SNAP workshop in April 2013.

While the SNAP discussion suggested broadening the scope of the project, much of the focus of the S-RIP discussion was on ensuring that the scope of S-RIP does not get so broad that the project becomes unwieldy or its goals unachievable. Fujiwara *et al.* (2012) listed a range of possible diagnostics to be produced by the project. However, the feeling from the discussion was to start small, with chapters covering the technical details of reanalysis systems and a basic product quality investigation (*e.g.*, zonal mean wind and temperature climatologies), and then to extend the scope of the project later, after input from those committed to the project. To facilitate this, it was suggested that a project working group be formed and the detailed structure of the project be discussed through a workshop. Subsequently, an S-RIP Working Group has indeed been formed, and a project planning workshop will take place from 29 April–1 May 2013 at the Met Office, Exete , UK.

Regarding gravity waves, a recommendation from last year's workshop was that a project focused on intercomparison of the missing body force due to sub-grid scale gravity wave drag be set up. No such SPARC project was set up, and discussion returned to this topic. J. Alexander is leading a project supported by ISSI in Bern, Switzerland, entitled "Atmospheric Gravity Waves in Global Climate Prediction and Weather Forecasting Applications", which will include assessments of missing body force due to gravity waves. This may partially meet the requirements set out above.

More generally, M. Geller suggested an intercomparison of models with different vertical resolutions. The focus could include both the troposphere and stratosphere, as well as various sub-topics such as tropopause resolution and impacts on the QBO. It was felt that this proposal was too wide-ranging to take any action on, other than to continue to discuss and possibly refin the proposal, in consultation with colleagues in WGNE. However, it emerged that there is considerable scope for a resolution intercomparison project focused solely on gravity waves. The results from the presentations by J. Alexander and D. Siskind, and the subsequent discussion, underline the fact that there is no fixed answer to the amount of model resolution required to adequately represent gravity waves and their effects. Rather, an appropriate level of resolution depends on the formulation of each model. There may be mileage in organising a project that intercompares the performance of various models in representing gravity waves for a range of both horizontal and vertical resolutions.

Progress toward the three other goals from the 2011 workshop was also discussed. The first was to produce a summary report on the representation of the stratosphere in global NWP systems. A preliminary presentation was given by D. Jackson, but further resources are needed to complete this work in a timely manner. There is also the possibility of overlap with the goals of the SNAP project. Second, there was little progress in developing greater interaction between the chemical assimilation and satellite retrieval communities, but informal discussions continue between interested parties, and presentations on this topic are welcomed at next year's meeting (see below). Third, updating the SPARC section of the WMO observations Rolling Requirements document (last updated 1998!) was discussed with J. Eyre (Chair of the WMO Evolution of Global Observing Systems team). It was decided that SPARC needs are met by other WMO Rolling Requirements themes (*e.g.*, global NWP, atmospheric chemistry), and that a separate SPARC theme was not needed.

At the conclusion of the workshop,

attendees were invited to participate in a tour of the Very Large Array (VLA) radio telescope facility, located about 80km west of Socorro. Those who participated were treated to a close-up inspection of one of the telescope dishes (see **Figure 13**) as well as sightings of New Mexico wildlife such as antelope (and fortunately, no rattlesnakes!).

Figure 13: Participants at the 9th SPARC Data Assimilation Workshop held in Socorro, New Mexico, USA.

Next meeting

Because of the large number of meetings next year (including SNAP and S-RIP workshops, and the first meeting of the gravity wave project in Bern), it was decided that there will be no SPARC Data Assimilation workshop next year. However, we encourage those interested in SPARC data assimilation activities to submit presentations to the American Meteorological Society Conference on the Middle Atmosphere, which will be held from 17–21 June 2013 in Newport, Rhode Island, USA. We anticipate that there will be a dedicated session on data assimilation at the conference, and we plan to hold a SPARC Data Assimilation side meeting there as well.

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Research using High Vertical-Resolution Radiosonde Data

Marvin A. Geller and **Peter T. Love**

School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY, USA, marvin.geller@stonybrook.edu, and peter.love@stonybrook.edu

One of the early SPARC initiatives was to promote research using high-resolution radiosonde data (Hamilton and Vincent, 1995). The intrinsic resolution of the measurements made by radiosonde devices is much higher than what is typically recorded for meteorological purposes. Allen and Vincent (1995) illustrated the utility of these high-resolution data for the purposes of gravity wave analysis. It was this study that largely inspired SPARC's effort to promote the archiving of high-resolution radiosonde data by meteorological organisations worldwide, as in Hamilton and Vincent (1995). The US National Oceanic and Atmospheric Administration (NOAA) began archiving radiosonde data from US upper air stations at six-second resolution in April 1995, which corresponds to approximately 30m vertical resolution given an ascent rate of 5m/s. With the support of the US National Science Foundation and National Aeronautical and Space Administration, these data have been made available at the SPARC Data Center (SPARC DC) at Stony Brook University since 1998. The SPARC DC operates a data server in support of SPARC projects, which is publicly accessible via the website: **http://www.sparc.sunysb.edu**, and ftp database, and via ftp at: **ftp://atmos.sparc.sunysb.edu**. Radiosonde data downloaded from the SPARC DC has been applied to research in a variety of fields leading to many peer reviewed publications.

In 2005 NOAA began progressively upgrading the US upper air network under the Radiosonde Replacement System (RRS), in which the radiosonde data are recorded at one-second resolution. These data have also been made available at the SPARC DC. While these new very high-resolution data have already facilitated new applications of radiosonde data through improved resolution and access to the raw data, the full potential of this data set has yet to be realised.

Applications

The high-resolution data available at the SPARC DC were originally acquired from NOAA by M.A. Geller in the interests of the SPARC Gravity Wave Initiative. Gravity wave research within the group at Stony Brook University has utilised these data in numerous publications, including studies on the spatial and temporal variations of gravity wave parameters (Wang and Geller, 2003) and on gravity wave spectral characteristics (Geller and Gong, 2010). Gravity wave research at Stony Brook continues, with recent efforts focused on characterising the distribution of gravity wave momentum flux to constrain gravity wave parameterisations in general circulation models (**Figure 14**). Recently, other groups have contributed to this research by extending the analysis period as the data set has been updated from year to year (Zhang *et al.,* 2010), as well as for investigating planetary waves (Wang *et al.,* 2010).

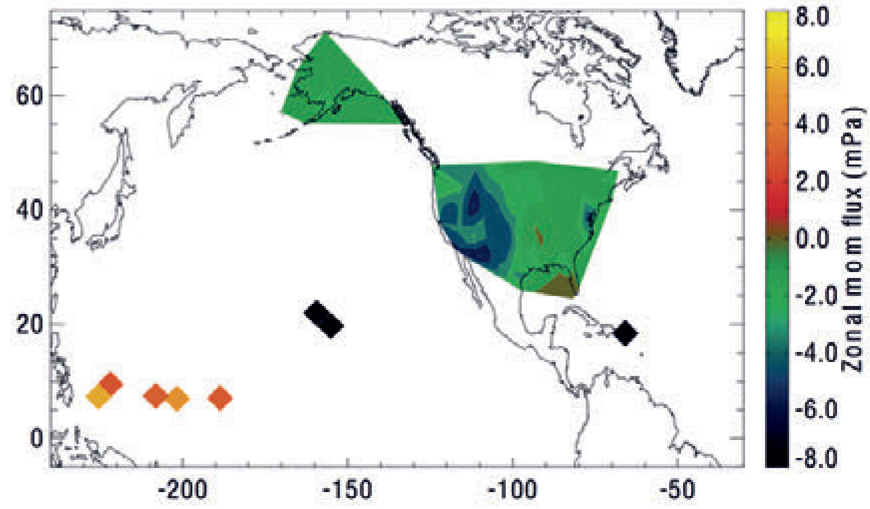

Figure 14: Distribution of zonal gravity wave momentum flux at 18-25 km from US upper air stations during the period March-May, 2006.

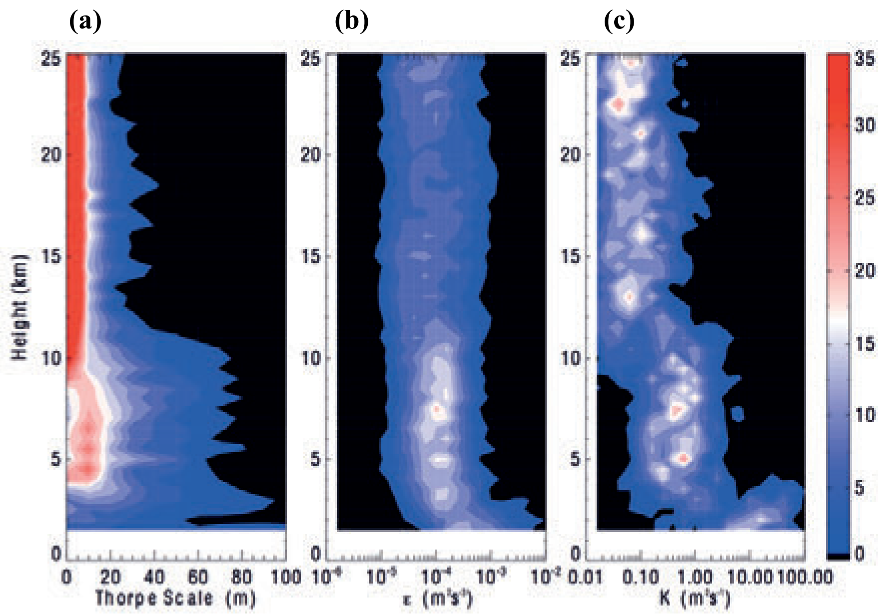

Figure 15: Probability densities (in %) of turbulence parameters derived from three months of 1-second resolution radiosonde soundings at Riverton, Wyoming, in winter 2007. (**a**) The Thorpe scale calculated from the potential temperature profile, which is taken to be proportional to the Ozmidov scale, (**b**) eddy dissipation rate, and (**c**) eddy diffusivity.

Having made these data publicly available, it was not long before other groups began using the data for different applications. Various studies have utilised data from tropical stations to investigate tropical convection in relation to mass flu and water vapour budgets (Folkins and Martin, 2005), parameterisation validation (Folkins *et al.,* 2006), and troposphere-stratosphere transport (Corti *et al.,* 2006).

High-resolution data have permitted important research into the structure of the tropopause. Birner (2006) analysed high-resolution US radiosonde data to investigate the fine-scale structure of the extra-tropical tropopause, while Gettelman and Birner (2007) used the data to assess the ability of GCMs to resolve key features of the tropical tropopause layer. Bell and Geller (2008) followed up the work of Birner (2006) by presenting a quantitative analysis of the latitudinal and seasonal variations of the tropopause inversion layer.

Other applications of high-resolution US radiosonde data have included validation of satellite observation techniques, studies of pyrocumulonimbus processes, studies of polar regions and effects of geomagnetic storms on the lower atmosphere.

Clayson and Kantha (2008) highlighted the potential for routine broad-range analysis of clear air turbulence parameters permitted by the increase to one-second resolution. The technique they applied was developed for oceanic turbulence and had been adapted in previous studies to atmospheric radiosonde data from localised, short-duration observation campaigns. With the advent of routine high-resolution sounding over broad geographic areas, the potential exists for both local and regional, as well as short time-scale and climatological studies of clear air turbulence; a topic of research currently being pursued at Stony Brook University. The climatological information being compiled will be made publicly available, an example is shown in **Figure 15**.

These data also make possible new research into gravity wave breaking into turbulence. **Figure 16** shows profiles from 8-17km from a sounding made at Riverton, Wyoming, of potential temperature (θ); wind fluctuations, differences from the mean wind profile as determined by low-order polynomial fitting the Brunt-Väisälä frequency; gravity wave wind shear; the Richardson number; the Thorpe scale; the turbulence kinetic energy dissipation rate (ε); and the turbulence diffusion (K). Clearly evident are the gravity waves in the wind fluctu - tions and the turbulence associated with wave-induced shear instability between 12-13km and in a deeper layer between 14-16km through which the wave dissipates. Such information will, for example, be useful for identifying turbulence produced from gravity waves with different sources.

The above are just some of the many papers that rely on the high-resolution radiosonde data that have been made available at the SPARC DC. As mentioned above, the full potential of these data, particularly at one-second resolution, has yet to be realised in two respects. First, there are potential applications that have not yet been explored, for example, the one-second resolution data could be particularly useful for studies of the boundary layer. The second aspect of the high-resolution radiosonde data that has yet to be realised is the move from regional analysis using databases from individual meteorological organisations to global analysis facilitated by improved access to data, potentially at a collective repository.

Availability

The SPARC DC currently holds high-resolution radiosonde data from more than 90 US upper air stations for the period 1998-2008. Data for the years 2009-2011 should also be available on the SPARC DC by the middle of 2013. The majority of stations have a continuous record for this period, with a transition from six-second to one-second resolution occurring for each station at some time during the period 2005-2011. Both six- and one-second resolution data are available

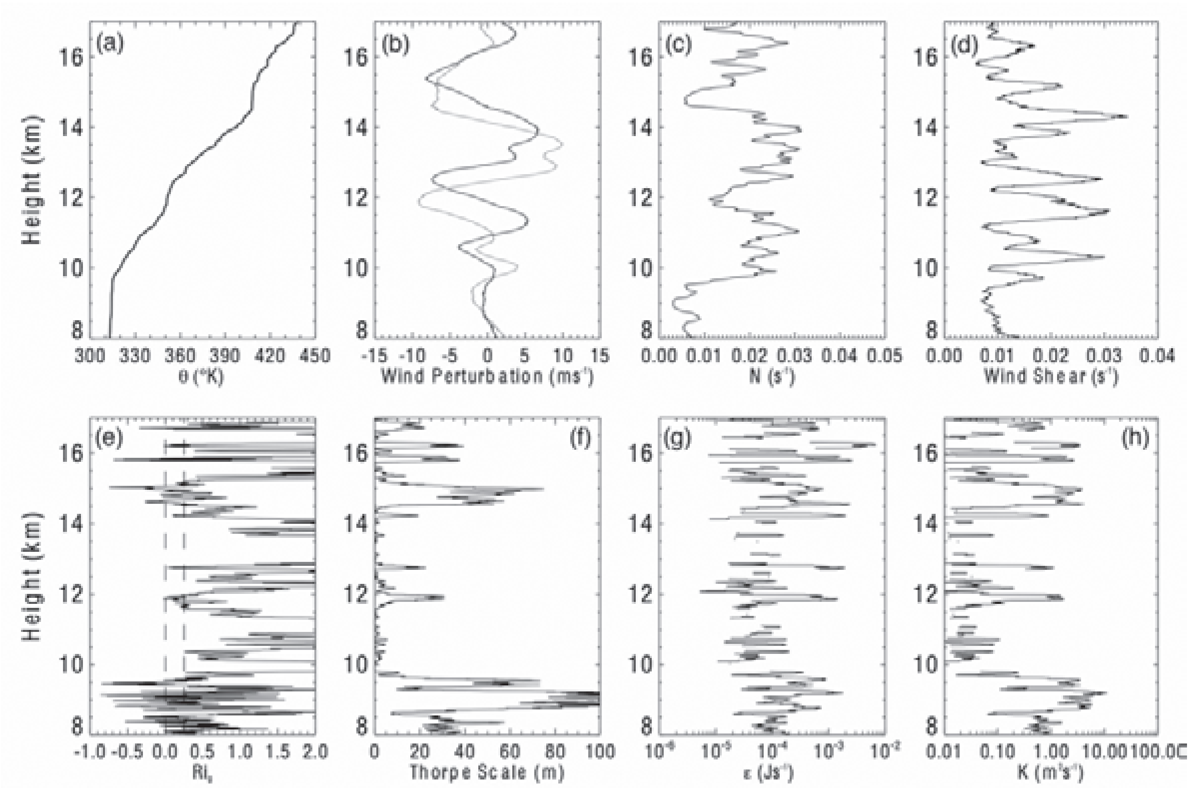

Figure 16: Gravity waves and turbulence parameters derived from 1-second resolution sounding made on 2 February 2007, Riverton, Wyoming. (**a**) potential temperature, (**b**) zonal (black) and meridional (grey) wind perturbations, (**c**) buoyancy frequency (N), (**d**) mean shear, (**e**) gradient Richardson number (Rig), (**f**) Thorpe scale, (**g**) TKE dissipation rate and (**h**) eddy diffusivity. Note that N was calculated from the sorted potential temperature profile while Rig was calculated using the unsorted profile, hence the regions of Rig<

in their native resolution, while the one-second data is also available in the six-second format to provide a continuous 11-year data set. At one-second resolution, both raw and processed data are included in each record. Access to the data is available through the SPARC DC website at **http://www.sparc.sunysb.edu/html/hres.html**.

Workshop

The SPARC DC will host a workshop on research applications of high-resolution radiosonde data, to be held from 27-29 May 2013 at Stony Brook University, New York. The workshop will have three main goals: to provide a forum for research using high vertical-resolution radiosonde data, to explore and encourage new applications of these data, and to explore the possibility of expanding the availability of international high vertical-resolution data for use by the international research community. Further information regarding the workshop can be found at **http://www.sparc.sunysb.edu/workshop**.

Contact

Interested parties are encouraged to contact the authors with any ideas, issues or questions relating to the database. We welcome expressions of interest to attend the workshop. Some funding is being made available through the NSF and SPARC to subsidise transport expenses for invited speakers, young scientists, and some others who need financia assistance to attend. Similarly, we seek any interest in contributing to the establishment of an expanded high-resolution radiosonde database. The SPARC DC scientist is available to provide help with the download and interpretation of data.

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Report on the 1st Joint SOLARIS-HEPPA Meeting, 9-12 October 2012, Boulder, CO, USA

Katja Matthes[1], Bernd Funke[2], Cora Randall[3]

[1]GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany, kmatthes@geomar.de, [2]Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain, bernd@iaa.es, [3]University of Colorado, Boulder, CO, USA, Cora.Randall@lasp.colorado.edu

The 4th HEPPA (High Energy Particle Precipitation in the Atmosphere) workshop was held for the first time together with the 3rd SOLARIS (SOLAR Influences for SPARC) workshop from 9-12 October 2012 in Boulder, Colorado, hosted by the National Center for Atmospheric Research. 60 participants from 12 countries attended the four-day workshop, focusing on observational and modelling studies of the influences of solar radiation and energetic particle precipitation (EPP) on the atmosphere and climate. In order to join the two diverse communities, the first three days were organised with a mixture of invited tutorial and overview talks for a general audience, in plenary sessions as well as extended poster sessions. The tutorials and overviews covered topics including the causes and phenomenology of solar radiation and energetic particle variability, mechanisms by which radiative and particle forcing affect atmospheric chemistry and dynamics, contributions of solar and Energetic Particle Precipitation (EPP) forcing to climate variability and space weather, as well as the current state-of-the-art and future needs in space observations and chemistry-climate models. The three two-hour poster sessions, with a total of 52 poster presentations, dealt with solar and particle variability in general, solar and particle effects on the stratosphere and above, solar and particle effects on the troposphere and climate, atmosphere and ocean-atmosphere coupling, as well as tools for assessing solar and particle infl - ences. Each of the poster sessions was introduced by one-slide summaries of the posters in the plenary session in order to advertise and give an overview of the poster contents.

After a welcome by the local organising committee (Cora Randall, Dan Marsh and Stan Solomon), **H. van Loon** gave an impressive talk starting with a brief historical perspective of how he started Sun-Earth connection research with his colleague Karin Labitzke in the 1980's, and continuing through to his most recent work on the 11-year solar cycle influence on the monsoons, emphasising the effects over the Pacific. The effect of sunspot peaks is to enhance long-term means, in particular, of tropical convection in northern winter (during the Australian-Indonesian Summer Monsoon) and the dry zone in the Pacific The rising branch of the Hadley circulation is displaced poleward, while the Walker circulation extends westward. During northern summer (Indian summer monsoon) enhanced monsoon convection during solar maximum occurs over the Indian Ocean, while reduced convection is found over the tropical Pacific. Effects of solar influence on global mean temperatures in the troposphere are minimal.

