SPARC

STRATOSPHERIC PROCESSES AND THEIR ROLE IN CLIMATE

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Report on the 14th Session of the SPARC Scientific Steering Group

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Contents

The 14th session of the SPARC Scientific Steering Group (SSG) was held at the NOAA Earth System Research Laboratory in Boulder, CO, USA at the invitation of A. Ravishankara, Co-chair of the SPARC SSG. In opening remarks, **A. O'Neill** noted the range of activities and initiatives that have engaged SPARC over the past year, and future activities. SPARC has played a central role in the forthcoming 2006 ozone assessment as well as in the new WCRP–IGBP initiative on Atmospheric Chemistry and Climate (AC&C). The importance of understanding and characterising variability in detection and attribution of climate change, as well as in medium and long-range prediction, motivated the development of a strong new initiative on this topic.

Summary of SPARC activities in the past year

In addition to production of newsletters and special reports, (such as the ASAP report, published early in 2006) the SPARC IPO helps to organise and facilitate SPARC workshops and meetings that enable progress in the range of activities in the SPARC programme. In the past year there were a number of SPARC sponsored and related workshops and meetings, several of which are discussed below and/or in separate reports.

The high quality of the ASAP (SPARC Assessment of Aerosol Properties), produced early in 2006 under the joint editorship of L. Thomason and T. Peter, was noted by a number of SSG members, but considering the cost of producing such reports and the desirability of updating them, the usefulness of continuing this activity was discussed. It was noted that past SPARC reports have been found to be widely useful, and are natural places to document and assess current knowledge in ways that are complementary to the publication of reviews in refereed journals. However, review papers and SPARC newsletter articles may be useful ways to address the evolution of the relevant fields, and to update the knowledge base. T. Peter noted that review papers on some of the topics in the ASAP report are planned and these will go beyond what is included in the report.

T. Peter, on behalf of K. Carslaw and K. Drdla, reported on the progress of the SPARC Polar Stratospheric Clouds Assessment (SPA). The SPA hopes to address the uncertainty in the conditions necessary for solid-phase PSC formation and denitrification, to improve the treatment of PSCs in large-scale models by making it more physically based, to provide recommendations for how to treat PSCs in models, to set standards for defining PSCs so that intercomparisons are more meaningful, and to unite the available data sets to provide a universal data set that is not instrument specific. The list of chapters and outlines for them were assembled at the kickoff meeting in May 2005. Although some setbacks have been encountered, including the withdrawal of some co-authors, the first draft of chapters is expected by March 30, 2007. A planning meeting will follow in April of May 2007, and the assessment should be completed by the end of 2007. This should provide sufficient time for recommendations to be submitted and for SPA to be used in the 2010 Ozone assessment.

The SPARC-IPY Activity proposal was submitted in October, 2005 and approved by the IPY joint committee as Activity No. 217 (http://www.ipy.org/development/eoi/proposal-details.php?id=217). A major goal of this activity is to document the dynamics, chemistry and microphysical processes within the polar vortices during the IPY period. It includes a number of sub-activities as a result of the clustering of IPY proposals undertaken by the IPY JC. Also, SPARC-IPY is linked to other IPY activities (IASOA, POLARCAT, PANSY, ORACLE-O3). The data assimilation component of SPARC-PY is substantially funded but many of the components and linked activities are awaiting funding decisions.

Outcomes from the JSC meeting

The 27th session of the WCRP Joint Steering Committee was held in Pune, India in March 2006 and reported upon in SPARC Newsletter No. 27. A. O'Neill reviewed the SPARC presentation and the JSC response. As this session of the JSC was held in conjunction with a corresponding meeting of the IGBP, overlapping interests and collaborations between the two overarching programmes were explored in a single joint session.

The new collaborative initiative on AC&C, jointly led by SPARC and IGAC on behalf of WCRP and the IGBP, was discussed at length and received strong endorsement of its action plan. This new activity was also described in SPARC Newsletter No. 27, wherein the timeline for development of this initiative was laid out. The AC&C initiative is progressing as anticipated. A planning meeting was held in Boulder, CO in August, 2006 to define questions concerning initial scientific problems to be addressed, interactions among contributing and related projects (CCMVal, AIMES, AEROCOM, ACCENT), what has been learned to date, and ways of addressing problems (*e.g.* specification of CCM simulations, relevant data sets and achievement metrics, and interactions between measurement, modelling, and theory communities). The proposal to launch a new initiative on dynamical variability was also put forward to the JSC and strongly approved. In the intervening months this initiative has engaged the thinking a number of people in the SPARC community (see below).