K. Matthes gave an overview of our current understanding of solar irradiance effects on the Earth's atmosphere and climate, including observed solar climate signals in the stratosphere and troposphere, as well as a discussion of the stratospheric "top-down" UV and the tropospheric "bottom-up" mechanism and their representation in chemistry climate models. Open issues and uncertainties include the observed solar signal, non-linear relations between the solar signal and other external factors in the stratosphere and troposphere, the role of top-down *vs.* bottom-up effects, spectral solar irradiance forcing, the role of the sun for decadal climate predictability, as well as other contributions (particles) to solar infl - ences on climate.

R. Horne gave an overview of the structure and variability of particle precipitation. In contrast to sporadic solar energetic particle events that peak around solar maximum, auroral and radiation belt electron precipitation is enhanced during the declining phase of the solar cycle. Various types of wave-particle interactions are responsible for particle precipitation at different energies and different magnetic local times. Enhanced radiation belt electron precipitation in the Southern Hemisphere is thought to be linked to the South Atlantic anomaly.

C. Jackman summarized our current understanding of the effects of energetic particle precipitation (EPP) on the Earth's atmosphere. Both protons and electrons can

Figure 17: Group picture of the joint SOLARIS-HEPPA Meeting in front of Center Green, NCAR, Boulder, CO, USA. Photo courtesy Dan Marsh, NCAR.

influence the polar middle atmosphere through ionisation and dissociation processes and subsequent HO_x and NO_x formation. Middle and upper stratospheric Ozone depletion of more than 30% has been observed during several large solar proton events (SPEs) in the past 50 years. Model predictions indicate that some statistically significan SPE-caused ozone decreases can last for up to five months past the largest events. Model predictions and measurements also show that certain years are related to significant winter-time meteorological events, which result in more transport of EPP-induced NO_x enhancements from the upper mesosphere and lower thermosphere to the stratosphere.

K. Kodera gave an overview of the solar influence on the troposphere through dynamical processes, and concentrated on possible explanations for the solar surface signal. The extra-tropical solar signal in the polar front and subtropical jets can be explained with interactions related to solar-induced differences in planetary wave propagation in the stratosphere, whereas tropical solar signals in the Hadley and Walker circulation are related to solar-induced changes in the mean meridional circulation of the stratosphere. A challenge will be to reproduce the stratospheric footprint shown in idealised model experiments in simulations using realistic solar forcing. Solar effects in the troposphere are regional and are therefore not visible in global mean temperatures.

A. Seppälä focused on tropospheric and stratospheric dynamical variations that have been linked to EPP and geomagnetic forcing. Though model simulations and statistical studies using reanalysis data have shown an impact of geomagnetic activity variations on climate variables such as tropospheric temperatures, the mechanism able to communicate EPP-induced changes from the source altitudes in the thermosphere, mesosphere or stratosphere, all the way to the troposphere and surface has remained unclear. Potential linkages between high altitude EPP effects and lower altitude dynamical variables, as well as how these may be affected by or linked with other natural variations in the atmosphere, such as the solar irradiance cycle, were also discussed.

J. Meehl presented an overview of the role of the ocean in solar irradiance effects on climate variations, focusing on the bottom-up, coupled air-sea mechanism and its combined influence with the top-down stratospheric UV mechanism in modelling studies. Both mechanisms together strengthen tropical convection and amplify cloud feedbacks. The peak solar signal in SSTs resembles the La Niña-like pattern in the Pacific, whereas studies using a broad decadal solar peak show a lagged, warm SST response. Simulation of a grand solar minimum with a high-top coupled chemistry-climate model starting in 2020 and lasting 50 years shows a slight slow down of the warming due to the reduced solar forcing, but an overwhelming greenhouse gas effect after a few decades.

L. Goncharenko discussed atmospheric coupling processes by planetary waves, gravity waves, and tides. Experimental and modelling evidence illustrates how variations in the stratosphere are communicated upward, and how variations in the mesosphere/lower thermosphere are communicated downward. Specific examples for the periods of sudden stratospheric warming were shown.

P. Pilewskie gave an overview of historical, current, and planned solar irradiance measurements. Total Solar Irradiance (TSI) measurements from SORCE/TIM with an absolute value of 1361W/m^2 are in agreement with PICARD/PREMOS. A new TSI mission (GLORY/TIM) was lost in 2011, and a new mission, JPSS-FreeFlyer1/TSIS, will be delayed until mid 2016. Solar spectral irradiance (SSI) measurements from SIM and SOLSPEC agree within 1% over most of the spectrum and rotational SSI variability is well captured. The solar cycle variability in some SIM spectral bands exhibits a trend that is out of phase with the TSI. This phenomenon requires further observational validation, and more study in order to understand its climate implications, as well as continued instrument validation. This work is already underway.

C. Rodger presented recent evidence that energetic electron (greater than about 10keV) and relativistic electron (greater than about 500keV) precipitation can lead to significant production of HO_x and NO_x in the mesosphere, and hence may couple to the downward travelling NO_x produced by auroral electrons. Existing observations of precipitating electrons from the radiation belts (such as MEPED/POES) have been reviewed and remaining uncertainties, in particular regarding high-energy and relativistic electron fluxes, were discussed in the context of using these measurements to directly drive atmospheric chemistry-climate models.

J.-E. Kristjánsson discussed the effects of galactic cosmic rays (GCRs) on the atmosphere and climate via cloud modulation, which occurs either via cosmic ray-induced ionization (CRII) and aerosol formation, or via electrical charges associated with clouds. Such effects have been proposed on various time scales, ranging from days in the case of Forbush Decrease Events, to decades in the case of solar cycle variations, to time scales of millions of years in the case of galaxy spiral band variations. Despite the controversy, global aerosol models and even global climate models have started accounting for CRII as a possible catalyst for aerosol formation in the presence of supersaturated precursor gases.

N. Schwadron provided a heliospheric view of the recent anomalous deep solar minimum and firs extreme events in solar cycle 24. Observed changes in the space environment during the last years provide insights into a very different regime of solar behaviour than observed during the space age. These changes also provide critical hints about the regimes that may have prevailed in historic periods such as the Maunder Minimum and during the Carrington Event. A review of the historic record of Solar Energetic Particle (SEP) events from ice cores shows that considerable controversy exists and several fundamental questions have been raised concerning the timing, accuracy or even the ability of ice cores to store information concerning SEP events.

B. Funke gave an overview of past and present observations of the middle atmosphere used in the analysis of the impact of solar irradiance variations and particle precipitation effects and their impact on recent scientific advances. Observational data needs for SOLARIS-HEPPA have been identified in order to consolidate recommendations for future observations, such as currently conducted within the SPARC measurement requirement initiative. These include the need for continuous improvements of existing data products and the generation of merged data sets. Follow-up missions targeting vertically resolved temperature and trace gas observations (in particular ozone and NO_x) are urgently required to fill the expected observational gap. The need for global wind observations in the mesosphere has also been identified

D. Marsh described the numerous ways in which solar and energetic particle forcings are implemented in current chemistry-climate models (CCMs). The majority of CCMs used for climate studies simply neglect particle forcing, however, recent event studies have included both energetic electron and proton particles covering a broad range of energies. As more models used for future climate prediction incorporate chemistry, the solar and atmospheric communities should continue to critically evaluate solar and geomagnetic forcing within CCMs, and provide clear recommendations for their future use.

Conclusions and future plans

C. Randall and **K. Matthes** collected and summarized the participants' input concerning recent advances and major outstanding issues with respect to solar irradiance variations and energetic particles (EPP, SPEs, and GCRs). The collected and condensed information will be the basis for a white paper regarding solar influences on climate, also geared towards the next SCOSTEP science programme. The recognition of solar influences by radiation, particles and GCRs as important drivers of climate variability is one of the major advances of recent years, which has been achieved by significant improvements in both atmospheric modelling (inclusion of relevant processes and forcings) and observations. The importance of the top-down stratospheric UV (SSI) mechanism is nowadays well established and more effort is spent on the regional response to SSI and particle forcing. The following major outstanding issues have been identified: (i) remaining uncertainties in observational constraints on forcing terms (both SSI and particles), including the vertical distribution of EPP-induced ionisation; (ii) uncertainties in the determination of the solar signal from observational records related to insufficient temporal coverage; (iii) the relative roles of the top-down and bottom-up mechanisms and the role of the sun for climate predictability; and (iv) the role of GCRs on cloud formation.

During the discussion session the recommendations for the next chemistry climate model intercomparison (CCMI), including solar radiative and particle forcings, were discussed. These forcing recommendations, which were ready by the end of December 2012, include daily solar spectral irradiance data from the NRLSSI dataset (Lean, 2005) and ionisation rates to account for SPEs in the reference simulations from 1960 to 2010, as well as a method for how to extend the solar cycle into the future through to 2100. An additional scenario run will be proposed in which another SSI dataset with larger UV variability will be used instead of the standard NRLSSI data set to investigate the sensitivity of the projections to solar forcing. These recommendations and data will be available through the SOLARIS website (**http://sparcsolaris.gfz-potsdam.de/input_data.php**).

Awards

E. Peck, a graduate student at the University of Colorado, was nominated for the IAGA Young Scientist Award in recognition of the high quality of his poster presentation "Solar Cycle Influences on Southern Hemisphere Polar Lower Stratospheric Ozone". If he is selected by IAGA, he will receive the registration fees to attend the next IAGA conference in Merida, Mexico, next summer (26-31 August 2013).

Working group meetings

The last day of the workshop was reserved for the SOLARIS and HEPPA model/measurement intercomparison working group meetings, which were open to all interested participants. After a plenary session, two splinter meetings for the working groups were held, and the day ended with a joint session with reports from the breakout session. In the morning, **K. Matthes** and **B. Funke** gave an overview of recent SOLARIS-HEPPA activities. These included a recently published overview paper on the variability of solar spectral irradiance and its impact on climate modelling (Ermolli *et al.*, 2012), as well as first results from the HEPPA-II model measurement intercomparison activity (Funke, 2010). Afterwards, a few related projects were presented: **J. Meehl** reported on the status of ongoing IPCC activities and chapters where solar variability is mentioned, **A. Seppälä** reported on recent CAWSES-II Task Group I activities and their link to SPARC-SOLARIS/HEPPA, and **Dan Marsh** presented the recently launched ISSI Project "Quantifying hemispheric differences in particle forcing effects on stratospheric ozone".

During the HEPPA MMI breakout session, first results of the HEPPA-II model-measurement intercomparison activity (see Funke, 2010) were discussed. This activity focuses on observed and modelled polar winter descent of EEP-produced NO_x in the 2009 Northern Hemisphere winter. Comparisons of 7 satellite data sets (ACE-FTS on SciSat; GOMOS, MIPAS, and SCIAMACHY on Envisat; MLS on Aura; SABER on TIMED, and SMR on Odin) with nudged simulations of various models (B3dCTM, EMAC, FinROSE, KASIMA, and WACCM) were presented. These models include either an auroral EEP source or were prescribed with observed NO_x at the upper boundary. Although all models reproduce the NO_x descent, there are differences in the magnitude and vertical distribution of modelled NO_x compared to the observations, and further work is needed to understand these differences. Next steps have been identified and responsibilities have been assigned. One important focus will be the intercomparison of meteorological parameters in simulations in the free-running domain and how they compare to observations. Further effort will be made to assess the consistency of different NO_x observations in the mesosphere and lower thermosphere.

During the SOLARIS breakout session, coordinated offline and time-slice experiments designed to understand uncertainties in solar forcing following up on the ACPD paper (Ermolli *et al.*, 2012) using the SATIRE, COSI, SRPM, SORCE/SIM and SCIAMACHY SSI data sets were discussed. Groups that provide SSI data sets will be contacted and a description of the planned experiments will be prepared within the next six weeks. Additionally, the CCMI recommendations for solar forcing were discussed. It is hoped that through interactions between the SSI and CCMI communities a commonly accepted method on how to extend the solar cycle in future simulations can be established.

Coordinated analysis of the solar signal in the CMIP5 (high-top) simulations was discussed and responsibilities were distributed. In six weeks a questionnaire about the respective model configurations and low *vs*. high-top model runs from the same model will be circulated to the modelling groups. For a first intercomparison of the results a small, dedicated workshop will be held in England in summer 2013 with a lot of time to discuss and write up the current research.

The next joint SOLARIS-HEPPA Workshop will be held in Baden-Baden, Germany, from 5-9 May 2014, and will be hosted by the Karlsruhe Institute of Technology.

Acknowledgements

We would like to acknowledge the tremendous contribution of Kuni Kodera to solar influence studies. He now retires from the SOLARIS leadership, after having initiated solar intercomparison studies with GCMs under GRIPS (GCM Reality Intercomparison Project for SPARC) in the mid 1990's. He will continue to be an essential advisor of our future activities.

Additionally, we would like to thank WCRP/SPARC for its support, as well as sponsorship from NCAR, CU Boulder, SCOSTEP/CAWSES, NASA/Living With a Star, ATOC, and IAGA.We especially thank the local organising committee for an excellent venue and organisation of the meeting.

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U.S. - Japan Bilateral Workshop on the Tropical Tropopause Layer: State of the Current Science and Future Observational Needs, 15-19 October 2012, Honolulu, HI, USA

A. Gettelman[1], K. P. Hamilton[2], G. A. Morris[3], F. Hasebe[4], H. B. Selkirk[5]

[1]NCAR Earth System Laboratory, Boulder, CO, USA, andrew@ucar.edu, [2]University of Hawaii, Honolulu, HI, USA, kph@hawaii.edu, [3]Valparaiso University, Valparaiso, IN, USA, Gary.Morris@valpo.edu, [4]Hokkaido University, Hokkaido, Japan, f-hasebe@ees.hokudai.ac.jp, [5]NASA Goddard, Green Belt, MD, USA, henry.b.selkirk@nasa.gov

The Tropical Tropopause Layer (TTL) is the dominant region for entry of tropospheric air into the global stratosphere. The TTL is a several kilometre thick layer in which air has characteristics of both the troposphere and stratosphere (**Figure 18**). Despite significan theoretical advances and a rapidly growing archive of observations, important science questions related to the control of humidity and the chemical composition of air entering the stratosphere remain unanswered. Many different processes are involved, including convective transport, large-scale ascent, atmospheric waves, and cloud microphysical processes. Further progress requires better analysis of current observations and new observational campaigns in which *in situ* observations on both balloons and aircraft platforms are coordinated with satellite observations.

To this end, a bilateral Japan-US workshop was held at the University of Hawaii (Honolulu), from 15–19 October 2012. The workshop assembled scientists from Japan, the United States, and several other countries, with the goal of catalysing new collaborations and studies of the TTL. The workshop was sponsored by the National Science Foundation's 'Catalyzing New International Collaborations Program' (Award #1158805). The overall objectives for the workshop were three-fold: 1) coordination of TTL campaigns planned for the next few years; 2) development of new collaborations involving the next generation of Japanese and U.S. scientists; and 3) dissemination of educational materials on the TTL developed for this workshop to faculty and students worldwide.

The workshop focused on refinin science questions and coordinating planned TTL observation and analysis campaigns in the Tropical Western Pacific, to ensure that the scientific impact of the combined effort will be greater than the sum of individual projects. Catalysing specific cooperation and collaboration for field projects maximises the coordination of observations, enables joint analysis of the data and leaves a legacy of important data sets for the community. Such effort ultimately improves knowledge of the climate system and atmospheric chemistry, while training the next generation of U.S. and Japanese scientists who establish lasting collaborations. An innovative electronic tutorial component to the workshop including archived presentations and posters is now available on the world wide web (**http://scholar.valpo.edu/ttlworkshop**).

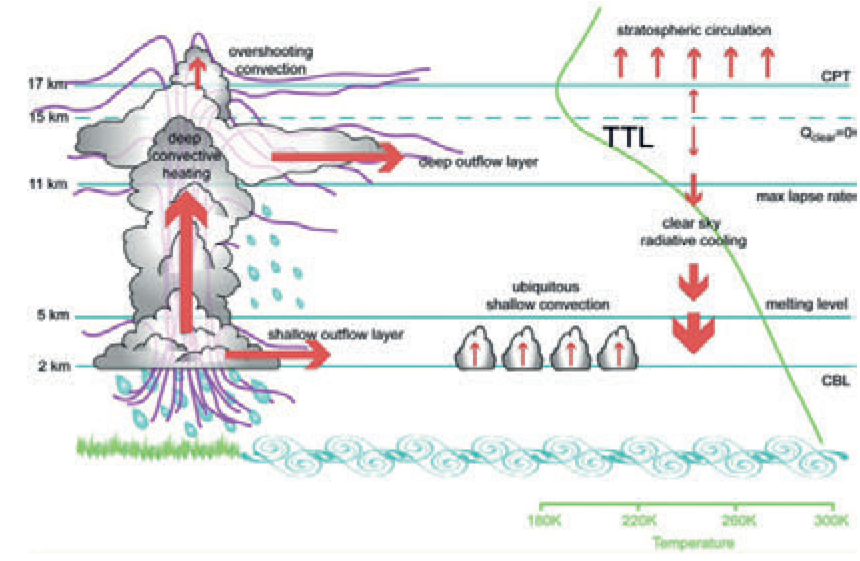

Figure 18: Schematic of the tropical atmosphere and the Tropical Tropopause Layer (TTL). Figure from L. Pan (personal communication). Original from Pendlebury, 2007 (for SPARC).

Science questions

There were several common themes among the tutorials and projects presented at the workshop, broken down into a series of critical topics and science questions. Many of these questions are being addressed in some way by upcoming campaigns in the TTL (see section on campaign descriptions).

The **boreal summer Asian Monsoon**, marked by a large anticyclone in the TTL, dominates the June-September season and has profound implications both regionally and globally. Observations indicate that tropospheric air (with high water vapour and CO content) is found even at high altitudes in the anticyclone (Randel and Park, 2006). An example is shown in **Figure 19**, where high water vapour is seen in the region of the anticyclone, which is not coincident with regions of deep convection. Exactly how air with water vapour, trace gases and aerosols is transported from the boundary layer into the TTL and stratosphere is not well understood. There are simulations on the impact of the Asian Monsoon for the global TTL (*e.g.*, Gettelman *et al.*, 2004), but monsoon effects are not well characterised from observations. There are several campaigns with components all or partly in the June-September time frame that will try to constrain tracer budgets and observe convective transport in the region (see below). Several current and proposed projects (see below and **Table 1**) are focused on the Asian Monsoon. These projects include: StratoClim (Thailand), ATTREX (Global Hawk, Australia, 2014), SEAC4RS (cloud, chemical tracers, regional/global air quality), SWOP (soundings of O_3 and H_2O) and SEACIONS (O_3).

Wave processes are critical in the TTL, and occur at small to global scales. Several important aspects of TTL waves were discussed. It is important to quantify mixing associated with horizontal Rossby wave-breaking from mid-latitudes in the TTL (Waugh, 2005). **Figure 20** shows an example of the relationship between a large-scale equatorial Kelvin wave and TTL cirrus formation with variations in temperatures,

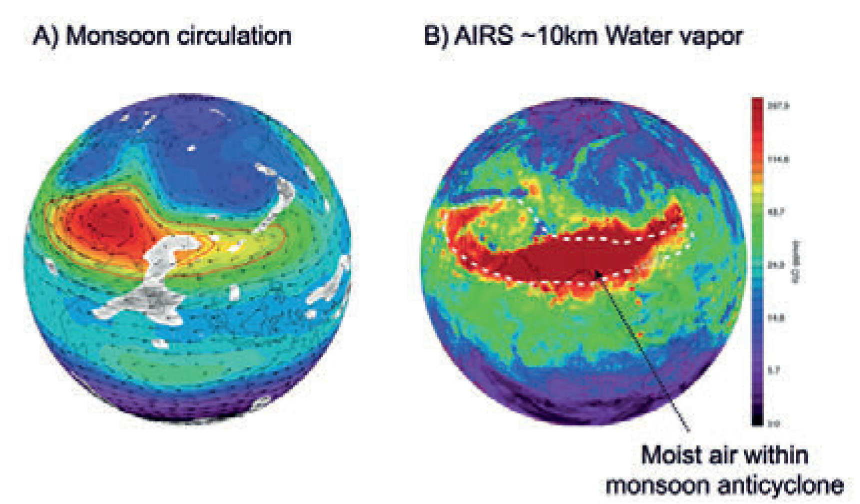

Figure 19: Based on Randel & Park 2006, JGR, Figure 1. (**a**) June-August climatological Monsoon Circulation (Streamfunction) and wind vectors. Also shown are low values of outgoing longwave radiation representing deep convective clouds. (**b**) AIRS 150hPa water vapor (contours).

Table 1: Current and proposed projects and campaigns:

CAMPAIGN/ PROGRAM	Status (Oct. 2012)	SCIENCE FOCUS	Region of Study	Deployment base; site(s)	Key observations	Primary platform(s)	Observational program	Duration	Lead organi-zations	Science Leadership (present/not present)
JF 2013										
SOWER 2013	Go	TTL water vapor and ozone	Pacific warm pool	Biak [1°S, 136°E]	Water vapor/ozone [CFH/ECC]	Balloon; ground-based lidar	Approx. 5 launches	One week	Hokkaido University; Kyoto University	**F. Hasebe (PI) and M. Fujiwara; M. Shiotani**
ATTREX (1)	Go	TTL structure and microphysics	Eastern and central equatorial Pacific	NASA-DFRC [southern California]	Water vapor, ozone, temperature, ice microphysics	Global Hawk (high-alt UAV)	Up to 6 long-duration (>24-hours) flights	Six weeks	NASA ARC	**E. Jensen (PI) and L. Pfister**
JJA 2013										
SEAC4RS	Go	Summer monsoon: tropospheric aerosols and chemistry; upper-level anticyclone; biomass burning	Southeast Asia	Singapore *(tentative)*	Aerosol, atmospheric composition, radiation and microphysical measurements	DC-8 (to 12 km) & ER-2 (high altitude)	coordinated and separate flights	6-7 weeks	NASA	B. Toon (PI), **E. Jensen**
SEACIONS	Go	Vertical structure and variability of ozone, water vapor		Kuala Lumpur, Malaysia; Ha Noi and Bac Lieu, Viet Nam; SEAC4RS site	Ozone, water vapor	Balloon	launches daily or every other day; concident with SEAC4RS	6-7 weeks	Penn State Univ.	**A. Thompson (PI) and H. Selkirk**
SWOP	Go	TTL structure and microphysics	Tibetan plateau	Lhasa [29.7°N, 91°E]	Ozone [ECC], water vapor [CFH], aerosols [COBALD]	Balloon	balloon sonde profiles		Inst. Atmos. Physics (IAP), China	**J.-C. Bian (PI)**, H. Vömel
Palau 2013	Go	TTL microphysics	Pacific warm pool	Koror, Palau [7.4°N, 134°E]; Guam, Yap [9.5°N,138°E]	Water vapor, cloud particle imaging	Balloon	CFH & HYVIS @ Koror; 4X daily radiosondes @ Guam, Yap & Koror		JAMSTEC; NOAA	J. Suzuki (JAMSTEC) **B. Ward (NOAA)**
DJF 2013/4										
ATTREX (2)	Go	TTL structure and microphysics	Pacific warm pool	Guam [13.5°N, 145°E]	Water vapor, ozone, temperature, ice microphysics	Global Hawk (high-alt UAV)	long-duration (>24-hours) flights; up to 6	Six weeks	NASA ARC	**E. Jensen (PI) & L. Pfister**
CAST-Airborne	Go	TTL composition and transport; VSL species in tropical troposphere; role of cirrus in tropics		Guam/Chuuk	Ozone, WV, CO, Halocarbons,NMHCs, OVOCs, DMS, CO_2, CH_4, N_2O, BrO, Black carbon	BAe146	sample PBL to 4-6 km	Jan 2014	Univ. of Cambridge; Univ. of Manchester; NCAS (UK)	**N. Harris and G. Vaughan (PIs)**
CAST-SONDE	Go			Chuuk [7.5°N, 153°E]	Ozone	Balloon; lidar	up to 60 ozonesondes	Jan 2014		
CONTRAST	In final review	Role of deep convection in TTL chemistry -> chemistry-climate interactions		Guam	Ozone, water vapor, CO, CH_4,CO_2,H_2CO,NOx, Br species, NMHC, VOCs, aerosols, clouds, MTP, UV/VIS	NCAR GV (to 45 kft)	convective outflow, jet crossing flights	Jan-Feb 2014	NCAR; U. Miami; U. Maryland	E. Altas, R. Salawitch, and **L. Pan** (Co-Pis)
SOWER 2014	Proposed	TTL water vapor and ozone		Tarawa [1.4°N, 173°E]; Biak; Kototabang [0.2°S, 100°E]	Water vapor/ozone [CFH/ECC]; *ice particles [OPC]; water vapor [FLASH-B] (tentative)*	Balloon; ground-based lidar	approx. 5 launches	One week	Hokkaido University; Kyoto University	**F. Hasebe (PI) and M. Fujiwara; M. Shiotani**
BATTREX (A)	Proposed	TTL structure and dynamics		TWP Manus [2°S,147°E]	Water vapor, ozone, aerosols; temp and winds	Balloon	CFH/EEC/COBALD Radiosondes 4,8X daily	Six weeks	Valparaiso Univ.; Penn State Univ.; NWRA; ARM	**G. Morris (PI); A. Thompson, J. Alexander (Co-Is)** and Chuck Long (Co-Is)
JJA 2014										
ATTREX (3)	Go	TTL structure and microphysics	Pacific warm pool	Townsville [19.3°S, 147°E]	Water vapor, ozone, temperature, ice microphysics	Global Hawk (high-alt UAV)	up to 6 long-duration (>24-hours) flights	Six weeks	NASA ARC	**E. Jensen (PI) and L. Pfister**
BATTREX (B)	Proposed	TTL structure and dynamics		TWP Manus [2°S,147°E]	Water vapor, ozone, aerosols; temperature and winds	Balloon	CFH/EEC/COBALD Radiosondes 4,8X daily	Six weeks	Valparaiso Univ.; Penn State Univ.; NWRA; ARM	**G. Morris (PI); A. Thompson, J. Alexander (Co-Is)** and Chuck Long (Co-Is)
DJF 2014/5										
SOWER 2015	Proposed	TTL water vapor and ozone	Pacific warm pool	Tarawa [1.4°N, 173°E]; Biak; Kototabang [0.2°S, 100°E]	Water vapor/ozone [CFH/ECC]; *ice particles [OPC]; water vapor [FLASH-B] (tentative)*	Balloon; ground-based lidar	approx. 5 launches	One week	Hokkaido University; Kyoto University	**F. Hasebe (PI) and M. Fujiwara; M. Shiotani**
StratoClim (airborne) (A)	Proposed	Processes that determine the TTL/LS sulfur and aerosol budget	Pacific warm pool	Phillipines	SO_2/H_2SO_4 mass spec; COS and HCN; aerosol mass spec	M-55 Geophysica (high-alt)				**M. Rex**
JJA 2015										
StratoClim (airborne) (B)	Proposed	Processes that determine the TTL/LS sulfur and aerosol budget	Asian monsoon	Thailand	SO_2/H_2SO_4 mass spec; COS and HCN; aerosol mass spec	M-55 Geophysica (high-alt)				**M. Rex**
Multi-year observational programs										
NOAA Water Vapor	Continuing	Long-term global trends in UT and/or LS WV, radiative impacts of WV trends, and response of WV to changing climate	NH, Tropics, SH	Boulder, CO; Hilo, HI; Lauder, NZ	Water vapor [FPH]; ozone [SHADOZ]	Balloon	monthly	Boulder, 1980+ Lauder, 2004+ Hilo, 2010+	NOAA ESRL/GMD	**D. Hurst (PI); K. Rosenlof**
SHADOZ	Continuing	Vertical structure and variability of ozone; tropospheric ozone	Southern Hemisphere and Tropics	11 stations active, 8 tropical	Ozone profiles [ECC]	Balloon	weekly and bi-weekly	since 1998	Penn State Univ; NASA, NOAA GMD	**A. Thompson (PI)**
Ticosonde	Continuing	Variability of tropical water vapor and ozone and covariance; validation of space-borne water vapor measurments	Tropical Americas	San José, Costa Rica [10°N, 84°W]	Water vapor [CFH], ozone [SHADOZ] and SO_2 (new)	Balloon	weekly [ECC], semi-monthly [SO_2], monthly [CFH]	ECC and CFH since 2005	NASA GSFC, Valparaiso Univ., Univ. de Costa Rica	**H. Selkirk (PI)**, H. Vömel, J. A. Diaz and **G. Morris** (Co-Is)
GRUAN	Continuing	Network of reference observations of RH, P, T & wind; ozone	Global	16 sites, 3 tropical; goal to expand to 30-40 worldwide	Water vapor [CFH, NOAA FPH, Snow White, FLASH-B]; PTU [RS92]	Balloon	once or twice per month	Long-term	Deutscher Wetterdienst	H. Vömel (lead)
StratoClim (ground)	Proposed	Processes that determine the TTL/LS sulfur and aerosol budget	Pacific warm pool	Palau	FTIR profiles of O_3, CO, C_2H_2,HCHO,HCN, COS, NO, NO_2; O_3 sondes; Water vapor [CFH]; backscatter [COBALD]; aerosol lidar [CNR]	FTIR; Balloons; lidar		2-3 years, 2014-2016	Alfred Wegener Institute	**M. Rex (PI)**

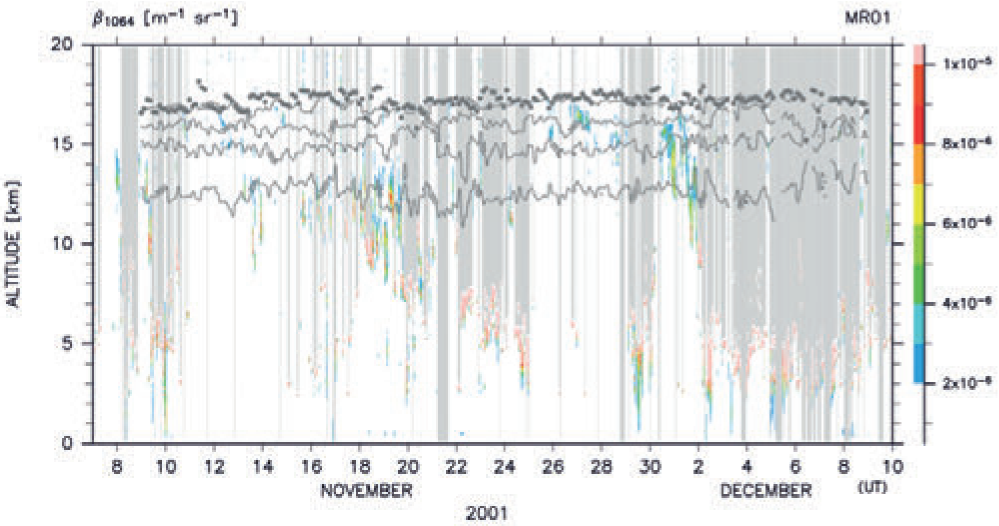

Figure 20: Lidar (Nd:YAG laser with 1064nm and 532nm) 1064nm backscattering coefficient in coloured contours and 3-hourly radiosonde measurements of the cold point tropopause (dots) and potential temperature surfaces (lines) from measurements taken from the R/V Mirai in the tropical West Pacific (2.0°N, 138.5°E). From Fujiwara *et al.*, 2009.

illustrating how waves are important for cloud formation and dehydration in the TTL. Planetary scale equatorial, Kelvin, Rossby, gravity and mixed Rossby-gravity waves, excited by stationary and moving convection, have a large impact on the climatology and intra-seasonal variability in the TTL. The impact of waves on horizontal and vertical transport has not been fully described or assessed. Smaller-scale gravity waves are also important for transport and mixing. These waves also feature strongly in driving the QBO and the Brewer-Dobson circulation. How they may change over time (see below) is a subject of investigation in models (Shepherd and McLandress, 2011; Garcia and Randel, 2008), and there is an urgent need for better observations. Several projects will focus on TTL waves, including BATTREX (gravity wave, turbulence, subtropical mixing, global scale model analysis) and ATTREX (slow, large-scale ascent, waves).

Cirrus clouds in the TTL radiatively impact tropospheric climate and the microphysical processes in these clouds help determine the water vapour content of air entering the stratosphere. These clouds are unique in many ways, and the ice nucleation mechanisms and aerosols that control large- and small-scale ice supersaturation continue to be highly uncertain, despite repeated observations of cirrus cloud microphysics (*e.g.*, Jensen *et al.*, 2009; Krämer *et al.*, 2009). Many questions remain. What factors contribute to the frequency and formation of supersaturated layers? What is the aerosol population of the TTL and how does it affect ice nucleation? How can we better characterise cloud presence and radiative impact? Can we simulate these processes from the cloud to global scale? We are beginning to understand some of our observations of clouds, number concentrations and ice supersaturation (see **Figure 21**), and the planned observations from a variety of platforms may enable us to make progress (see below). Initial results from new aircraft platforms in the TTL (Figure 21) illustrate relationships between cirrus cloud microphysics and environmental supersaturation: at some point ice concentrations are high enough to reduce relative humidity back to ice saturation, but high supersaturations may persist in thin clouds. Cirrus clouds are prevalent in all seasons in the TTL, but are critical for fina dehydration in the 'cold' boreal winter. Projects that will address these questions include: ATTREX (cirrus), SOWER (lidar, aerosol, WV), BATTREX, CAST(aircraft), and TICOSONDE (H_2O).

Understanding the transport of chemical constituents into the stratosphere requires a comprehensive

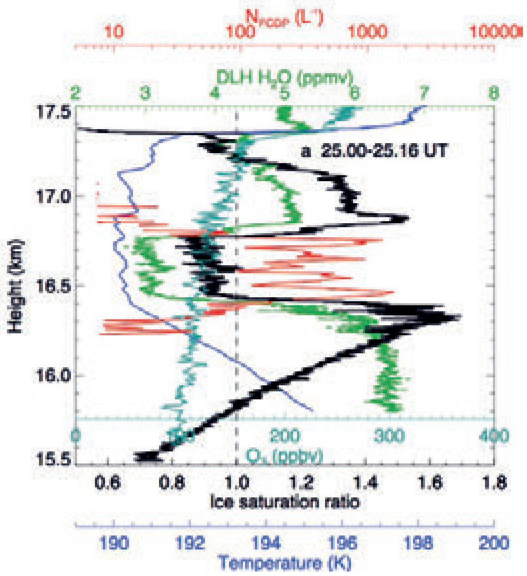

Figure 21: TTL Cirrus observations from ATTREX flight on 5-6 November 2011 near 10°N in the tropical eastern Pacific. Red: Particle number concentrations from the FCDP. Dark Blue: Temperature. Light Blue: Ozone. Black: ice saturation ratio. Green: Specific Humidity from DLH. E. Jensen and L. Pfiste , pers. communication, 2012.

understanding of the **TTL Chemical Budget** of transport, chemical production and chemical loss. We do not fully understand the role of deep convective transport and how it may alter the chemical environment in the TTL. The chemical transformations that occur in the TTL are not well characterised for key constituents, such as sulphur species, halogens or even ozone. **Figure 22** shows an example of very low ozone in the TTL (<20ppb) that occurs climatologically in the wet season due to convective transport of near-surface air into the TTL. In addition to being a tracer of convection, at low ozone concentrations, HO_x chemistry (and thus chemical lifetimes of trace species) is altered. Changing HO_x chemistry will affect the transport of species through the TTL into the stratosphere. Projects that will focus on looking at the chemical budget of the TTL include the multi-aircraft experiment of ATTREX-CAST-CONTRAST, SEAC4Rs and the proposed StratoClim project.

Large-scale Transport in the TTL, governing the transport of trace species into the stratosphere, is also not fully understood. The transit time for air affects the distribution of short-lived species that enter the stratosphere, and the chemical budget of the TTL (see above). Critical to this is understanding the roles of overshooting convection, large-scale upwelling and horizontal mixing, for determining the lifetime of air in the TTL and how it varies in space and time. Trajectory studies and new data (*e.g.*, Schoeberl *et al.*, 2012; Wang *et al.*, 2012) show the locations of the last dehydration due to large-scale transport, and the advection of air in planetary-scale circulations (**Figure 23**), which vary with different modes of variability in the tropics, such as differences with the El Niño-Southern Oscil-

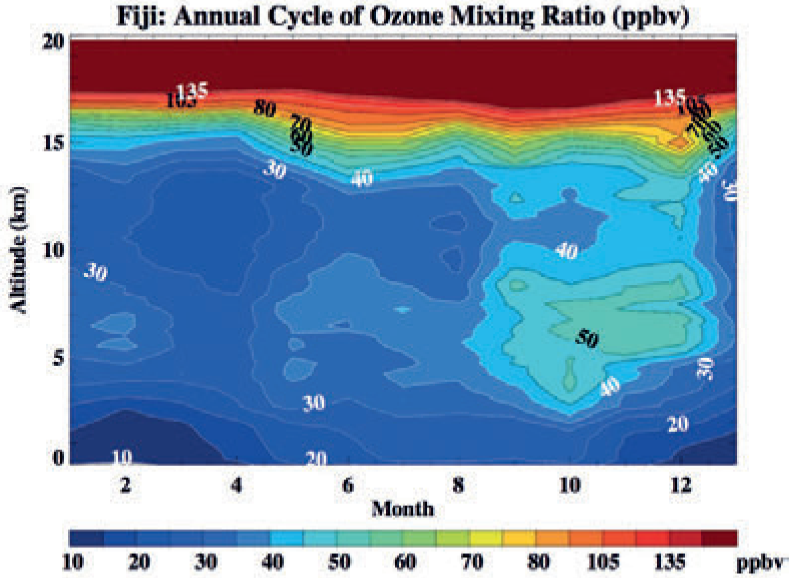

Figure 22: Annual cycle of tropical ozone at Fiji from ozonesonde data showing low ozone in the UT seen climatologically from sondes (adapted from Figure 3 of Thompson *et al.*, 2011).