In a short presentation dealing with WCRP JSC perspectives **A. Ramaswamy** noted that the two original foci of the WCRP were (a) to determine the predictability of climate and (b) to determine the effect of human activities on climate. The WCRP role in advancing the first of these is well perceived and appreciated but its role in the second is not, despite substantial WCRP contributions to it. This misperception of the contributions of the WCRP is being addressed through a series of proactive measures to elevate the profile of the WCRP. These include: (a) a global survey of scientists, agencies, sponsors and end-users to seek direction from the community; (b) opening a dialog with SBSTA to address gaps and identify advances; (c) exploring the potential partnerships/deliverables with other international research organizations, and with other sectors (ESSP, World Bank, private sector) on the various issues concerning climate change; and (d) an ICSU review of the WCRP.

Among the issues that remain in need of enhanced attention are improvement of the global observing system, better understanding of the role of GHGs and aerosols in forcing climate change, and understanding the role of land use change and natural forcings such as solar variability and volcanic eruptions. To be successful in addressing the issue of determining human influence on climate the WCRP must be able to contribute in fundamental ways in providing deliverables such as identifying "dangerous" interference with climate and "tipping points," producing and communicating credible regional climate information, and assessing the needs of the end-user community.

The WCRP activity on Anthropogenic Climate Change (ACC), outlined in SPARC Newsletter No. 27, is a key component of this new approach. The ACC activity will streamline WCRP's climate change research activities, link them within the different WCRP projects in order to present the WCRP's climate change research as a coherent whole, and link with other international and national research. While maintaining high scientific rigour, it is important for the WCRP to engage in a dialog with the "Stakeholders" to help provide appropriate deliverables to the "end-users."

Assessments (*e.g.* the IPCC AR4 and 2006 WMO/UNEO Ozone Assessment) permit identification of key gaps in the science and plans for advancing research, and therefore the knowledge base. SPARC is making key contributions to these assessment activities and with the AC&C initiative, which is an important input into ACC. Also key to ACC is participation by CCMVal, ACCENT and AeroCom.

Review of Assessments

A special presentation by **S. Solomon** summarised the process and the results from the Fourth IPCC Assessment (AR4). The report is structured with climate change drivers (natural and anthropogenic), observations (including paleo), understanding and attributing climate change with rigorous statistical comparisons of data and models, projections of future changes (long and short term), and robust findings and key uncertainties. Of particular interest to SPARC are the effects of downward transport from the stratosphere of such species as ozone, the magnitude and reasons for the recent stratospheric water vapour trends, the level of stratospheric ozone forcing, the importance of the stratosphere in reconciling the temperature trends in the troposphere, and the role of forcing agents such at CO_2 on NAM/SAM and how this relationship may change in a future climate. A fifth assessment (AR5) will likely occur and WCRP can play a role in defining its timetable and structure. A proactive involvement of SPARC would be useful at this development stage to ensure that proper attention is given to the role of the stratosphere.

M. Giorgetta reported on the recent WGCM/AIMES meeting (September 25-29, 2006, Victoria, Canada). A major focus was anticipating modelling needs for the next IPCC assessment (AR5). Assuming that AR5 is to be completed in 2013, modelling groups must soon decide on what model systems and which climate change projections to use. The Earth System Models (ESM) workshop at the Aspen Global Change Institute (July 31-August 3, 2006) was held in anticipation of the WGCM/AIMES meeting. In addition, a WGCM questionnaire was sent to major modelling groups to assess the general characteristics and status of models that may be used for AR5. The Aspen workshop brought together participants from the WCRP, IGBP communities and the IPCC TGNES (Task Group on New Emission Scenarios) and TGICA (Task Group on Data and Scenario Support for Impact and Climate Analysis).