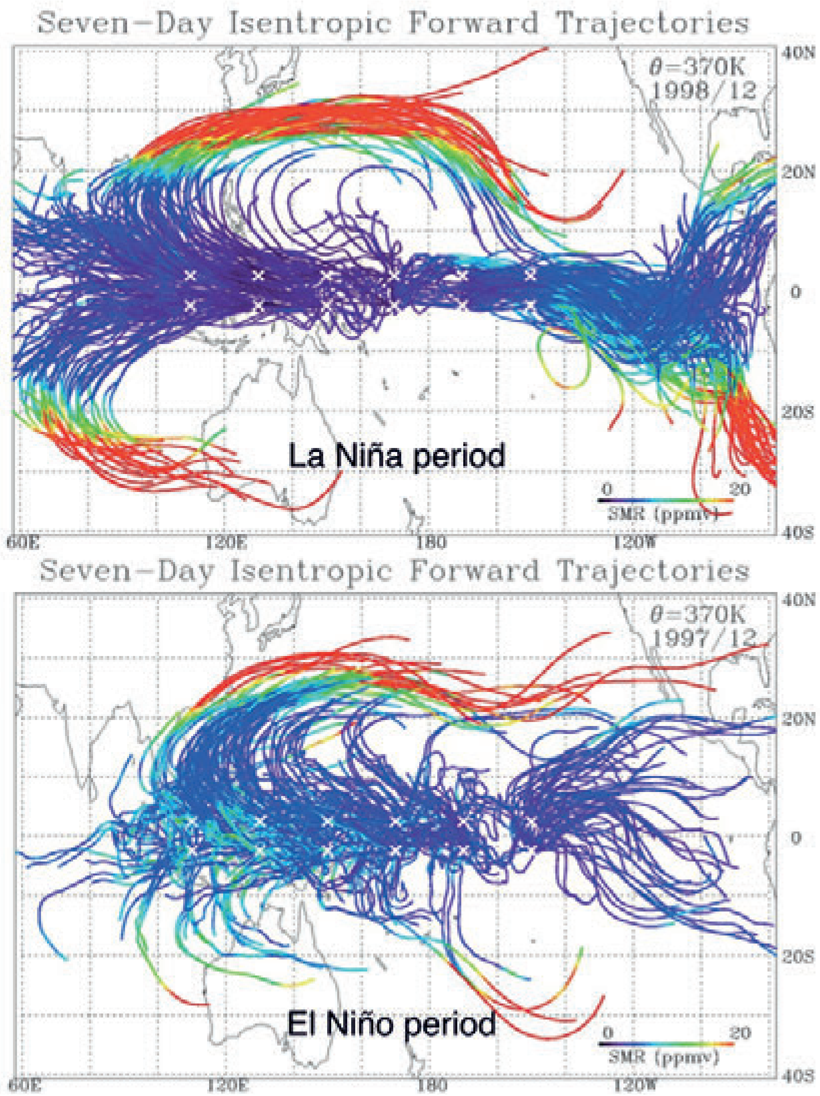

Figure 23: Large scale transport along trajectories in the TTL during a La Niña period (December 1998: **Top**) and an El Niño period (December 1997: **Bottom**). Saturation Mixing Ratio (SMR) shown in colors (in ppmv).

lation (ENSO). The importance of convection that overshoots its level of neutral buoyancy is highly uncertain. Some convection gets to the tropopause level and into the stratosphere (*e.g.*, Danielsen, 1982), such as the example shown in **Figure 24**. But just how much convection overshoots the tropopause is still uncertain. Recent work with active satellite sensors (Pan and Munchak, 2011; Yang *et al.*, 2010; Liu and Zipser, 2005) indicates that overshooting occurs only a small fraction of the time. The impact of this convection on air mass fluxes and particularly the hydration or dehydration of the lower stratosphere is not well constrained. Large-scale transport and convection are a focus of several projects, including SEAC4Rs, ATTREX-CAST-CONTRAST, SOWER and StratoClim.

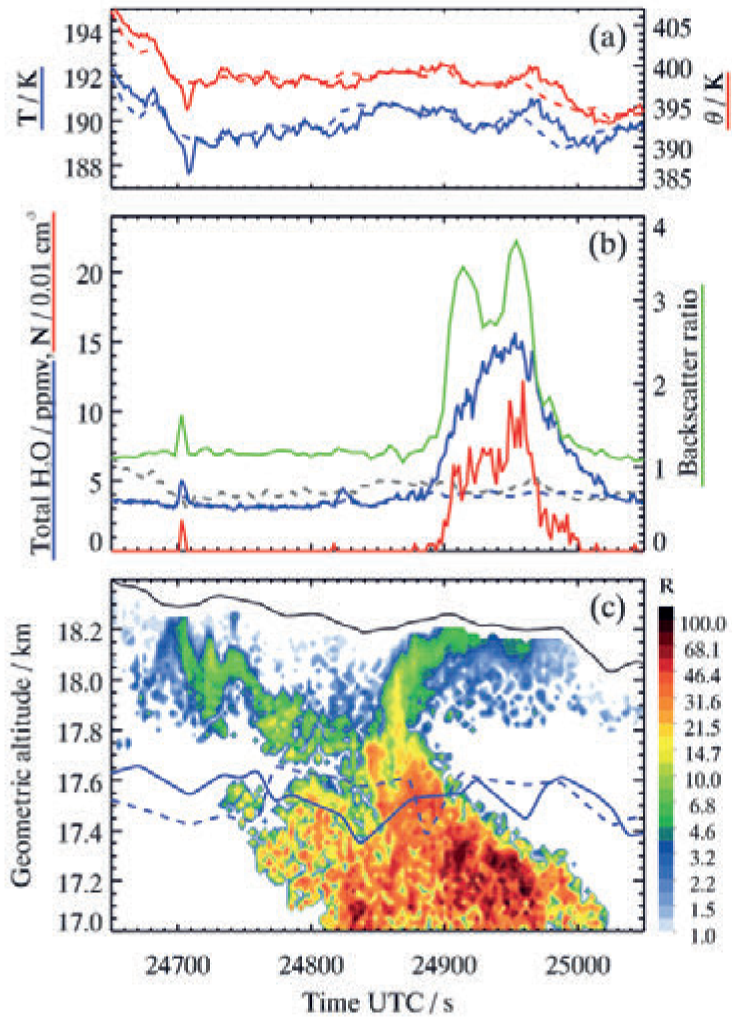

Figure 24: Overshooting convection near Darwin Australia from the SCOUT campaign. **Top**: Temperature. **Middle**: Backscatter Ratio (green), Total water (blue) and particle number concentration (red). **Bottom**: lidar backscatter (contours), tropopause altitude (blue) and aircraft altitude (black). From Corti *et al.*, 2008, Figure 3.

Finally, Long-term Changes in the TTL are not well understood, and critical uncertainties remain. Due to changes in the radiative balance with increasing greenhouse gases in the UTLS region (tropical TTL warming and cooling of the extra-tropical lower stratosphere), thermal wind balance is expected to result in an increase in the sub-tropical jet speed and poleward movement of the jet (*e.g.*, Polvani and Kushner, 2002), but how this impacts the details of the TTL radiative balance is not well understood. The large-scale thermal structure of the TTL and the cold point tropopause temperature is highly correlated with interannual variability of water vapour (Fueglistaler and Haynes, 2005). This is nicely illustrated in **Figure 25**, showing that large-scale cold point temperature variability along trajectories (the 'Lagrangian Cold Point') dominates interannual variability of stratospheric water vapour (though cirrus processes and transport set the exact level). However, the long-term (decadal) variability of tropical tropopause temperature is not well characterised or simulated. How changes in the TTL (specifically TTL water vapour and cirrus clouds) impact tropospheric climate (*e.g.*, through cloud radiative effects) and stratospheric chemistry (through changes in ozone chemistry and H_2O entry into the stratosphere) is uncertain. These topics cannot be directly addressed through campaigns, but ongoing projects such as GRUAN, SHADOZ, NOAA long term monitoring and global reanalyses will help reveal the nature of long-term climate variations in the TTL.

Campaign Description

Planned campaigns in the TTL are listed in **Table 1**. Most of these campaigns are scheduled in the Asia/Pacific region over the next several years, or are ongoing projects. During the workshop there was much discussion regarding these projects and campaigns. Details are provided in the table, but we chronologically summarise some of the key features of the campaigns here, and also highlight some of the coordinated activities that were discussed at the workshop. This information is also being distributed via interactive Google Maps layers that are

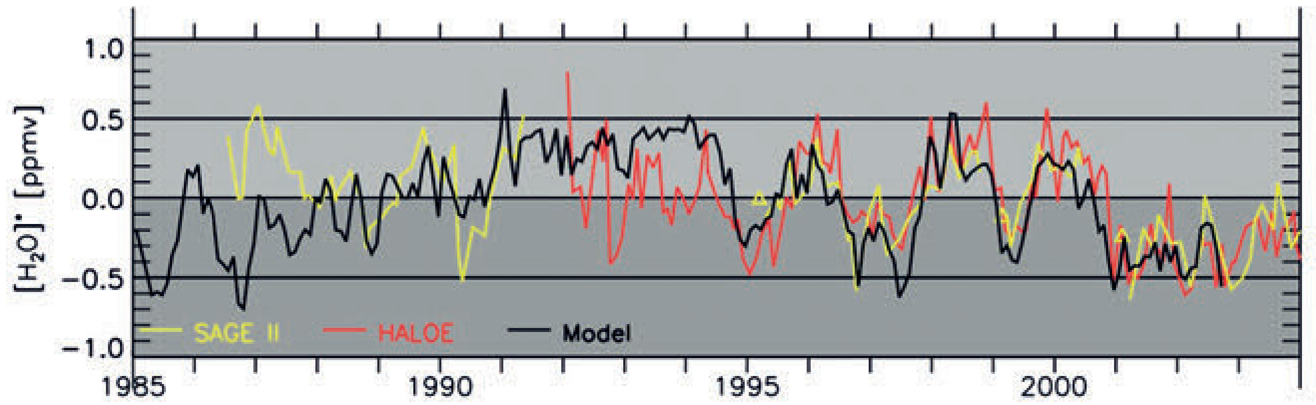

Figure 25: From Fueglistaler and Haynes 2005, Figure 2a: Interannual variability in tropical lower stratospheric water vapour and temperatures. Lower stratospheric (at 400K potential temperature) tropical (30°S to 30°N) monthly mean water vapour mixing ratio ($[H_2O]T400$) anomalies. Yellow, SAGE II; red, HALOE; black, model predictions.

available to the community, and available for sharing information, as detailed below.

Starting in January 2013, there will be several projects in the TTL, along with ongoing projects that currently operate continuously. The Soundings of Ozone and Water Vapor in the Equatorial Region (SOWER) campaign will launch radiosondes from Biak, Indonesia, and Hanoi, Vietnam. In addition, the Southern Hemisphere Additional OZonesonde (SHADOZ) project will continue their launches from several sites, as will the Ticosonde project in Costa Rica. The GCOS Upper Air Reference Network (GRUAN) will continue its launches of ozone and water vapour soundings, but mostly not in the TTL, and there will be monthly NOAA Frost Point (FP) soundings from Hilo, Hawaii, at the edge of the tropics (19°N). There will be additional Radiosondes launched from Palau (7°N, 134°E), and the Airborne Tropical Tropopause Experiment (ATTREX) will be flying a NASA Global Hawk over the central and eastern Pacifi from southern California.

In boreal summer of 2013, several other activities are planned. In addition to ongoing NOAA FP, GRUAN, SHADOZ and Ticosonde launches, there will be a coordinated aircraft campaign, the Southeast Asia Composition Cloud and Climate Coupling – Regional Study (SEAC4RS) with two aircraft (NASA DC8 and ER2). The plans for SEAC4RS are currently being finalised and NASA is currently considering Singapore as its base of operations. SEAC4RS also has a sounding compliment at several sites in south east Asia: SEAC4RS Intensive Ozonesonde Network Study (SEACIONS). The Sounding of Water Vapour Ozone and Particles (SWOP) campaign of soundings will also occur at this time in Lhasa, China.

From December 2013 - February 2014, several more campaigns are planned in the Asia-Pacific region. These campaigns are documented in **Figure 26**, showing an example of the Google Maps layers. Soundings from the ongoing projects (SHADOZ, GRUAN, NOAA-FP, Ticosonde) are indicated in blue and red. SOWER launches are also indicated in blue. There will be campaigns with aircraft at Guam (13°N, 144°E) and Chuuk (7°N, 152°E). Guam is expected to host the ATTREX Global Hawk, the UK National Environmental Research Council (NERC) BAe-146 in the Coordinated Airborne Studies in the Tropics (CAST) project, and the US National Science Foundation (NSF) Gulfstream 5 for the Convective Transport of Active Species in the Tropics (CONTRAST) project. CONTRAST is still subject to final approval. Chuuk will also feature soundings as part of CAST. A sounding complement to ATTREX, the Balloon Tropical Tropopause Experiment (BATTREX) is planned for Manus, Papua New Guinea (2°S, 147°E), shown in green on Figure 26.

Finally, there are campaigns planned for the boreal summer of 2014 and beyond. ATTREX is expected to fly from north Australia, and BATTREX is also planning on operating from Manus Island. Beyond this, the StratoClim project (recently proposed) would continue observational soundings and ground-based observations in the Pacific in 2014 or 2015, with an aircraft campaign in 2015.

Google Maps layers for Figure 26, and the other seasons, are available on the workshop web page (**http://physics.valpo.edu/ttlworkshop/maps.html**). These layers represent an interesting opportunity to work together, and share information on an open source platform. These maps are useful for information sharing, and presentations. They can be displayed in Google Maps or Google Earth, and exported into

Figure 26: Global TTL campaigns in DJF 2013-2014 from a shared Google maps layer. Blue indicates 'operational' sounding stations from SOWER and SHADOZ (**http://croc.gsfc.nasa.gov**; Thompson *et al.*, 2011). Aircraft location indicates CONTRAST, ATTREX and CAST in Guam. Purple are CAST soundings, Green is BATTREX location (Manus Island). The inactive sites have balloons without dots in them. The active sites show balloons with dots. See workshop web page for a link to the interactive map.

the Google Earth standard Keyhole Markup Language (KML). In addition, there is the ability to link with other pieces of information. Geotagged twitter messages for example, can be made to display on the map, to share information (such as times and locations of sounding launches). Flight tracks of aircraft (in KML format, for example) can also be displayed. Some of the common flight planning software being used for managing aircraft campaigns can work with this information for input and export. Those who are interested in participating, and even contributing, should visit the workshop website for access to the maps, and for instructions on how to post information to the maps.

The maps, for example, can be used to help share information about sounding launches and aircraft fligh tracks. This information can be used for Lagrangian studies of air parcels: trying to sample the same air parcel from an aircraft, and later a balloon sounding, linked using trajectory information, often called a 'match' of air parcels (Hasebe *et al.*, 2007). Trajectory model runs from sounding locations and aircraft flight tracks are planned as part of these campaigns to assist with this information.

Finally, the wealth of campaign information can also hopefully be supplemented by high-resolution sounding information from existing sites. Much of the information from Radiosondes is not archived or transmitted, and there was a commitment on the part of the participants to try to work to improve the reliability of operational sounding networks, and collect high-resolution information from regular soundings. This exchange may take a number of forms, but making the exchange sustainable will be a challenge.

There is thus wonderful potential to make all these campaigns work together to add to their individual reach, and to enable further progress to be made. The bilateral TTL workshop was a start, by beginning coordinated planning, and improving communication. The ultimate goal is to obtain better data to make progress on understanding the key questions noted above.

Expected Progress

The campaigns described represent an exceptional opportunity for *in situ* observations of the TTL. Several aircraft campaigns in different seasons (SEAC4RS, ATTREX, CAST, CONTRAST, StratoClim) will provide a wealth of data, combined with numerous balloon campaigns (CAST, SOWER, BATTREX, SWOP). Ongoing projects (GRUAN, SHADOZ, SOWER, NOAA, Ticosonde) with new instrumentation will add to this campaign data. The next three years will be a prime time for making progress in many areas.

The hope for progress stems from new instrumentation and new platforms. In particular, there is a focus on observing cirrus cloud microphysics, ice supersaturation, and ice nucleation. New instrumentation is available that provides better constraints on ice crystal number, and more confidence has been built up in water vapour observations at cold temperatures and high supersaturations (see Figure 21). In addition, simultaneous measurements of humidity (with frost point instruments), temperature, ozone and ice particles (with small optical measurements) from balloons are providing a wealth of new data. All this will enable us to make progress on these questions.

Furthermore, the unprecedented suite of aircraft, many flying in formation (as in CAST, ATTREX, CONTRAST, and SEAC4Rs) will be important for understanding convective transport and TTL composition. This will occur both in the boreal summer near the Asian monsoon (SEAC4Rs), as well as in boreal winter in the Western Pacifi (CAST-ATTREX-CONTRAST). These campaigns will probe many tracers, both at convective inflo in the lower atmosphere, and outflow in the TTL. The scope of these campaigns will be extended by a network of sounding stations (SOWER, BATTREX, SWOP), and several ground sites with significan instrumentation. The TTL workshop made great progress in discussions among these groups about how to use innovative coordination strategies to expand the reach of different projects and to share data. These projects are backed up by several ongoing and mature reanalysis efforts, geosynchronous and polar-orbiting satellite information on TTL humidity and clouds, as well as active lidar and radar sensors from space that may still be available.

Several of the science questions are more difficult to address on a campaign basis. While individual convective events can be sampled, understanding the roles of convective transport, TTL circulation and stratospheric wave-driven mean circulation is difficult. Understanding the climatological TTL radiative balance is also difficult on a campaign basis. These campaigns can be linked together and to existing data records with satellites, global models and reanalysis systems. In turn, these campaigns, and particularly the high density of campaigns and observations, are important for validation of satellite measurements and understanding TTL processes represented in models. Understanding potential long-term (interannual) changes in the TTL cannot be accomplished in a single campaign. Several campaigns over a few years will help, but critically the campaigns need to be linked with continual long-term measurements in the TTL, and with satellites, global models and reanalysis systems.

Critical Needs

The workshop participants recognised some critical needs beyond the observations to be carried ou over the next few years. With respect to the campaign observations themselves, it is critical to have additional balloon measurements in the Western Pacific and Asian region to provide high vertical and spatial resolution views of the larger picture around the campaigns, and to help evaluate satellites and reanalysis systems in the region. Innovative strategies for observing similar air masses through 'Match' observations (Hasebe *et al.*, 2007) will allow these campaigns to be linked in space.

In the long term, in order to make continued progress, two key steps are necessary. The first is critical support of ground-based monitoring programs based in the tropics that observe the TTL with balloons and ground-based remote sensing. These include the Network for the Detection of Atmospheric Composition Change (NDACC), SHADOZ, GRUAN, and individual country efforts such as work conducted by the US Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility program. Regular radiosonde stations could also save higher resolution data to archives at little or no cost. Sustaining regular measurements is low cost and critical for climate records.

The second step is continuation of high quality satellite observations. The last five years or so have been a very good time for satellite observations of the TTL. The combination of active satellite sensors for precipitation (TRMM), thick clouds (CloudSat) and thin cirrus (CALIPSO) from active sensors, combined with water vapour, ozone and other tracers from multiple platforms (MLS, HIRDLS, ACE, SMILES and the European satellites) has enabled progress on several fronts. This continues a long tradition of observations in the TTL, particularly of water vapour and ozone. The history of many of the satellite sensors in the TTL is illustrated in **Figure 27**. While the majority of the space-borne measurements shown in Figure 27 that were current in early 2012 are continuing as of this writing (November 2012), although the loss of ENVISAT in spring 2012 was a big loss. Many of the satellite systems that are currently operational have already or will soon have exceeded their expected operational lifetimes, and the science community should expect to lose one or more of the A-Train[1] satellites in the next five years or so

The end-of-life of the current generation of sensors may endanger future progress on TTL science and will create gaps in climate records if satellite measurements of TTL ozone and water vapour, in particular, are not maintained. With regard to ozone, the outlook for data continuity is good, with the successful launch of the NPOESS Preparatory Project (NPP) satellite in October 2011 (now rechristened Suomi NPP in honour of Vern Suomi). On board NPP is the Ozone Mapper Profiler Suite, OMPS. OMPS will be supplemented by the launch of the Dutch TROPOMI instrument in 2014. Middle-to-upper tropospheric water vapour coverage is also in relatively good shape, with the AIRS instrument on Aqua and the IASI instrument on the MetOp satellites providing unprecedented coverage for operational data assimilation, along with the recent addition of the CrIS-ATMS system

[1]Among those shown in Figure 27, the NASA EOS Aqua and Aura satellites, CloudSat, and Calipso are all part of the "A-train".

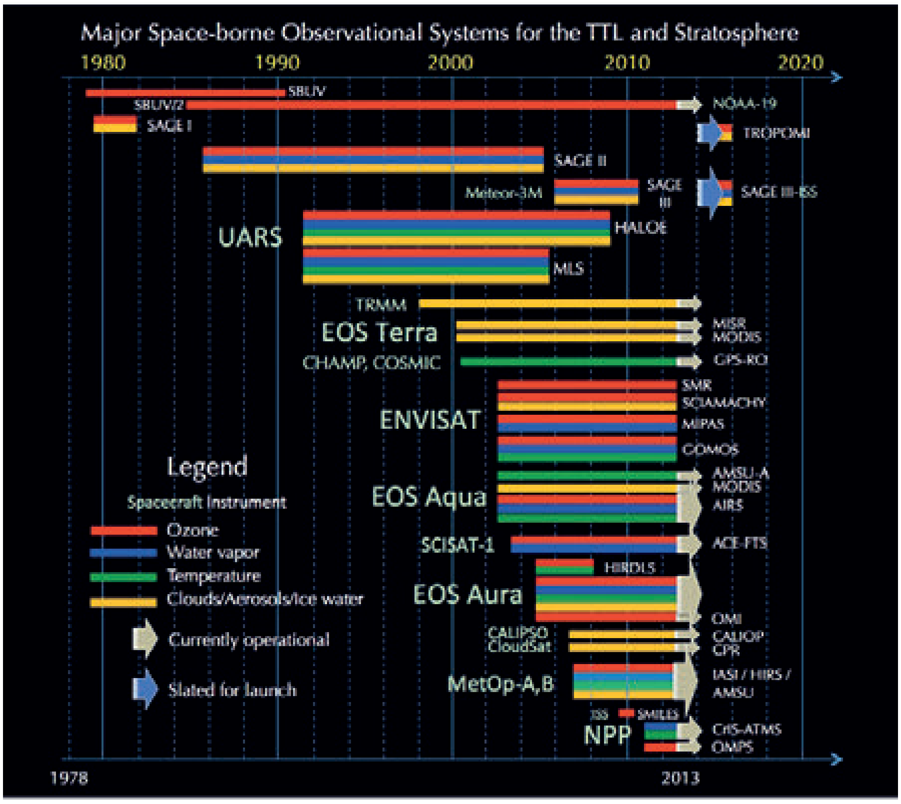

Figure 27: Timeline of TTL Satellite Measurements. Original by Sakazaki, for the TTL Workshop.

on board Suomi NPP. However, for stratospheric water vapour, the long run of the combined HALOE/MLS record is threatened, and we can only hope that SAGE III-ISS, also set for launch in 2014, will operate long enough to provide overlap between both MLS and whatever may succeed it.

This highlights the critical importance of the few proposed satellite missions that will take measurements in the TTL. Among these is the ESA Process Exploration through Measurements of Infra-red and Millimeter-wave Emitted Radiation, PREMIER, mission. PREMIER is currently undergoing a feasibility study and will launch no earlier than 2016. Such missions are a critical part of scientific progress and maintaining long-term climate records.

Of equal importance is the continuing allocation of the rather modest resources for maintaining ground-based records, in particular soundings of water vapour. In addition to NOAA's Boulder soundings, which now encompass a more than 30-year record of mid-latitude water vapour, tropical water vapour has been measured regularly in Costa Rica since 2005 by the Ticosonde program. More recently, NOAA has established a program at Hilo, a key site located at the margins of the tropics.

Summary and further activities

The TTL workshop finished with extensive discussion of coordination among field projects. The group intends to launch a collaborative page to share information on projects in the TTL during the next few years, and link to the tutorial materials presented during the workshop. As part of the workshop coordination activities, we are developing Google Maps layers for observations in the next few years. An example is shown in Figure 26, with locations for some of the projects already on the map. These maps will be continually updated and publicly accessible. URLs are available at the workshop web pages. It is hoped that some of these open source collaboration tools can be used in real time to better share information among participants.

The workshop ended on a positive note. The next few years represent a 'Golden Age' for TTL observations with a rise of observation campaigns in the critical regions of south and east Asia and the western Pacific. The community attending the workshop represented a confluence of international projects that are attempting to better understand this critical region. The funded projects form the current core of efforts in the TTL, and will be carried out in both boreal summer and winter. Other projects currently being planned will provide critical synergies.

Perhaps the Hindu term 'Satya Yuga' (Golden age, or age of Truth) is appropriate to describe the wealth of knowledge we will gain about the TTL during these 'Several Accentuated Tropical Years for Analysis' (SATYA), a new 'golden age' for TTL observations. Like a Hindu age, it is hoped that the impact may last for a long time, and this would be particularly true if the observations can be used by many researchers and integrated within long-term projects to understand the evolving climate of the TTL. The participants in the workshop are committed to sharing knowledge amongst themselves and the community, and urge support for continued observations. For those interested in the TTL, please see the workshop web pages for tutorial archives, and updated maps and links to upcoming campaigns.

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At the 20**th** SPARC Scientific Steering Group meeting held in Buenos Aires, Argentina, November 2012, the results from the blog on "Should SPARC change its name?" were presented. The overwhelming majority within the SPARC community agreed to keep the acronym "SPARC" but change its meaning to "Stratosphere-troposphere Processes And their Role in Climate". The WCRP Joint Scientific Committee endorsed SPARC's decision. In order to depict the project's new, extended mandate and to demonstrate that SPARC is making a serious effort to achieve this mandate, the decision was made to create a new logo.

We are inviting the SPARC community to join in the discussions on how the new logo should look. More at www.sparc-climate.org.

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Overview of IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) Community Simulations in Support of Upcoming Ozone and Climate Assessments

Veronika Eyring[1], Jean-François Lamarque[2], Peter Hess[3], Florian Arfeuille[4], Kevin Bowman[5], Martyn P. Chipperfiel [6], Bryan Duncan[7], Arlene Fiore[8], Andrew Gettelman[2], Marco A. Giorgetta[9], Claire Granier[10], Michaela Hegglin[11], Doug Kinnison[2], Markus Kunze[12], Ulrike Langematz[12], Beiping Luo[13], Randall Martin[14], Katja Matthes[15], Paul A. Newman[7], Thomas Peter[13], Alan Robock[16,] Tom Ryerson[17], Alfonso Saiz-Lopez[18], Ross Salawitch[19], Martin Schultz[20], Theodore G. Shepherd[11], Drew Shindell[21], Johannes Staehelin[13], Susann Tegtmeier[22], Larry Thomason[23], Simone Tilmes[2], Jean-Paul Vernier[23], Darryn W. Waugh[24], Paul J. Young[25]

[1]DLR Institut für Physik der Atmosphäre, Germany, veronika.eyring@dlr.de, [2]National Center for Atmospheric Research, USA, lamar@ucar.edu, andrew@ucar.edu, dkin@ucar.edu, and tilmes@ucar.edu, [3]Cornell University, USA, pgh25@cornell.edu, [4]Bern University, Switzerland, florian.arfeuille@giub.unibe.ch, [5]NASA Jet Propulsion Laboratory, Pasadena, USA, kevin.w.bowman@jpl.nasa.gov, [6]University of Leeds, UK, martyn@env.leeds.ac.uk, [7]NASA Goddard Space Flight Center, USA, Bryan.N.Duncan@nasa.gov, and Paul.A.Newman@nasa.gov, [8]Columbia University, USA, amfiore@ldeo.columbia.edu, [9]Max Planck Institute for Meteorology, Germany, marco.giorgetta@zmaw.de, [10]IPSL, Paris, France, cgranier@latmos.ipsl.fr, [11]University of Reading, UK, m.i.hegglin@reading.ac.uk, and theodore.shepherd@reading.ac.uk, [12]Freie Universität Berlin, Germany, markus.kunze@met.fu-berlin.de, and ulrike.langematz@met.fu-berlin.de, [13]ETH Zürich, Switzerland, beiping.luo@env.ethz.ch, thomas.peter@env.ethz.ch, and johannes.staehelin@env.ethz.ch, [14]Dalhousie University, Canada, randall.vaughn.martin@gmail.com, [15]GEOMAR Kiel, Germany, kmatthes@geomar.de, [16]Rutgers University, USA, robock@envsci.rutgers.edu, [17]NOAA, USA, Thomas.B.Ryerson@noaa.gov, [18]Laboratory for Atmospheric and Climate Science, Spain, a.saiz-lopez@ciac.jccm-csic.es, [19]University of Maryland, USA, rjs@atmos.umd.edu, [20]Forschungszentrum Juelich, Germany, m.schultz@fz-juelich.de, [21]NASA Goddard Institute for Space Studies, USA, dshindell@giss.nasa.gov, [22]Helmholtz Centre for Ocean Research (GEOMAR), Germany, stegtmeier@geomar.de, [23]NASA Langley Research Center, USA, l.w.thomason@nasa.gov, and jeanpaul.vernier@nasa.gov, [24]Johns Hopkins University, USA, waugh@jhu.edu, [25]Lancaster University, UK, paul.j.young@lancaster.ac.uk

1. Introduction

The IGAC and SPARC communities are jointly defining new reference and sensitivity simulations to address emerging science questions, improve process understanding and support upcoming ozone and climate assessments. These simulations were discussed as part of the IGAC/SPARC Global Chemistry-Climate Modelling and Evaluation Workshop (Davos, May 2012) and are described in this document.

1.1 Background

The workshop participants recommended the creation of a joint IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) to coordinate future (and to some extent existing) IGAC and SPARC chemistry-climate model evaluation and associated modelling activities. The CCMI has now been approved by both the IGAC and SPARC scientific steering committees at their respective steering committee meetings. The IGAC/SPARC CCMI is superseding the SPARC Chemistry-Climate Model Validation (CCMVal) activity, expanding the goals and deliverables of CCMVal to include tropospheric chemistry-climate questions. Similarly, the IGAC hindcast activity is now embedded into the CCMI rather than being a separate activity, so as to benefit from overlapping interests and approaches of the tropospheric and stratospheric chemistry modelling communities. Also, new phases of the Atmospheric Chemistry-Climate Model Intercomparison Project (ACCMIP, see **http://www.giss.nasa.gov/projects/accmip/**) may merge with the CCMI activities. A white paper summarizing the goals of the CCMI will be published in the IGAC and SPARC newsletters in 2013. A website for the CCMI has been created at **http://www.pa.op.dlr.de/CCMI/**, where further information can be found and ongoing efforts are reported.

1.2 Purpose and scope of the proposed CCMI community simulations

In this document, the **CCMI reference (REF)** and **sensitivity (SEN)** simulations for Chemistry-Climate Models (CCMs), Earth-System Models (ESMs) with interactive chemistry, and Chemistry-Transport Models (CTMs) are proposed. The over-arching principle behind the choice of the CCMI simulations is to produce the best possible science.

There are two overall goals for the choice of REF simulations:

1. Quantify how well the models can reproduce the past behaviour (climatology, trends and interannual variability) of tropospheric and stratospheric ozone, other oxidants, and more generally chemistry-climate interactions, as well as to understand processes that govern these interactions. This is the rationale behind the "past" transient hindcast reference simulations in either free-running (**REF-C1**) or specified dynamics (**REF-C1SD**) mode. These simulations are forced by boundary conditions specifie from observations or empirical data (*e.g.*, sea surface temperatures (SSTs), sea ice concentrations (SICs), emissions, greenhouse gas (GHG) concentrations) and meteorology in the case of REF-C1SD. One of the goals for the new REF-C1SD simulation is to provide an improved evaluation against observations, in particular new satellite, ground-based, and *in situ* measurements.
2. Analyse projections of the future evolution of tropospheric and stratospheric ozone. This is the rationale behind the "future" transient reference simulation (**REF-C2**), which is forced by trace gas projections and either prescribed modelled SSTs and SICs, or an interactively coupled ocean. Experience gained from the evaluations performed for the SPARC-CCMVal (2010) report shows that it is important to have a continuous time series from the models, covering both past and future, in order to avoid inhomogeneity in the data sets (in terms of both absolute values and variability), and also that the simulations extend to 2100 in order to fully capture the process of ozone recovery from the effects of ozone-depleting substances (ODSs). Accordingly, REF-C2 simulations should cover the period 1960-2100, with a 10-year spin-up starting in 1950.

It is recommended that groups perform a small ensemble of simulations covering the 'past' 1960-2010 (**REF-C1**) and 'future' 1960-2100 (**REF-C2**) periods, so as to establish an uncertainty range in the simulations.

The proposed **SEN** simulations are designed to augment the science that can be obtained from the reference simulations. These simulations include investigating the sensitivity to various GHG scenarios, ODSs, and emissions. Further sensitivity simulations that might be proposed to answer specific science questions will be made available on the CCMI website.

All simulations are open to a broad range of participating CCMs, as well as to ESMs with interactive stratospheric and/or tropospheric chemistry. The specific dynamics simulation **REF-C1SD** is designed for CTMs, CCMs or ESMs with the capability of nudging using meteorological input.

All participating models should use the s**tandard set of specifie forcings** that is specified in this document. The forcings to drive the models can be downloaded from the CCMI website or through the links given throughout this document.

1.3 Scientific question and timelines

While the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations are now being studied in great detail in support of the IPCC Fifth Assessment Report (AR5), along with analysis of simulations performed under ACCMIP, Geoengineering Model Intercomparison Project (GeoMIP) and Aerosol Comparisons (AeroCom) activities, the next WMO/UNEP Scientific Assessment of Ozone Depletion should be supported by updated simulations of stratospheric ozone. It is envisaged that the new simulations broadly follow the recommendations of the SPARC-CCMVal (2010) report, in particular:

- CCM simulations of ozone depletion/recovery should be performed seamlessly over the entire 1950-2100 period with consistent forcings, and with data produced in a standard format to allow for multi-model intercomparison.
- A range of different scenarios should be simulated, *e.g.*, using fixed GHG and different GHG projections. To be consistent with CMIP5, these scenarios should generally follow the four Representative Concentration Pathways (RCPs; Moss *et al.,* 2010; van Vuuren *et al*., 2011a), but with ODS values replaced with those from WMO (2011). These simulations will allow correct attribution of the projected changes and an understanding of the sensitivity to the GHG scenario employed.
- Development should continue towards comprehensive troposphere-stratosphere CCMs, which include an interactive ocean, tropospheric chemistry, a naturally occurring QBO, spectrally resolved solar irradiance, and a fully resolved stratosphere.
- The next generation of CCMs should also include a better representation of tropospheric chemical processes (*e.g.*,

non-methane hydrocarbons, lightning NO_x production, detailed inclusion of dry and wet deposition processes). This is certainly important for science studies in the troposphere and Upper Troposphere Lower Stratosphere (UTLS) region, but may also be important for better representation of the overall climate system.

- The coupling of CCMs to interactive oceans is recommended in the future, in order to make the representation of climate change in the models more physically self-consistent.
- The community should address the issue of how to include very short-lived (VSL) organic bromine species into the boundary conditions and chemical mechanisms of CCMs.
- An accurate knowledge of the atmospheric lifetime of gases is essential for predicting ozone depletion and the climatic effects of emissions. A re-evaluation of the lifetimes of important halogen source gases (*e.g.*, CFC-11, CCl_4, halons, HFCs, HCFCs, and related species) is currently underway as part of the SPARC activity on 'Lifetime of halogen source gases' (see **http://www.sparc-climate.org/activities/lifetime-halogen-gases/**), since evidence has emerged that in many cases the actual lifetimes may be considerably longer than those currently assumed in the 2010 WMO/UNEP Ozone Assessment (WMO, 2011) and in the scenarios used to drive the CCMs. This represents a major uncertainty in reconciling top-down and bottom-up emission estimates, and in model projections.

Some of the above-mentioned points are already considered in existing simulations. For example, a subset of models participating in CMIP5 has interactive chemistry and a coupled ocean. These runs can be included in studies that analyse the ozone evolution under different GHG scenarios. On the other hand, some of the model groups that did not participate in any of the above mentioned model intercomparison projects (MIPs) might want to additionally run simulations that extend the science beyond what was possible for WMO (2011).

In addition, the scientific questions that can be addressed through a new hindcast simulation with models including interactive chemistry are diverse. A non-exhaustive list of questions includes:

i. How well does the current generation of global chemistry models capture the interannual variability in tropospheric and stratospheric constituents?
ii. How well do we understand the tropospheric OH budget? Can we capture the estimated interannual variability and trends?
iii. How have changes in atmospheric forcings impacted chemical composition and chemistry over the last 30 to 50 years? These forcings include: a) changes in climate forcing with resulting impacts on temperature, water vapour and meteorology, possibly extending to stratosphere-troposphere exchange, b) changes in ozone and aerosol precursor emissions, c) changes in land cover, and d) changes in ODSs.
iv. How have changes in aerosol loading impacted oxidative capacity of the troposphere over the last 30 to 50 years?
v. To what extent do the increased satellite retrievals of tropospheric and stratospheric constituents constrain constituent variability over the last 10-15 years?
vi. To what extent can CCMs forced with observed SSTs and solar particles capture the observed interannual variability of the hindcast simulations?
vii. What is the role of very short-lived halogen species (VSLS)?

The proposed hindcast simulations will address these questions through observationally-based simulations and sensitivity tests. Additionally, a re-assessment of temperatures, trace species and ozone in the simulations will allow documenting the progress of individual models and overall progress on the representation of key processes compared to the last CCM assessments. The comparison of CCM results with observations will also allow some groups to identify and correct previously unrecognised model errors and will help to indicate a range of model uncertainties. The hindcast simulations are also incorporated in the work plan of the UNECE/EMEP Task Force Hemispheric Transport (**http://iek8wikis.iek.fz-juelich.de/HTAPWiki/WP3.6**), focusing on aspects specifically relevant for hemispheric transport of air pollution and its contribution to observed pollution trends.

Overall, there are two competing timescales for performing these simulations: the shorter term ozone assessment timescale, including the need to perform new hindcast simulations for improved understanding, and the longer term timescale for integrated climate and chemistry assessment of both the troposphere and stratosphere. These competing timescales have been recognised, and a key aspect of this document is to detail a long-term strategic plan for simulations that can meet the complex needs of simulating chemistry-climate interactions, while also

Table 2: Summary of proposed IGAC/SPARC CCMI reference simulations:

Name of Reference Simulation	Period	Greenhouse Gases	ODSs	SSTs/SICs	Background & Volcanic Aerosol	Solar Variability	VSLS	QBO	Ozone and Aerosol Precursors
REF-C1	**Transient simulation 1960-2010** Appropriate spin up prior to 1960	**OBS** GHG used for CMIP5 simulations, updated until 2010.	**OBS** (WMO, 2011)	**OBS** HadISST1	**OBS** Surface Area Density data (SAD)	**OBS** Spectrally resolved irradiance data, Proton ionization, Ap	**YES**	**OBS or internally generated**	**OBS** Based on Lamarque *et al.* (2010), but annual emissions
REF-C1SD (nudged for CCMs, or CTMs)	**Transient simulation 1980-2010**	**OBS** Same as **REF-C1**	**OBS** Same as **REF-C1**	**OBS** Consistent with met. reanalysis	**OBS** Same as **REF-C1**	**OBS** Same as **REF-C1**	Same as **REF-C1**	Same as **REF-C1**	**OBS** Same as **REF-C1**
REF-C2	**Transient simulation 1960-2100** 10-year spin up prior to 1960	**OBS to 2005 then RCP 6.0 (Masui *et al.*, 2011)**	**OBS + A1 scenario from WMO (2011)**	**Modeled SSTs**	**OBS** Background SAD	**YES** Spectrally resolved irradiance data, Proton ionization, Ap	**YES**	**YES**	**Same as REF-C1 until 2000 + RCP 6.0 scenario in the future**

seeking to prioritize simulations for near term (~next 3 years) needs. The result is that these simulations are envisaged to occur in two main phases over the next few years, see further details Section 5 and **Figure 28**.

1.4 Outline

The three, highest priority reference simulations that should be run by the various modelling groups are described in Section 2. It is recommended that, in addition to the reference simulations, the sensitivity simulations described in Section 3 are performed by as many groups as possible. It is important that groups simulate the full time period specified, to allow a reliable comparison between the different models and observations, and to provide projections until the end of the 21st century. Section 4 describes model output, dynamics and composition diagnostics, and comparison to observations. Section 5 outlines a timeline for the CCMI and Section 6 closes with a summary and outlook.