A major outcome of the workshop was a draft proposal for the experimental design for 21st century climate change experiments, which includes both short-term and long-term components, and an attempt at assessing the general characteristics of the models that would be best suited for these purposes. Shorter term experiments (2005-2030) would focus on weather extremes at regional scales and air quality, and use high resolution and vertical domains adequate to represent stratospheric processes, hopefully with the capability of including chemistry and aerosols interactively, but with a single GHG concentration scenario. Since a central objective of this class of experiments is to quantify variability and identify changes in extremes, large ensembles of model runs will be needed. The longer term experiments (to 2100 and beyond) will focus on climate change for given CO_2 scenarios, climate change feedback, and will help to determine stabilization emission scenarios. These experiments will use coupled ESMs of conventional resolution with small ensembles, with the option of allowing coupled GCMs without fully functional carbon cycles to participate. A major objective of these experiments will be to identify possible emission scenarios that are consistent with the climate changes that are projected to accompany a specified stabilised GHG concentration scenario.

The assistance of SPARC is needed for the success of the proposed modelling activities. The majority of the coupled ESMs will likely require specified ozone fields and/or fields of ozone depleting substances (ODS). These could be supplied from output of 21st century CCM projections carried out under the auspices of CCMVal. Also, through the SOLARIS activity, it may be possible to provide consistent solar forcing projections. The different time scales of the IPCC assessments (2013 for AR5) and the WMO/UNEP Ozone Assessments (2010 for the next assessment) make it important to coordinate supporting modelling activities. In many cases the same modelling groups may be contributing to both assessment processes.

SPARC Themes

Chemistry-Climate

T. Shepherd gave an overview on the CCMVal activity. Over the past two years the aim of CCMVal was to assess the current generation of CCMs to support the WMO/UNEP Ozone Assessment for 2006. Two scenarios, past (1960-2004) and future (present-2100), were used to study stratospheric temperatures, transport characteristics, ozone, variability and trends, and inorganic chlorine loading. The past (REF1) studies have shown reasonable agreement with observations in temperature trends, total ozone trends and variability, although there is a greater spread in ozone trends in polar regions, and improved transport chararcteristics (*e.g*. methane concentrations, mean age of air, and the tape recorder) compared with previous model comparisons, but substantial differences in terms of inorganic chlorine Cly. The differences in Cly are key to diagnosing the inter-model differences in ozone hole recovery.

The future runs (REF2) are multi-model projections of ozone recovery in the 21st century (13 CCM groups participated). While there is a wide spread in the predicted evolution of ozone, the CCMs agree in several important respects. Global total ozone is projected to increase to 1980 values before a corresponding decrease in Cly due to GHG-induced cooling, except Antarctic spring ozone which is predicted to follow halogen concentrations and recover later (~2065). In the tropics, CCMs predict ozone less than or equal to 1980 values even when Cly decreases, likely due to increases in tropical upwelling resulting in decreases in tropical lower stratospheric ozone. The ozone evolution in the 21st century is mainly determined by decreases in halogen amounts and continued cooling of the global average stratosphere due to increases in GHGs.

Successful mechanisms for model evaluations were found to be: a restricted set of standard well-tested core diagnostics (with some more exploratory ones pursued as research topics); common reference simulations with forcing data sets (*e.g*. SSTs, GHGs) available to all participating groups; archiving of the model data in a central data base (the British Atmospheric Data Centre is now the standard data centre for CCMVal); and evaluation of diagnostics obtained from various observational data sets. The first coordinated assessment of CCMVal and ozone was finished in time to be included in the WMO/UNEP Assessment. Multi-model evaluation also proved to be an advantage since it provided a range of model uncertainties, and, in some cases, has allowed groups to identify and correct previously unrecognised model errors. It was found that holding regular workshops and using the world wide web for sharing model and forcing data and discussion, were effective means of communicating between the participating groups.

For the next phase of CCMVal several improvements will be implemented. First, a common diagnostic package designed specifically for CCMVal will be written and implemented. This will facilitate the calculation of the process-oriented diagnostics. In addition, scenarios and forcing data sets will defined much earlier to allow for more time to run the models, and a more detailed evaluation of models may be written prior to the 2010 Ozone Assessment. Other improvements include switching to a standard file format, standard processing packages, better cataloging and archiving techniques, and better coordination between similar projects such as AEROCOM and ACCENT. The addition of validation data sets available on the database would also be a great asset. It is also hoped that a threshold level of performance for those models that are used to make predictions will be defined and implemented.