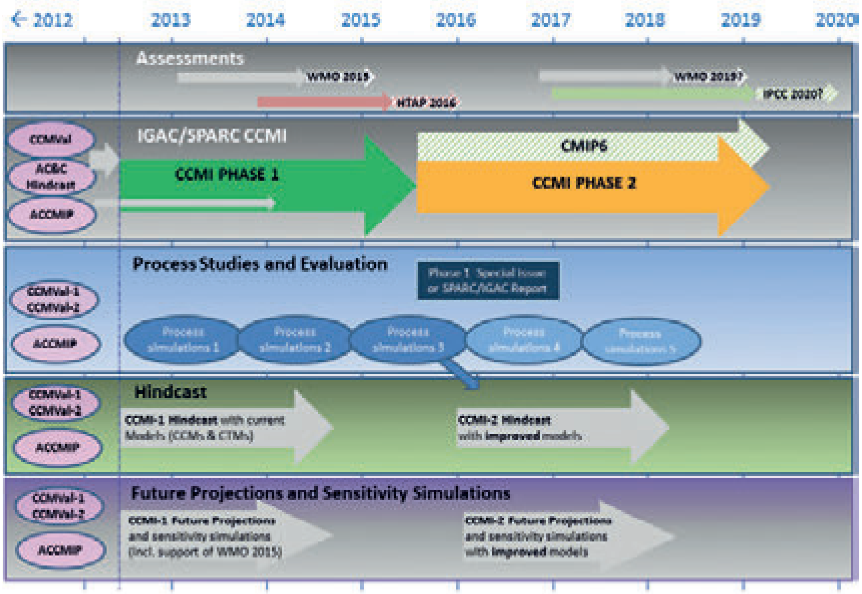

Figure 28: Timeline for the IGAC/SPARC CCMI community simulations.

2. IGAC/SPARC CCMI Reference Simulations

This section gives an overview of the main characteristics of the new IGAC/SPARC CCMI REF simulations. In many instances, the forcings follow the recommendations of CMIP5 (**http://cmip-pcmdi.llnl.gov/cmip5/forcing.html**). The key characteristics are also summarized in **Table 2**.

2.1 HINDCAST: Reference Simulation 1 (REF-C1, 1960-2010; REF-C1SD, 1980-2010)

REF-C1 (1960-2010) covers the time period from 1960 to 2010 (with a 10-year spin-up prior to 1960) to examine model variability and to replicate as closely as possible the atmospheric state in the period during which ozone and other atmospheric constituents were measured. It allows a detailed investigation of the role of natural variability and other atmospheric changes important for ozone balance and trends. All forcings in this simulation are taken from observations or empirical data, including anthropogenic and natural forcings based on changes in trace gases, solar variability (spectral irradiance and particles), volcanic eruptions, quasi-biennial oscillation (QBO), SSTs, and SICs; see details below. In contrast to CCMVal-2 simulations, the forcings are extended to 2010 based on observations as much as possible. Note, that many of these forcings are not necessary for models without explicit representation of stratospheric chemistry or alternatively, without explicit tropospheric chemistry. The primary focus of the proposed hindcast simulation is the evolution and variability of tropospheric and/or stratospheric ozone over the last 40-50 years. The proposed hindcasts will include a number of new aspects not previously examined in multi-model chemical hindcast simulations, including detailed evaluations of tropospheric oxidants and chemistry, in addition to stratospheric chemistry, interactions between stratospheric and tropospheric chemistry, chemistry-aerosol interactions, the inclusion of very short-lived species, and more generally, the impact of using stratospheric-tropospheric CCMs versus primarily tropospheric or stratospheric CCMs.

REF-C1SD (REF-C1 Specifie Dynamics) is a transient simulation from 1980 to 2010 (there is a discontinuity in meteorological reanalysis datasets near 1979 with the incorporation of satellite data into the reanalysis product, making the use of reanalyses prior to 1980 problematic) that is either nudged towards observed meteorology in a CCM or simulated with a CTM, where the meteorology is prescribed. Otherwise, all forcings are the same as in REF-C1. Compared to REF-C1, this simulation can be more directly compared to observations since there is a more direct correspondence between the simulation period and the observations. This is particularly beneficial since some observational data often only cover short time periods.

It should be noted that the proposed REF-C1 setup is similar to the historical simulation of the CMIP5 protocol (Taylor *et al.*, 2009), but covers a different time period (later starting date but extended to 2010 instead of 2005). Therefore, some of the multi-model analysis could include the historical simulations from the CMIP5 archive that were carried out with an ESM with interactive chemistry.

2.1.1 Chemical fields and emissions in the hindcast simulations

- **Greenhouse Gases** (N_2O, CH_4, and CO_2) between 1950 and 2005 are taken from Meinshausen *et al.* (2011) and continued to 2010 from the RCP 8.5 scenario (Riahi *et al.*, 2011). Values are available at **http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download**. Note that these are the same values that were used for CMIP5.
- **Surface mixing ratios of Ozone Depleting Substances** (CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, CCl_4, CH_3CCl_3, HCFC-22, HCFC-141b, HCFC-142b, Halon1211, Halon1202, Halon1301, Halon2402, CH_3Cl, and CH_3Br) are taken from Table 5-A3 of WMO (2011). The WMO mixing ratios provided in Table 5A-3 represent January 1 values, and are closely tied to observations in the years that are shaded, and are based on scenario calculations in future years (additional information on the scenarios can be found in WMO, 2011). For models that do not wish to represent all the brominated and chlorinated species, the halogen content of species that are considered should be adjusted such that model inputs for total chlorine and total bromine match the time series of total chlorine and bromine given in this table at about the year 2000. Missing species can be added to existing model tracers with similar lifetimes to preserve total chlorine or bromine. Table 5-A3 of WMO (2011) is available at **http://ozone.unep.org/Assessment_Panels/SAP/Scientific_Assessm nt_2010/index.shtml**. For convenience, the corresponding excel spread sheet with mixing ratios (ppt) of the ODSs given for every year from 1951 to 2100 is provided on the CCMI website, courtesy of Guus Velders.
- **Very short lived species (VSLS)**. In order for the models to have a realistic stratospheric bromine loading, and thereby be able to reproduce past ozone depletion, they will need to account for the transport of bromine to the stratosphere by VSLS. We recommend that models explicitly include the two major VSLS species $CHBr_3$ and CH_2Br_2. The tracers should decompose directly to inorganic Br_y. Based on past experience we expect that imposing a surface volume mixing ratio of 1.2pptv of each (6pptv bromine) should lead to about the required 4.5–5.0pptv Br_y reaching the stratosphere. For models who do not wish to include these VSLS and model tropospheric loss, the model CH_3Br tracer can be increased by a constant 5pptv.
- **Natural biogenic emissions and lightning NO_x emissions.** These emissions are sensitive to meteorological variability and climate change. It is preferable that models diagnose these emissions online through parameterisations sensitive to changes in meteorology and climate. However, we recognise that not all groups may have the capacity to specify internally interactive emissions.

We recommend that those groups obtain biogenic emissions, preferably consistent with their meteorology, from a group with the capability of diagnosing these emissions online (the PEGASOS project will provide biogenic emissions from 1980 to 2010). Climatological emissions may provide an acceptable solution for those models with an upper tropospheric emphasis. Lightning emissions are more difficul to specify in an externally consistent manner, but are important to upper tropospheric variability and the tropospheric oxidant balance.

- **Anthropogenic and biofuel emissions**. The MACCity emission dataset (Granier *et al.*, 2011) is proposed for anthropogenic and biofuel emissions and covers the full period 1960-2010. Since no global database existed which provided emissions of the main tropospheric gases for each year during the 1960–2010 period, a dataset was created, based on the 1960 and 2000 ACCMIP emissions (Lamarque *et al.*, 2010), and the 2005 and 2010 emissions provided by RCP 8.5. This scenario was chosen since it includes some information on recent emissions at the regional scale in Europe and North America. The emissions for each compound were linearly interpolated for each sector and each year between 2000 and 2005, and for each year between 2005 and 2010, using the ACCMIP and RCP 8.5 emissions. For anthropogenic emissions, a seasonal cycle was first applied sector by sector, species were then lumped to MOZART-4 species (21 species), and finall emissions were interpolated on a yearly basis between the base years (every decade 1960-2010 + 2005). Prior to 2005, the emissions are interpolated from decadal time slices. In 2005 and 2010 the emissions are extrapolated using the RCP 8.5 emissions scenario. The MACCity emission inventory translates from the ACCMIP VOC emissions to those appropriate for the MOZART mechanism. Stevenson *et al.* (2006) recommend using the global speciation given in Prather *et al.* (2001), with species not included either lumped into others or ignored. Regionally, there is likely to be more information for lumping VOCs, but to gather and incorporate this information would need additional work. The simulated VOC emissions, speciation and chemistry (Stevenson *et al.*, 2006) likely lead to important differences in the chemistry and need to be clearly documented in the output. In addition, sensitivity studies will also likely be needed to document the impact of different emission inventories. The MACCity emissions can be downloaded from the Emissions of atmospheric Compounds & Compilation of Ancillary Data (ECCAD) database website at **http://pole-ether.fr/eccad**, after registration as a user.
- **Biomass burning emissions.** Biomass burning emissions are provided for the 1960-2010 period from AEROCOM2, which has been extended to most chemical compounds used in models. This dataset is based on the ACCMIP historical emissions dataset (Lamarque *et al.*, 2010), work done as part of the CityZen European project (**www.cityzen-project.eu**), the GFEDv2 inventory (van der Werf *et al.*, 2006) for 1997-2008, and the RETRO inventory (Schultz *et al.*, 2008) for the 1960-1996 period. All emissions are provided on a monthly-basis at a 0.5°x0.5° resolution. Another set of biomass burning emissions for the 1960-2010 period will be made available to the CCMI modellers for sensitivity studies purposes. This dataset, called PEGAERESS, is based on the LPJ-GUESS surface emissions (Knorr *et al.*, 2012), which uses the dynamical vegetation model LPJ (Smith *et al.*, 2001).
- **Stratospheric boundary conditions for models without interactive stratospheric chemistry.** As recommended for CMIP5 simulations without interactive chemistry, ozone can be prescribed from the AC&C/SPARC ozone database (Cionni *et al.*, 2011). Other stratospheric boundary conditions need to be specified. Monthly-mean zonal-mean fields for CH_2O, CH_4, CO, H_2, H_2O, H_2O_2, HNO_3, HNO_4, HO_2, N_2O, N_2O_5, NO, NO_2, NO_y, and O_3 covering 1960 to 2006 (as available at **https://jshare.johnshopkins.edu/dwaugh1/public_html/ccmval/multi-model/**) have been formed by taking a mean over the CCMVal-2 simulations. All are monthly-mean zonal-means. The mean and standard deviation of the ensemble are both stored as functions of time, pressure level and latitude where time is from 1960.01 to 2006.12, the vertical distribution is given on 31 pressure levels, and the latitudinal grid ranges from -90° to 90° by increments of 2.5°.

2.1.2 Meteorological fields in th hindcast simulations

- **Sea surface temperatures (SSTs) and sea ice concentrations (SICs)** are prescribed as monthly mean boundary conditions following the global sea ice concentration and sea surface temperature (HadISST1) data set provided by the UK Met Office Hadley Centre (Rayner *et al.*, 2003). This data set is based on blended satellite and *in situ* observations and can be downloaded from **http://www.metoffice.go .uk/hadobs/hadisst/data/download.html**. To prepare the data for use in forcing a model, and in particular to correct for the loss of variance due to time-interpolation of monthly mean data, it is recommended that each group follows the procedures described on the C20C project web site (see **http://grads.iges.org/c20c/c20c_forcing/karling_instruct.html**). This describes how to apply the AMIP II variance correction method (see **http://www-pcmdi.llnl.gov/projects/amip/AMIP2EXPDSN/BCS/amip2bcs.php for details**) to the HadISST1 data.
- **Quasi-Biennial Oscillation**. The QBO is generally described by zonal wind profile measured at the equator. The QBO is an internal mode of variability of the atmosphere that dominates the interannual variability of wind in the tropical stratosphere and contributes to variability in the extra-tropical dynamics. It is recognised that the QBO is important for understanding interannual variability in ozone and other constituents of the middle atmosphere, in the tropics and the extra-tropics. Currently, only a few atmospheric General Circulation Models (GCMs) or CCMs simulate a realistic QBO and hence QBO-related infl -ences. Simulated QBOs are generally independent of observed time series because their phase evolutions are not bound by external boundary conditions. A realistic simulation of the QBO, however, would have similar periods, amplitudes and composite structures as the observations. Assimilation of the QBO, for example, by a relaxation of zonal winds in the QBO domain ("nudging"), may hence be useful for two reasons: first to obtain a QBO in GCMs that do not simulate the QBO internally, so that, for example, QBO effects on the general circulation are present, and second to synchronize the QBO simulated in a CCM with a given QBO time series, so that simulated QBO effects, for example, on ozone, can be compared to observed signals. As for CCMVal-2, a dataset is provided for this purpose, which is based on updated radiosonde measurements following the method of Naujokat (1986) and extended to the upper stratosphere as discussed on the CCMI website.
- **Reanalysis**. The meteorological fields for nudged CCMs and CTMs must come from a continuous reanalysis system (e.g., ERA-Interim (Dee *et al.*, 2011), MERRA (Rienecker *et al.*, 2011), or NCEP (Kanamitsu *et al.*, 2002)). ERA-Interim data are available from **http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_12458543158227759**. The complete MERRA dataset, as processed and re-gridded to 1.9°x2.5° for CESM/MOZART are available on the Earth System Grid (**http://www.earthsystemgrid.org/; search for MERRA**). The atmospheric and surface flu fields from the NCEP/NCAR reanalysis are available from **http://rda.ucar.edu/datasets/ds090.0/#description**. The Reanalysis Intercomparison wiki at **http://reanalyses.org/** provides an overview of current reanalyses.

2.1.3 Solar forcing in the hindcast simulations

- **Solar variability**. The solar radiative forcing data are provided at **http://sparcsolaris.gfz-potsdam.de/input_data.php**. Daily, spectrally-resolved solar irradiance data from the NRLSSI model (Lean *et al.*, 2005), which have been used in previous CCMVal and CMIP5 experiments, are recommended. In addition, the inclusion of atmospheric ionization by solar protons (and related HO_x and NO_x production) are strongly encouraged by using the GOES-based ionization rate data set and a methodology to derive HO_x and NO_x production rates from Jackman *et al.* (2009). Models capable of considering indirect particle effects by the inclusion of an Ap-parameterised auroral source or upper boundary condition are encouraged to do so.

2.1.4 Aerosols and heating rates in the hindcast simulations

- **Aerosol concentrations**. Models that do not simulate tropospheric aerosols interactively might need to specify a time varying aerosol climatology. In particular, a subset of models for CMIP5 have used decadal averages from Lamarque et al. (2010), which are available at

http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download.

- **Surface Area Densities (SADs)**. Monthly, zonal mean time series for SADs (units: $\mu m^2/cm^3$) and (if required) mean radii (r_{mean}, units: μm^2) in conjunction with the radiative parameters of the stratospheric aerosol (extinction coefficient, asymmetry factor, and single scattering albedo, see next bullet point) have been created, covering the full **REF-C1** period 1960-2010. These data sets are internally consistent with each other (which was not the case for CCMVal-2), based on a single lognormal particle size distribution (Arfeuille *et al.*, 2012). The cornerstone for this approach is the four-wavelength SAGE II extinction data, retrieval version V6, which span the period 1985-2005. The 525nm and 1024nm data from SAGE II V6 already featured in the SPARC Assessment of Stratospheric Aerosol Properties (ASAP) report (SPARC, 2006). Uncertainties of the SAGE II dataset are described in detail by Thomason *et al.* (2008). From 1979 to 1985 the data were retrieved from single wavelength extinctions measured by the SAM II and SAGE I satellite instruments (SPARC, 2006), relying on correlations between aerosol properties (SAD, r_{mean}) and the extinctions derived from the SAGE II period. The 1960-1979 pre-satellite period has been constructed from SAGE-II background measurements in the late 1990s, superimposing the volcanic eruptions of Agung and Fuego. These eruptions were calculated by means of the AER 2-D aerosol model (Weisenstein *et al.*, 1997), and the results were scaled by means of stellar and solar extinction data (Stothers, 2001). The 2006-2011 period is derived from CALIPSO 532nm backscatter data, again using correlations between aerosol properties (SAD, r_{mean}) and the CALIPSO backscatter, which were obtained during the SAGE II period. The altitude and latitude range of all derived data (SAD, r_{mean} and radiative parameters) for the entire 1960-2010 period is 5.0–39.5km and 80°S–80°N, respectively. It should be noted that the SAGE II data and hence the ASAP SAD (SPARC, 2006) have data gaps, in particular when the atmosphere became opaque directly after volcanic eruptions, which occurred mainly in lower tropical altitudes (below 16km). Above 26km there are also large data gaps in the mid-to-high latitude regions. Furthermore, there are missing data at all altitudes in the high latitude polar regions. After the eruptions of El Chichón and Pinatubo, the resulting data gaps were fille by means of lidar ground station data and interpolation, as described in SPARC (2006). As for CCMVal-2, for CCMI the remaining data gaps were fille using a linear interpolation approach in altitude and latitude. Large gaps of data above 26km were filled with background values obtained from SAGE II during years without gaps. See next bullet point for a recommendation on how to pass from tropospheric to stratospheric aerosols. SADs and mean radii can be found through a link on the CCMI website.
- **Stratospheric heating rates, aerosol albedo and tropospheric-surface cooling due to volcanic eruptions**. Data sets for the radiative parameters of the stratospheric aerosol (extinction coefficient (km^{-1}), asymmetry factors (–) and single scattering albedos (–) have been created based on a single lognormal particle size distribution in a similar way to the SAD data (Arfeuille *et al.*, 2012). These data cover the full **REF-C1** period 1960-2010. By means of a simple lookup procedure the radiative parameters can be derived for any wavelength band in each of the models participating in CCMI, whose radiation transport modules subsequently calculate stratospheric heating rates and tropospheric cooling. The progress with respect to CCMVal-2 is the internal consistency between the SAD and radiative datasets, and the use of the new SAGE II V6 retrieval. The V6 data are superior to the V5 data used in CCMVal-2, which should no longer be used. The V5 series had major difficu - ties handling dense volcanic aerosol layers and tended to spread the enhanced extinction several kilometres away from the layer, forcing low values to occur at other altitudes in compensation. During the densest parts of the Pinatubo period, it could significantly affect data as high as 30km. Also, the extrapolation down to the tropopause was done by filling the missing data simply by extending the last reported measurement down to the tropopause, leading regularly to too-high extinctions at the tropopause. The V6 filling is far more robust than that used in the earlier dataset. According to the standard SAGE grid, zonally averaged data will be provided on a grid with 5° latitude (averaged 0-5°, 5-10°, etc.). Altitude resolution will be 0.5km between 5.0-39.5km altitude. Every modeller needs to provide their

own tropospheric aerosols (see aerosol concentrations above). In order to avoid misrepresentations of tropopause altitude, which might lead to too strong heating at the tropopause, models should use their own tropospheric aerosol data set all the way up to (and including) the model's local tropopause, and use the stratospheric SAD and optical parameters only in the first grid cell above the model's local tropopause and higher up. At this altitude models should switch from the tropospheric data set to the stratospheric data set (*i.e.* not as addition). For those models that do not calculate this effect online, pre-calculated zonal mean aerosol heating rates (K/day) and net surface radiative forcing (W/m^2) monthly means from January 1960 to December 2010 for all-sky condition will be made available. The data can be found through a link on the CCMI website.

2.2 Future projections: Reference simulation 2 (REF-C2, 1960 to 2100)

REF-C2 is an internally consistent simulation from the past into the future between 1960 and 2100. This simulation is designed for CCMs. The objective of REF-C2 is to produce best estimates of the future ozone and climate changes up to 2100, under specific assumptions about GHG as well as tropospheric ozone and aerosol precursors that follow RCP 6.0 and a specifie ODS scenario that follows the halogen scenario A1 from WMO (2011). REF-C2 includes solar variability, but possible volcanic eruptions in the future are not considered, as they cannot be known in advance. In contrast to the **REF-C1** simulation, where forcings are as much as possible based on observations until 2010, the emissions in REF-C2 follow those used in CMIP5, *i.e.* Lamarque *et al.* (2010) until 2000 and RCPs from there on (this has to be done in 2000 because that was the reference period for the harmonization of the RCPs with the historical emissions).

2.2.1 Chemical fields and emissions in the future projections

- **Greenhouse gas concentrations** (N_2O, CH_4, and CO_2) are taken from Meinshausen *et al.* (2011), but extended so that they cover annual concentrations and the period from 1950 to 2100 from the RCP 6.0 scenario. Values are available at **http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download**. Note that these are the same values that were used for CMIP5.
- **Surface mixing ratios of Ozone Depleting Substances** are based on the halogen scenario A1 from WMO (2011). The new lifetimes from the SPARC Lifetime Assessment will be released in early 2013. The report will include new lifetime estimates along with uncertainties for those lifetimes. After the release of these new lifetimes, the production of a new scenario A1 will start. In addition to a new A1, a "high" ODS scenario and a "low" ODS scenario based upon the uncertainties of the lifetimes will be produced. Additional sensitivity simulations with the new ODS scenarios might be defined on the CCMI website
- **Very short lived species (VSLS)**. The same methodology as for **REF-C1** is recommended, namely that models that explicitly include the two major VSLS species $CHBr_3$ and CH_2Br_2 should impose a surface volume mixing ratio of 1.2pptv for each, through to 2100. For models who do not wish to include these VSLS and model tropospheric loss, the model CH_3Br tracer can be increased by a constant 5pptv through to 2100.
- **Anthropogenic and biofuel emissions** in **REF-C2** are the same as in **REF-C1** until 2000. After 2000 they follow RCP 6.0, as was done for the CMIP5 and ACCMIP simulations. These emissions can be found at **http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download**.
- **Biomass burning emissions** in **REF-C2** are as in CMIP5, *i.e.* using Lamarque *et al.* (2010) for the 1960-2000 period and RCP 6.0 for 2000-2100. These emissions can be found at **http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download**. Note that the **REF-C1** biomass burning emissions cannot be used because of the potential discontinuity between the AEROCOM2 emissions and RCP 6.0.
- **Stratospheric boundary conditions for models without interactive stratospheric chemistry.** As recommended for CMIP5 simulations without interactive chemistry, ozone can be prescribed from the AC&C/SPARC ozone database (Cionni *et al.*, 2011). Monthly-mean zonal-mean fields for CH_2O, CH_4, CO, H_2, H_2O, H_2O_2, HNO_3, HNO_4, HO_2, N_2O, N_2O_5, NO, NO_2, NO_y, and O_3 for the period 2006-2100 have been formed by taking a mean over the CCMVal-2 simulations (see **https://jshare.johnshopkins.edu/dwaugh1/public_html/**

ccmval/multi-model/ for details and data).

2.2.2 Meteorological fields in th future projections

- **Sea surface temperatures and sea ice concentrations**. Because of potential discontinuities between the observed and modelled data record, the **REF-C2** simulations use simulated SSTs and SICs for the entire period. There are three alternate approaches, depending on the resources of each modelling group.

1. First, groups that have fully coupled atmosphere-ocean models with coupled chemistry and a middle atmosphere should perform a fully coupled run that calculates the SSTs/SICs internally. Due to the inertia of the coupled atmosphere ocean system, such integrations should be started from equilibrated control simulations for preindustrial conditions, as is standard for the 20th century integrations in CMIP5 (*i.e.*, from 1850-2100). Solar forcing according to the CCMI recommendation (see 2.2.3) should be used.
2. Second, groups that have a coupled atmosphere-ocean model that does not include chemistry should use their own modelled SSTs/SICs to prescribe those in the CCM integration for the period 1960-2100. Solar forcing according to the CCMI recommendation (see 2.2.3) should be used.
3. Third, groups that do not have their own coupled ocean-atmosphere model should use SSTs/SICs from an RCP 6.0 CMIP5 simulation. Please make sure that you use the same solar forcing that was used for the CMIP5 simulations so that the SSTs/SICs and the atmosphere use the same solar forcing.

- **Quasi-Biennial Oscillation.** To take the QBO variability into account in future simulations, the data set provided for the **REF-C1** simulation has been extended to 2100. The **REF-C2** QBO data set includes observations from 1953 to 2011 and repeats past cycles in the future. Alternative time series for extensions of the observational dataset after 2011 can be composed individually following the procedure on the CCMI webpage.

2.2.3 Solar forcing in the future projections

- **Solar variability**. For the future solar forcing data, we recommend, as for CCMVal-2, to repeat the last four solar cycles (20-23) **http://sparcsolaris.gfz-potsdam.de/input_data.php**. Since data from 1960-2010 will be used for the **REF-C1** simulations and this passes the last solar cycle minimum in 2008 we will provide a point where the future solar cycles should be used. Note that the repetition of the last four solar cycles is not compliant with the recommendation for CMIP5, where a repetition of solar cycle 23 was recommended but was used only by a small number of modelling groups. Proton forcing and Ap data as described for REF-C1 should be repeated over the last solar cycles in consonance with the solar irradiance data.

2.2.4 Aerosols and heating rates in the future projections

- **Aerosol concentrations**. Models that do not simulate tropospheric aerosols interactively might need to specify a time varying aerosol climatology. In particular, a subset of models for CMIP5 used decadal averages from Lamarque *et al.* (2011) which are available at **http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download**.
- **Background aerosol**. Surface area densities (and, if required, mean radii) and radiative parameters (extinction coefficients, single scattering albedos and asymmetry factors for each wavelength band of each model participating in CCMI) will be prescribed by a perpetual average of the years 1998-1999 from the **REF-C1** data set, which is characteristic for a volcanically quiescent period. Data will be offered through a link on the CCMI website.
- **Stratospheric warming and tropospheric-surface cooling due to volcanic eruptions** are not specified for the future **REF-C2** simulation.

3. IGAC/SPARC CCMI Sensitivity Simulations

The following IGAC/SPARC CCMI sensitivity simulations are currently proposed and their specification summarized in **Table 3** (past) and **Table 4** (future). Additional sensitivity simulations that might be suggested to answer specific scientifi questions will be defined and documented on the CCMI website. No priority ranking is implied by the following list.

SEN-C1-Emis / SEN-C1SD-Emis is a sensitivity study that involves individual groups specifying their own emission inventory, different to that in **REF-C1** and **REF-C1SD**. Otherwise the specification of forcing is as in REF-C1 or REF-C1SD.

Table 3: Summary of proposed IGAC/SPARC CCMI past sensitivity simulations:

Name of Sensitivity Simulation	Period	GHGs	ODSs	SSTs/SICs	Background & Volcanic Aerosol	Solar Variability	VSLS	QBO	Ozone and Aerosol Precursors
SEN-C1-Emis	1960-2010	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Different from REF-C1
SEN-C1SD-Emis	1980 2010	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Different from REF-C1SD
SEN-C1-fEmis	1960-2010	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Fixed at 1960 levels
SEN-C1SD-fEmis	1980-2010	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Fixed at 1980 levels
SEN-C1-SSI	1960-2010	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Different SSI data set (SATIRE) Protons and Ap same as in REF-C1	Same as in REF-C1	OBS or internally generated	Same as in REF-C1

This simulation will assess the importance of using different emission inventories in tropospheric chemical variability.

SEN-C1-fEmis / SEN-C1SD-fEmis is a sensitivity study that involves using constant anthropogenic, biofuel, biogenic and biomass burning emissions. Otherwise the specification of forcings is as in **REF-C1** or **REF-C1SD**. This simulation will assess the importance of meteorology in tropospheric chemical variability.

SEN-C1-SSI (1960-2010, REF-C1 with a different SSI forcing data set, *i.e.* SATIRE (Krivova *et al.*, 2006) is designed to address the sensitivity of the atmospheric response to a higher UV forcing than in the standard NRLSSI data set (Lean *et al.*, 2005) used so far for all model experiments within CCMVal and CMIP5. The larger UV forcing has consequences not only for atmospheric heating but also for ozone chemistry. It is therefore important to understand the atmospheric impacts of using different SSI datasets in a consistent and coordinated way in a number of CCMs, as recently highlighted by Ermolli *et al.* (2012).

SEN-C2-RCP (2000-2100, REF-C2 with GHG scenario other than RCP 6.0) is a transient simulation similar to **REF-C2**, but with the GHG and ozone precursor scenario changed from RCP 6.0 to RCP 2.6 (van Vuuren *et al.*, 2011b), RCP 4.5 (Thomson *et al.*, 2011), and/or RCP 8.5 (Riahi *et al.*, 2011). Accordingly, if the model does not include an interactive ocean, SSTs and SICs are prescribed from an AOGCM simulation that is consistent with the GHG scenario. The ODS scenario in all these simulations remains as in REF-C2. The sensitivity of stratospheric ozone has been studied in Eyring *et al.* (2010b), but with a limited number of scenarios performed by only a small number of models. These sensitivity simulations will allow the assessment of the future evolution of ozone and climate change under GHG scenarios other than the RCP 6.0 scenario used in REF-C2.

SEN-C2-fODS (1960-2100, REF-C2 with halogens fixed at 1960 levels) is a transient simulation similar to **REF-C2**, but with halogens fixe at 1960 levels throughout the simulation, whereas GHGs and SSTs/SICs are the same as in REF-C2. It is designed to address the science question of what are the effects of halogens on stratospheric ozone and climate, in the presence of climate change (Eyring *et al.*, 2010a). By comparing **SEN-C2-fODS** with **REF-C2**, the impact of halogens can be identified and it can be assessed at what point in the future the halogen impact is undetectable, *i.e.*, within climate variability. This was the definition of full recovery of stratospher-

Table 4: Summary of proposed IGAC/SPARC CCMI future sensitivity simulations:

Name of Sensitivity Simulation	Period	GHGs	ODSs	SSTs/SICs	Background & Volcanic Aerosol	Solar Variability	VSLS	QBO	Ozone and Aerosol Precursors
SEN-C2-RCP2.6	2000-2100	OBS + RCP 2.6	Same as in REF-C2	SSTs/SICs consistent with RCP 2.6 GHG scenario	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as REF-C1 until 2000 + RCP 2.6 beyond
SEN-C2-RCP4.5	2000-2100	OBS + RCP 4.5	Same as in REF-C2	SSTs/SICs consistent with RCP 4.5 GHG scenario	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as REF-C1 until 2000 + RCP 4.5 beyond
SEN-C2-RCP8.5	2000-2100	OBS + RCP 8.5	Same as in REF-C2	SSTs/SICs consistent with RCP 8.5 GHG scenario	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as REF-C1 until 2000 + RCP 8.5 beyond
SEN-C2-fODS	1960-2100	Same as in REF-C2	Fixed halogens at 1960 level	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2
SEN-C2-fODS2000	2000-2100	Same as in REF-C2	Fixed halogens at 2000 level	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2
SEN-C2-fGHG	1960-2100	Fixed GHG at 1960 levels	Same as in REF-C2	1955-1964 average of values used in REF-C2, repeating each year	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2
SEN-C2-fEmis	1960-2100	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Fixed at 1960 levels
SEN-C2-GeoMIP	2020-various	4xCO_2, 1%/year CO_2 or RCP 4.5	Same as in REF-C2	Modeled or specified SSTs	Specified by GeoMIP experiment	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2
SEN-C2-SolarTrend	1960-2010	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Trend in SSI and Ap, Protons same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2

ic ozone from the effects of ODSs that was applied in WMO (2011).

SEN-C2-fODS2000 (2000-2100, REF-C2 with halogens fixed at 2000 levels) is a transient simulation similar to **REF-C2**, but with halogens fixed at 2000 levels throughout the simulation, whereas GHGs and SSTs/SICs are the same as in REF-C2. This simulation is designed to address the climate and composition change due to the implementation of the Montreal Protocol, which caused chlorine and bromine to go into reverse at around the year 2000. This simulation covers 2000 to 2100, and is initialized from REF-C2.

SEN-C2-fGHG (1960-2100, REF-C2 with GHGs fixed at 1960 levels) is a transient simulation similar to **REF-C2**, but with GHGs fixed at 1960 levels throughout the simulation and the adjusted scenario A1 halogens the same as in REF-C2. It is designed to address the science question of how non-linear are the atmospheric responses to ozone depletion/recovery and climate change (Eyring *et al.*, 2010a). To that end, GHGs are fixed at 1960 levels throughout the simulation. SSTs/SICs will be a 1955-1964 average of the values used in REF-C2. By comparing the sum of **SEN-C2-fODS** and **SEN-C2-fGHG** (each relative to the 1960 baseline) with REF-C2, the non-linearity of the responses can be assessed. SEN-C2-fGHG also addresses the policy-relevant (if academic) question of what the impact of halogens on the atmosphere would be in the absence of climate change.

SEN-C2-fEmis (1960-2100, REF-C2 with emissions fixed at 1960 levels) is designed to address the impact of climate change (Stevenson *et al.*, 2006).

SEN-C2-GeoMIP is a set of transient simulations to test the climate system response to solar radiation management with stratospheric aerosols, as part of GeoMIP. Kravitz *et al.* (2011) describe four sets of standardized experiments using solar constant reduction or stratospheric aerosol clouds to either balance anthropogenic radiative forcing or reduce it quickly. Many of these runs have been completed and are now being analysed, but there are still many interesting questions that can be addressed by CCMs. The G1 and G2 experiments involve reducing the total solar irradiance to balance either an instantaneous quadrupling of CO_2 or a 1%/year increase of CO_2, and would be most appropriate for models with interactive oceans. G3 and G4 involve balancing an RCP 4.5 forcing with sulphate aerosols in the stratosphere or a continuous 5Tg/year stratospheric sulphate injection, and all CCMs could simulate the stratospheric chemical and dynamical responses, in addition to other climate changes. Models without oceans will need to have SSTs provided from other GCM runs. SADs and net radiative flux changes will be needed for models that do not create their own stratospheric aerosols and the radiative response from SO_2 or sulphate injections. See **http://climate.envsci.rutgers.edu/GeoMIP/** for more details on GeoMIP.

SEN-C2-SolarTrend (1960-2100, REF-C2 but with a trend in future solar cycle) aims at looking at the effects of a possible new grand minimum in solar activity. Predictions of the solar cycle are extremely difficult and uncertain, but it is known that the sun will move out of its grand maximum, which peaked in the mid-20th century. There is a lot of ongoing research looking into whether or not the sun will move into a new Maunder Minimum-like period, and whether and how this might counteract the recent global warming. To avoid speculation and put research on firm ground, a simulation with a future trend in the solar cycle amplitude will be prescribed and the atmospheric response will be investigated. This future trend will be based on past cycles that will be repeated in reversed order (cycles 20, 18, 17, 16, 15, 14, 13, 12). A detailed description and the data set will be provided on the SOLARIS website at **http://sparcsolaris.gfz-potsdam.de/input_data.php**.

4 Model output, online diagnostics, and comparison with observations

4.1 Requested output and format

Output from this new set of CCMI simulations will be collected in Climate and Forecast (CF) standard compliant netCDF format from all models, and held in the central CCMI database at the British Atmospheric Data Centre (BADC). The use of CMOR is strongly encouraged. We will provide CMOR tables for all requested output and will make them available on the CCMI website. CMOR-compliant data will be published through the Earth System Grid Federation (ESGF) system.

Output requests will broadly follow the requests made by the ACCMIP and CCMVal activities, with some additional output for new suggestions for process-oriented model evaluation and improved comparison with observations. These additional specific diagnostics are discussed in Section 4.2. It is recommended that model groups provide these data to the extent possible. CMOR tables for these additional diagnostics will also be provided on the CCMI website.

4.2 Additional transport and composition diagnostics

Diagnostics not yet available from the previous ACCMIP and CCMVal activities include synthetic tracers (Section 4.2.1), diagnostics for tropospheric ozone and HO_x budgets (Section 4.2.2 and 4.2.3, respectively), and output of some high-frequency model data for tropospheric OH (Section 4.2.4).

4.2.1 Synthetic tracers

Following discussions at the Davos workshop, modellers are encouraged to include the following synthetic tracers:

1. NH_5: Fixed surface layer mixing ratio over 30°-50°N (100ppbv), uniform fixed 5-day exponential decay (e-folding time τ=4.32x10^5s).
2. NH_50: Fixed surface layer mixing ratio over 30°-50°N

(100ppbv), uniform fixed 50-day exponential decay.

3. NH_50W: Fixed surface layer mixing ratio over 30°-50°N (100ppbv), uniform fixed 50-day exponential decay, wet removal as HNO_3.
4. AOA_NH: Fixed surface layer mixing ratio over 30°-50°N (0ppbv), uniform fixed source (at all levels) everywhere else (source is unspecified but must be constant in space and time and documented). Note that the source could be 1yr/yr, so the tracer concentration provides mean age in years.
5. ST80_25: Fixed mixing ratio above 80hPa (200ppbv), uniform fixed 25-day exponential decay in the troposphere only.
6. CO_25: emitted as anthropogenic CO (emission file available from HTAP, **ftp://ftp.retro.enes.org/pub/emissions/aggregated/anthro/0.5x0.5/2000/RETRO_ANTHRO_V2_2000_CO_aggregated.nc** but only use annual mean), uniform fixed 25-day exponential decay.
7. CO_50: emitted as anthropogenic CO (emission files available from HTAP), 50-day exponential decay.
8. SO2t: emitted as anthropogenic year 2000 SO_2 (as specified in **REF-C1**), wet removal as SO_2.
9. O3S: stratospheric ozone tracer set to ozone in the stratosphere, then destroyed in the troposphere using the ozone chemical loss rate.
10. SF6: specified using emissions from **http://edgar.jrc.ec.europa.eu/datasets_grid_list.php#d**. Note that these emissions are available only as annual averages (1970-2008; emissions before 1970 should be set to 0 while emissions after 2008 should be kept at their 2008 level). Monthly emissions should be built using the available annual file and assigning the value as representative of July 15. Special care should be made that the annual global integral at the model resolution matches the EDGAR generated total (available as argument from the netCDF v42 files)
11. AOA: Stratospheric mean age-of-air. Use existing implementation or implement the same as AOA_NH (item #4) except fixed surface layer mixing ratio is set to 0ppbv over the surface of the whole globe.

The "NH" tracers (NH_5, NH_50, NH_50W, and AOA_NH) are used for defining the transport times and time since air has encountered the surface layer over the latitude band 30°-50°N. From AOA_NH, NH_5 and NH_50 we will be able to estimate the transit time distribution. The NH_50W tracer will, in comparison to NH_50, provide information on the relative role of wet deposition in transport from the northern mid-latitudes. By referencing the age at the tropical tropopause, AOA_NH can also be used for stratospheric age-of-air diagnostics. The tracer ST80_25 is used for diagnosing stratosphere-troposphere exchange. The tracers CO_25, CO_50, and SO2t can be used as surrogates for surface pollution and $PM_{2.5}$, therefore allowing for the diagnosis of the importance of changes in circulation on surface pollutant concentration. In addition, the inclusion of the stratospheric ozone tracer (O3S), SF6 (specifie from observations as a concentration in the surface layer) and mean age-of-air (AOA) tracers are recommended. The SF6 and AOA tracers can be compared with observations. For the analysis, only monthly output for each tracer is requested. Specific models with the capacity for daily output for surface layer mixing ratio CO_25, CO_50, and SO2t are encouraged to generate them to the extent possible.

4.2.2 Tropospheric ozone budget

In order to accurately document the tropospheric ozone budget, we recommend saving the monthly average output of the following fiv fields (see CMOR Tables for additional information):

1. Net chemical tendency dO_3/dt (production *minus* loss, excluding deposition)
2. Production: **only** provide the sum of all the HO_2/RO_2 + NO reactions (as k*[HO_2]*[NO])
3. Loss: **only** provide the sum of the following reactions
   (i) O(1D) + H_2O
   (ii) O_3 + HO_2
   (iii) O_3 + OH
   (iv) O_3 + alkenes (isoprene, ethene,…)
4. Dry deposition flux: **only** of O_3
5. Tropopause pressure

At the minimum the net chemical tendency, tropopause pressure and deposition fields should be provided.