In the near future, CCMVal plans to further analyse the REF1, REF2 and SCN2 simulations in terms of changes in dynamics (N. Butchart *et al*.), processes in the UTLS (A. Gettelman, T. Birner *et al*.), dynamical containment of Antarctic ozone depletion (H. Struthers, G. Bodeker *et al*.), assessment of chemistry (R. Salawitch, M. Chipperfield), and other studies. The working group will also focus on developing the diagnostics package, interacting with the new SPARC initiatives such as AC&C and Dynamics, suggest a strategy for CCM simulation for the next Ozone and IPCC Assessments, coordinate a SPARC report on the evaluation of CCMs, provided enough diagnostic work has been done. A CCMVal workshop will be held in Leeds, UK in June 2007.

Stratosphere-Troposphere Dynamical Coupling

Dynamics Initiative

Three key issues in the role of the stratosphere on climate are stratospheric ozone depletion and recovery, the effect of the stratosphere on tropospheric variability, and the effect of solar variability. Dynamical variability plays a very significant role in all of these. Although CCMVal includes a dynamical component, the computational constraints of CCMs limit the scope of study, and while validation diagnostics for chemistry, transport and radiation are fairly clear, the dynamics diagnostics still contain uncertainties in quantifying key processes.

While many of the basic principles of atmospheric dynamics are understood, in practice understanding variability is difficult. Because the atmosphere is inherently chaotic, dynamical variability can occur independently of external forcing and with a wide range of time scales. Therefore, in order to obtain meaningful statistics to define climate change, long simulations are needed. The dynamics initiative will be complementary to CCMVal and use a hierarchy of models to allow more extensive experimentation to understand circulation variability and changes. (Interactive chemistry is not a requirement for the study of dynamical variability.) The initiative would study such dynamical mechanisms as downward influence and its response to climate change, the effect of the stratosphere on tropospheric variability, and the response of the stratosphere and Brewer-Dobson circulation to climate change. Modelling issues such as robustness to resolution and vertical domain, and the dependence on parameterised processes, will also be addressed.

Stratospheric dynamics is a critical component for understanding chemistry-climate interactions, and may have an important impact on tropospheric climate. Known problems in these models stemming from dynamical issues are the cold pole problem, the uncertainty about the role of parameterised gravity waves, and the lack of stratospheric warmings and tropical oscillations such as the QBO. Models do not in general accurately reproduce the observed interannual variability in the winter polar regions. Documenting and understanding model biases is fundamental to prediction and climate projection. **F. Sassi** discussed a new model inter-comparison project with a set of baseline experiments to help define the model biases, and this activity would greatly benefit from international coordination. **P. Kushner** also suggested follow-on experiments that add a prescribed SST perturbation to represent global warming.

P. Kushner presented a recent proposal on stratospheric dynamics (see Newsletter No. 27) under the SPARC stratosphere-troposphere dynamical coupling theme. The focus is on dynamical changes stemming from changes to wave driving, particularly the Brewer-Dobson circulation, in response to climate change. Also, there is evidence that a realistic stratospheric representation is required to accurately simulate air-sea interactions and predict changes to the tropospheric circulation. A worthwhile goal of the new SPARC dynamical variability initiative is to persuade modelling centres to make a resolved stratosphere part of their coupled models, and, in the same vein, for SPARC to give more attention to coupled atmosphere-ocean atmosphere modelling.

Task Force on Seasonal Prediction

M. Baldwin reported on the recent activities of the Task Force on Seasonal Prediction (TFSP) in the context of the problem of seamless prediction (weather through to climate time scales), which is central to the WCRP strategic framework, COPES (Coordinated Observation and Prediction of the Earth System). Currently, there is untapped seasonal predictability due to interactions (and memory) among all the elements of the climate system (Atmosphere-Ocean-Land-Ice). The goal of the TFSP is to identify the current limitations of the climate system models and observational data sets used to determine seasonal predictability. The TFSP draws on expertise from all WCRP core projects (CLIVAR, SPARC, GEWEX, CliC), and WGNE and WGCM. SPARC's role in the task force has been to advocate for the inclusion of the stratosphere as having memory in climate system, recognise the stratosphere's role in seasonal prediction, and to define "seasonal" as beginning with a 7-10 day period and longer.

The third and final meeting of the TFSP will be held in Barcelona 4-8 June 2007, after which the project will be headed by CliVar. The SPARC community is strongly encouraged to participate, advising the TFSP on exploiting the statistical predictability afforded by the Arctic Oscillation during winter, the effect of stratospheric NAM/SAM on tropospheric weather, and using stratospheric conditions to improve forecasting skill out to a timescale of 15-20 days. It is also important to note that many NWP centres already include the stratosphere in their forecast models for data assimilation reasons, so it is important to have a good representation of the stratosphere. A follow-on to the 2003 Whistler meeting on the role of the stratosphere-troposphere coupling will be held in Santorini in September 2007. This will be an AGU Chapman Conference on the Role of the Stratosphere in Climate and Climate Change, and also sponsored by SPARC, NSF, and possibly USAF, NASA, NOAA, RPI, and ESA.

M. Baldwin also mentioned the role of the QBO on hurricanes, a topic taken up by **M. Geller**. He presented new work that uses a new ISCCP product to show that the QBO modulates tropical deep convection such that during its easterly phase, deep convection is enhanced in regions that are especially prone to deep convection, and deep convection is suppressed in adjacent regions. The early result look very promising but there is much more work to be done.

S. Yoden presented several studies on the linkages between stratospheric phenomenon and tropospheric phenomenon, such as the QBO and Stratospheric Sudden Warmings (SSWs), El Niño and SSWs, the predictability of stratosphere-troposphere coupling during an SSW, and a study on the seasonal dependence on trend detectability in different regions of the atmosphere. For example, due to the occurrence of SSWs and the high degree of internal interannual variability at the winter pole, and the variability of the breakdown of the polar vortex, longer time records are needed for the winter NH to determine trends. Indeed, since the summer is dynamically quite different, the use of an annual mean to detect a trend in this region may be suspect. There is evidence of seasonal dependence of internal interannual variability in the tropospheric climate system due to such nonlinear processes as the influence of snow cover on surface temperature, precipitation from monsoons, *etc*.

Detection, Attribution and Prediction

W. Randel reported on the recent SPARC activities pertaining to this theme. At the Trends meeting in October 2005, there was agreement in regard to omitting stations with apparent biases and homogeneity problems when determining trends from historical radiosonde data. These problems are due to changes in radiosondes and result in discontinuities in the record when compared with MSU4 data. There was also an initial look at updated satellite data sets and it was decided to ask Carl Mears (MSU) and John Nash (SSU) to join the working group to provide their expert knowledge. Overall comparisons suggest biases in the SSU15x channel trends compared to the MSU4 data. A draft outline of an observations paper was drawn up.

A second meeting of the SPARC Temperature Trends Assessment group took place in July, 2006. The meeting focused on issues pertaining to SSU data, which has evidence of uncertainties in the trends, particularly after NOAA-14, due to instrumentation, satellite drift relative to measurement time, and the construction method of the data set, which changes in 1998. There appears to be an unphysical nature to the trends after 1996 compared to MSU4 and radiosondes for SSU26, 26x and 15x, and it is important to understand this data for future reanalyses. Comparison with lidars may be useful since they provide accurate vertical temperature profiles between 30-80 km, and several stations have relatively long (and continuing) records. However, these measurements have a lot of variability in monthly data between stations so that it is difficult to constrain satellite trends.

For the future, the Trends working group will continue to update the radiosonde data sets, and will further analyse the historical satellite data, ideally with an independent compilation of SSU data. Careful consideration will be given to the possibility of merging AMSU data (after 1998) with the satellite record, since the last SSU instrument ended in 2005. The use of GPS as a climate monitoring tool will also be looked into. A complete observations paper for SPARC, using the revised SSU data sets, is in the planning stages, along with the systematic comparison of observations to models, including those from CCMVal. The next Trends meeting will be in April 2007 in Washington, DC.

A short discussion to evaluate the effectiveness of the SPARC theme structure followed the theme reports. There was agreement that the themes themselves gave a useful general structure for individual process studies and projects, but that some of the processes, particularly solar variability, were not given enough emphasis, and that SPARC must do more to reach out to these communities. It was also clear that SPARC's interests are moving beyond the stratosphere itself through collaborative projects, in order to deal with issues such as coupling, downward influence and solar variability. One community that SPARC has not connected well with yet is CliC, although **K. Steffen** attending the meeting and gave a special seminar on CliC activities.