4.2.3 Tropospheric HO_x budget

Similarly, specific output for the study of tropospheric OH is recommended as monthly averaged file for the following fields

1. J(NO_2)
2. J(O^1D)
3. 3D lightning NO production
4. Rate of (O^1D)+H_2O (three-dimensional distribution of k*[O^1D]*[H_2O])
5. Total loss of OH (rate of OH loss from all reactions)
6. Rate of CO+OH and CH_4+OH
7. Production rate of H_2O_2
8. Production rate of HNO_3

9. Production rate of all hydrogen peroxides (*e.g.*, CH_3OOH)
10. Aerosol reactions rates as separate diagnostics (as an example, the MOZART reactions are listed)
  - N_2O_5 -> 2 * HNO_3
  - NO_3 -> HNO_3
  - NO_2 -> 0.5*OH + 0.5*NO + 0.5*HNO_3
  - HO_2 -> 0.5*H_2O_2
11. Reaction rate of SO_2 + OH

In addition, it would be very useful if modellers could provide the additional rates (to further diagnose the fate of hydrogen peroxides) as monthly averages:

1. RO_2+NO
2. RO_2+NO_3
3. RO_2+HO_2
4. RO_2+RO_2
5. RC(O)O_2+NO_2

where R refers to the organic peroxy radical pool.

4.2.4 High-frequency output for tropospheric OH

The following targeted, high-frequency output for evaluating tropospheric OH and related species should be generated if possible:

REF-C1SD: hourly (instantaneous) output for July 1st 2004 (to "coincide" with INTEX-A)
REF-C2: hourly (instantaneous) output for July 1st every decade (1960-2100)

These are therefore 24 time samples of 3D instantaneous fields for one model day for **REF-C1SD** and for every 10 years **for REF-C2**.

- Requested fields: Temperature and either pressure or density
- Chemical species (if applicable):
  – OH, HO_2, NO, NO_2, HNO_3, PAN, H_2O, CH_4, CO, O_3, $O(^3P)$, $O(^1D)$, CH_3, CH_3O_2, CH_3OOH, CH_3O, CH_2O, CHO, H, $(CH_3)_2CO$, CH_3OOH, H_2O_2 & full suite of biogenic & anthropogenic VOCs
  – or- all chemical species (if more convenient)
- Photolysis rates:
  – $J(O_3)$ >> $O(^1D)$, $J(O_3)$ >> $O(^3P)$, $J(NO_2)$, cloud and aerosol optical depth, surface albedo
  – or- all J values (if more convenient).

4.3 Model output for comparison with satellite observations

There is now a wealth of satellite data with which to evaluate processes and trace gas distributions within models. Each of these datasets has its own strengths and limitations, and often provides complementary information to other datasets.

A proper comparison between satellite observations and models requires sampling the model output at the times and locations of the measurements and interpolating the model data to the observed vertical levels. Comparisons to satellite data should, in addition, consider *a priori* profiles and averaging kernels from the retrievals when sampling model output, for example, to calculate tropospheric columns for trace gas species. During the last few years, several satellite simulators have been developed, which either involve online calculations or post-processing to provide model output more directly comparable to remote sensing observations from satellites. Some models now have the capability to sample model output along sun-synchronous satellite orbits (see for example the SORBIT routine in Jöckel *et al.*, 2010). To facilitate and encourage a proper comparison with satellite data, we therefore provide local times and measured species for some remote sensing products that could potentially be used for evaluating trace gases, see **Tables S1**, **S2**, and **S3**[2].

Evaluation of the CCMI simulations will benefit from the Obs4MIPs effort (**http://obs4mips.llnl.gov:8080/wiki**), a pilot activity to make observational products more accessible for climate model intercomparisons, such as CMIP5. Obs4MIPs was initiated by NASA and the Program for Climate Model Diagnosis and Intercomparison (PCMDI; **http://www-pcmdi.llnl.gov/**). Participants of the IGAC/SPARC CCMI are encouraged to use and contribute satellite datasets to the Obs4MIPs database, adhering to the prescribed requirements (**http://obs4mips.llnl.gov:8080/wiki/requirements**). Interested parties should contact the Obs4MIPs team at **obs4mips@lists.llnl.gov**.

The focus of the initial data sets listed in Table S1 is to constrain the magnitude and distribution of those species that are radiatively important in the troposphere or important for controlling tropospheric ozone and OH. Table S1 lists some potential data sets. Methane, ozone, aerosols and water vapour are directly radiatively important. The other factors in Table S1 control the distributions of ozone and OH, such as meteorological variables (*e.g.*, cloud albedo), solar irradiance variables (*e.g.*, ozone column) and chemical variables (*e.g.*, CO, methane, NO*x*, ozone, water vapour). For example, ESMs typically have high biases for water vapour in the mid- and upper troposphere as compared to AIRS data, which can translate into high

[2]Find Tables S1, S2 and S3 in the Supplementary Material uploaded to **http://www.sparc-climate.org/publications/newsletter/**.

biases of model OH. In addition to evaluating the distributions of trace gases, these data sets can be used to assess the response of model processes to perturbations (*e.g.*, the response of ozone to ENSO).

In addition, we ask for output of cloud properties (cloud fraction and cloud liquid water content), temperature, H_2O, NO_2, CH_2O, SO_2, CO, NH_3 and O_3 at **two local times** (10:00am and 2:00pm). From these local time values, a monthly-average composite can be generated to limit output requirements while still being useful (Aghedo *et al.*, 2011). In the case of **REF-C1SD**, daily output for 2006 is, however, requested to fully document the importance of sub-sampling.

The SPARC Data Initiative offers an archive (soon accessible via the SPARC Data Center website) with vertically-resolved, monthly, zonal mean time series of stratospheric trace gas climatologies obtained from current and past limb-viewing satellite instruments (Table S3). The climatologies are provided on a latitude-pressure grid using the CCMVal pressure levels (300, 250, 200, 170, 150, 130, 115, 100, 90, 80, 70, 50, 30, 20, 15, 10, 7, 5, 3, 2, 1.5, 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1hPa) and a horizontal binning of 5°, with latitude bins centred at -87.5°, -82.5°, -77.5°,…,87.5°. For longer-lived species (*e.g.*, O_3, N_2O, H_2O, CH_4, CFCs, CO, HF, SF_6), the climatologies can be directly compared to zonal mean model output. For the shorter-lived species, however, model output should be sampled in the same way as the satellite data (*e.g.*, with the help of a satellite simulator) in order to avoid zonal mean differences due to inhomogeneous sampling or diurnal variations. Alternatively, if sampling the model output along the exact sampling pattern cannot be carried out, the zonal mean model output should be based on data sampled at the specific local solar time (LST) of the satellite measurement of each latitude bin. In addition, model profiles output at the observational tangent points (see Table S2) are very important, in particular for the profile-by-profil evaluation of species with large diurnal variation. Detailed sampling patterns and simplified sampling instructions based on LST-latitude relations will be provided by the SPARC Data Center. We specifically ask for the following targeted output from the **REF-C1SD** simulations using the detailed or simplified sampling patterns in order to evaluate the representation of the diurnal cycles of different species and polar stratospheric chemistry (see *e.g.,* Santee *et al.*, 2008):

- O_3, NO_2, NO_x, HNO_3, N_2O_5, $ClONO_2$, and HCl according to the ACE-FTS sampling pattern between 1 July 2004 and 31 June 2006.
- O_3, HNO_3, ClO, HOCl, $ClONO_2$, NO_2, N_2O_5 according to the MIPAS sampling pattern between 1 February 2005 and 31 June 2006.
- O_3, N_2O, HNO_3, HCl, ClO, HOCl according to the Aura-MLS sampling pattern between 1 July 2004 and 31 June 2006.
- O_3, HNO_3, HCl, ClO, HOCl, BrO according to the SMILES sampling pattern between 1 October 2009 and 31 March 2010.
- BrO, NO_2 according to the OSIRIS sampling pattern between 1 July 2004 and 31 June 2006.

4.4 Model output for comparison with aircraft observations

In addition to observations that monitor climate on a global scale, process study observations are made, which are usually more localised and cover limited time periods. Regional field experiments provide the basis for much understanding about key processes in the atmosphere. Examples include field projects such as the SCOUT-O3 Darwin Aircraft Campaign; the African Monsoon Multidisciplinary Analyses (AMMA) experiment; the Tropical Convection, Cirrus and Nitrogen Oxides Experiment (TROCCINOX) aircraft campaign; the HIAPER Pole-to-Pole Observations (HIPPO) of the carbon cycle and greenhouse gases; and the Transport and composition in the UTLS (TACTS) / Earth System Model Validation (ESMVal) campaign carried out with the High Altitude and Long-Range Research Aircraft (HALO).

Comparisons to more local measurements made, for example, during *in situ* aircraft campaigns exhibit the problem of a mismatch of spatial and temporal scales between observations and models. CCMs and ESMs usually run at horizontal resolutions of a few hundred kilometres, whereas field experiments sample local air masses. Similar to sampling model output along sun-synchronous satellite orbits, some models now have the capability to interpolate the model data to the flight path during the model simulation (see for example the S4D routine in Jöckel *et al.,* (2010)). This comparison is very useful, in particular for the **REF-C1SD** simulation, which has specified dynamics matching the meteorological situation of particular years and thus allows a more direct comparison. To facilitate this comparison, we provide the flight paths of several aircraft campaigns on the CCMI website in NASA AMES or ICARTT format. We refer to the CCMI website for updates on this list (follow the link 'Observations for model evaluation').

For the free-running **REF-C1** simulations where the meteorological situation and atmospheric dynamics do not match those observed in a particular year, a comparison to observations is thus only meaningful if longer time records are considered. A possibility to compare with *in situ* data is to combine different campaigns into one database with a horizontal grid comparable to that used in ESMs (Emmons *et al.*, 2000). However, it has to be kept in mind that since aircraft campaigns are often targeted at specific events they do not necessarily provide a good representation of the mean climate or composition.

A CCMI expert team, which was established as part of the Davos workshop, will further work on this topic and will particularly address the following tasks:

- Identify a methodology to meaningfully evaluate CCM simulations against *in situ* observations via analyses that bridge the disparate temporal and spatial scales.
- Following the successful CCMVal exercise, carry out observation-model comparisons by improving access to vetted *in situ* data sets to facilitate the evaluation of models.
- Identify diagnostics suitable for a climatology and provide this climatology (update of Emmons *et al.*, 2000).

Updates from the expert group will be reported on the CCMI Website.

4.5 Model output for comparison with ground measurements

A document describing the availability of ground-based measurements and suggestions for comparisons to ground-based data is available from the CCMI website (follow the link 'Observations for model evaluation'). These comparisons are, in general, possible with the standard monthly output generated using CMOR tables (see Section 4.1).

5. Timeline IGAC / SPARC Chemistry-Climate Model Initiative

A key aspect of this document is to detail a long-term strategic plan for simulations that can meet the complex needs of simulating chemistry-climate interactions, while also seeking to prioritize simulations for near-term (next 3 year) needs. The result is that the CCMI simulations are envisaged to occur in two main phases over the next few years. The timeline is summarized in **Figure 28**.

Near-term efforts in **CCMI Phase 1 (CCMI-1)** focus on hindcast simulations and on simulations in support of the 2014 WMO/UNEP Scientifi Assessment of Ozone Depletion with currently existing models. A comprehensive set of hindcasts and future projections will be repeated in **CCMI Phase 2 (CCMI-2)**, with improved models that are also likely to be more complex and run at higher resolutions than at present. The long-term target of the IGAC/SPARC CCMI initiative is 2017/2018, when chemistry-climate could be addressed in a much more comprehensive way than now, *e.g.* with interactive stratospheric chemistry, aerosols, tropospheric chemistry, biosphere and an ocean. It could be envisaged that the simulations of Phase 2 be part of the sixth phase of CMIP (CMIP6), thus bridging the gap with the climate community at that stage. CCMI Phase 2 simulations are to be delivered only in several years time and are therefore not defined in this document

CCMI PHASE 1 (CCMI-1, near-term, ~next 3 years):
The focus of CCMI PHASE 1 is on hindcast simulations and simulations in support of the 2014 WMO/UNEP Scientific Assessment of Ozone Depletion. The new community-wide hindcast simulations are **REF-C1** and **REF-C1SD**, which are also used in several projects currently underway and thus fulfil multiple purposes. It also includes **REF-C2**, which will be run in support of the 2014 WMO/UNEP Scientific Assessment of Ozone Depletion, and possibly additional sensitivity simulations, with results that can also be taken from existing similar simulations performed for CMIP5 and the SPARC lifetimes assessment.

The timeline for the 2014 Ozone Assessment is predicated on several specific milestones: The co-chairs will start working on a draft outline in fall 2012, and an author team will be assembled in spring 2013. The 1st draft will have to be complete around November 2013, the 2nd draft around February 2014, and the 3rd draft in May 2014. The chapters would be finalized by July-August 2014. Therefore, results from the simulations would be required by around mid- or early autumn 2013.

CCMI PHASE 2 (CCMI-2, long-term, until ~2017/2018):
One of the overall recommendations of the SPARC-CCMVal (2010) report was that the CCMVal assessment and projection process should be synchronized with that of CMIP to make the most of human and computer resources, and to allow time for model improvements. Assuming that there will be another IPCC and WMO/UNEP assessment, they would be much better in phase than today and would present an opportunity to define chemistry-climate simulations as part of the CMIP6 protocol. Hence, as a community, 2017/2018 could be considered as a major target where things could come together in a much more comprehensive way: strato-

spheric change, aerosols, tropospheric chemistry, biosphere, and ocean. There is thus a long-term vision for the IGAC/SPARC CCMI that will need to be more thoroughly define in future.

6. Summary and Outlook

CCM groups are encouraged to run the proposed CCMI-1 reference simulations with the specified forcings. In order to facilitate the set-up of the reference simulations, the forcings and other data sets have been made available on the CCMI website (**http://www.pa.op.dlr.de/CCMI/**) and through the specific links given in this document. The CCMI website has been created to report on ongoing CCMI activities and to serve the needs of the CCM and CTM community. The forcings are made available to encourage consistency of anthropogenic and natural forcings in future model/model and model/observation intercomparisons. Any updates as well as detailed explanation and further discussion will be placed on the CCMI website. In addition to the reference runs, the groups are encouraged to run as many CCMI-1 sensitivity simulations as possible. The hope is that these additional runs will be available in time to provide useful input for the anticipated 2014 WMO/UNEP Ozone Assessment, so that the ozone projections from the CCMs can be assessed for different GHG scenarios and the fixe ODS simulation. A community-wide workshop will be held from 13-17 May 2013 in Boulder (USA), where initial results from the CCMI-1 simulations will be discussed.

The data will be collected in CF compliant netCDF format at BADC. For the collection of the data, a data policy similar to those used in previous CCMVal and ACCMIP intercomparisons will apply. It is expected that the groups submitting model output to BADC, as well as the wider community who will be working with these data, will disseminate the results of this effort through a series of publications.

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Atmospheric Composition and the Asian Monsoon: Results from a Side Meeting at the 12th IGAC Science Conference in Beijing

Jim Crawford[1] and Laura Pan[2]

[1]NASA Langley Research Center, Hampton, VA, USA, james.h.crawford@nasa.gov, [2]Atmospheric Chemistry Division, NCAR, Boulder, CO, USA, liwen@ucar.edu

A side meeting on Atmospheric Composition and the Asian Monsoon was held at the 12th IGAC Science Conference in Beijing. The meeting was organised by **L. Pan** and **J.Crawford** as a forum to gather interested scientists, to identify common interests, and to initiate a dialogue that might lead to future collaborative projects, working groups, or workshops. The session was attended by thirty-one scientists representing seven different nations.

To date, research focused on the interaction between atmospheric composition and the Asian monsoon has largely capitalized on satellite observations and the use of global models. Of foremost importance is the need to observe the full atmosphere over this region where satellites and models indicate that summer monsoon convective transport perturbs upper troposphere-lower stratosphere (UTLS) composition and forms a significant pathway for pollutants to enter the stratosphere. Convective transport occurs across a considerable range of surface conditions and diversity in sources, all in close proximity to each other. The terrestrial environment ranges from mega-cities to rainforest, while the marine environment ranges from shallow, biologically-productive waters to some of the densest shipping lanes in the world. Seasonal burning, both natural and human induced, is a major air quality concern with potential climate feedbacks. Add a growing population and economy with increasing energy demands, and it becomes evident that this is a region where much can be learned about processes and trends influencing atmospheric composition and associated impacts.

Progress in understanding these processes can only come from both **periodic and sustained activities in this region, where observations are sparse and access is difficul** . Thus, participants were invited to share relevant research efforts. Ten presentations shared details of ongoing measurements at key ground sites in Mohali, India (**V. Sinha**) and Hong Kong (**J. Z. Yu**) as well as balloon soundings of ozone, water vapour, and cloud particles from Kunming and Lhasa (**J. Bian**). **R.-S. Gao** shared details on development of a low-cost, lightweight optical particle counter for balloons and other platforms. Plans for future field studies were presented by **M. Lawrence** and **A. Panday** (ground-based and ultra-light aircraft observations in the Kathmandu Valley), **H. Harder** and **H. Schlager** (high-altitude airborne observations of the Asian Monsoon UTLS), and **W. Junkermann** (aerosol-cloud studies from ultra-light aircraft). **L. Thomason** presented analysis of UTLS aerosol observations from CALIPSO and SAGE, emphasising the need for validation measurements.

Discussion on community building was initiated by **H. Tanimoto**, who shared his proposal with the IGAC Science Steering Committee (SSC), suggesting the establishment of a Working Group focused on SE Asia. The role of this working group would be to strengthen the links between IGAC and atmospheric scientists in different countries. A report on the feasibility of forming this group will be presented to the IGAC SSC in September 2013. As this idea is further developed, H. Tanimoto welcomes nominations and suggestions. It was also agreed that the results of this meeting should be shared with the SPARC and iLEAPS communities to establish interest in co-sponsoring workshops and possible initiatives.

The discussion culminated in a consensus that a topical workshop on "Atmospheric Composition and the Asian Monsoon" is a logical next step to promote community interest and synergy. A. Panday suggested holding the workshop in Kathmandu with ICIMOD as a local sponsoring organisation. This workshop would help build a larger core of scientists in support of the formation of an IGAC/SPARC/iLEAPS joint initiative or working group. Convening a community workshop is particularly important given the significant number of countries and scientists that could not be represented at this IGAC Side Meeting. The publication of this report is intended to help reach interested scientists and lead to their input and involvement in this effort. Contact information and workshop updates can be found online at: **http://www.acd.ucar.edu/utls/2013/**.

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ODS Lifetimes meeting, Zurich, Switzerland

20-21 February
SPARC Data Requirements Workshop, Frascati, Italy

25 February-1 March
Climatic Effects of Ozone Depletion in the Southern Hemisphere: Assessing the Evidences and Identifying the Gaps in Current Knowledge, Buenos Aires, Argentina

1-3 April
Stratosphere-troposphere Processes and their Role in Climate, Kyoto, Japan

22-26 April
SPARC DynVar and SNAP, Reading, UK

29 April-1 May
S-RIP planning meeting, Exeter, UK

22-26 April
Gravity Wave ISSI meeting, Bern, Switzerland

13-17 May
Chemistry Climate Model Initiative, Boulder, CO, USA

27-29 May
Research Applications of High-Resolution Radiosonde Data, Stony Brook, NY, USA

9-12 June
IGAC Workshop on composition and Asian Monsoon, Kathmandu, Nepal

17-19 June
7th Atmospheric Limb workshop, Bremen, Germany

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Director:
J. Staehelin
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Office Manager:
A. Witten

Contact

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

SPARC Scientific Steering Group

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D. Pendlebury
F. Tummon
Communication Manager:
C. Arndt
Office Manager:
A. Witten

Contact

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