Cross-Cutting Issues

TTL Workshop

N. McFarlane reported on the SPARC-GEWEX/GSCC-IGAC Workshop on modelling of deep convection and its role in the TTL, held in June 2006 in Victoria (see full report in this issue). The purpose of this workshop was to bring together researchers from the SPARC community, the GEWEX-GCSS community (modelling of deep convection), and the IGAC community (atmospheric chemistry), to set the stage for a collaborative research programme to better understand the role of deep convection in determining the structure and composition of the Tropical Tropopause Layer (TTL). It is important to the stratosphere because it sets the chemistry, water vapour, short-lived species (*e.g.* bromine), and aerosols and precursors (*e.g.* sulfur) of the lower stratosphere. An initial working group consisting of the workshop organising committee plus Leo Donner, as a representative of the cumulus parameterization community, was formed to move forward on the basis of these ideas.

SOLARIS and Solar Variability

K. Matthes reported on the recent SOLARIS activities and **K. Kodera** gave a presentation on the importance of solar variability. SOLARIS is a continuation of the solar variability study started under GRIPS (GCM-Reality Intercomparison Project for SPARC), and is joint with CAWSES under the modelling component of Theme 1 (Solar Influence on Climate). However, unlike GRIPS, which used Atmospheric GCMs, SOLARIS will use middle atmosphere CCMs, either alone or coupled with an ionosphere. A report on the recent SOLARIS meeting may be found in this newsletter. K. Kodera also presented evidence of correlations of ice core data (a proxy for temperatures) and solar variability; evidence that a solar influence on climate through stratospheric dynamical processes may be important for centennial time scales.

Data Assimilation

S. Polavarapu reported on the recent SPARC Data Assimilation Workshop, held at ESTEC in Noordwijk, the Netherlands from 2-4 October, 2006. As with previous workshops, the core of participants was data assimilators, with invited speakers from other key communities, encouraging active discussion between the DA community, users of DA and experts from other fields. This year the themes were transport errors, polar processes, and the TTL. Linkages through CCMVal and IGACO were also discussed, along with a special discussion on the International Polar Year (IPY) activities (see report in this issue).

The goal of the SPARC-IPY proposal, entitled "The Structure and Evolution of the Polar Stratosphere and Mesosphere and Links to the Troposphere during IPY," is to document the dynamics, chemistry and microphysical processes within the polar vortices during IPY, with a focus on the stratosphere-troposphere and stratosphere-mesosphere coupling. The outcome will be a well organised data set of measurements and analyses of the polar stratosphere during IPY. The SPARC Data Assimilation Working Group will contribute to the IPY effort by archiving assimilation products at the SPARC Data Center, and link to available observations, including mesospheric data and ASSET data for validation and comparison, and linking to other IPY activities such as PANSY or IASOA. A key need is making links with special purpose measurement campaigns for validation or reanalysis.

Report from the SPARC Data Centre

The SPARC Data Center holds data archives from SPARC projects, and is in the planning stages to hold the IPY-SPARC DA data. In order to accommodate the large amounts of new data expected and new restrictions due to some of the SPARC-IPY data, upgrades to the hardware have been proposed, and password protection will be implemented. Funding for the Data Center is secured to Feb 2007, and a renewal proposal is approved, although exact funding is still unknown. The SPARC Data Center mirror site, led by M. Shiotani and S. Yoden at Kyoto University, Japan, now has a new server and FTP policy issues at the university have been solved. The mirror site is the safest option as a back-up for the data, and secures a fast connection from different locations.

From left to right: 1st row: *S. Hayashida, K. Rosenlof, E. Manzini, S. Polavarapu, J. Waters, D. Pendlebury, A. Ravishankara, P. Kushner, J. Burrows;* ***2nd row:*** *V. Ramaswamy, V. De Luca, P. Rasch, S. Doherty, T. Peter, S. Liess, T. Shepherd, J. Perlwitz, K. Matthes, N. McFarlane, K. Kodera, A. O'Neill;* ***3rd row:*** *M. Giorgetta, D. Hartmann, P. Haynes, G. Braathen, F. Sassi, M. Baldwin, S. Yoden, M. Geller;* ***4th row:*** *A. Gettelman, W. Randel, M. Kurylo*

SPARC's Role in Earth Observation Programmes

The intent of the session on Earth observations programmes was to provide the SSG with and overview of current observations programmes and encourage a discussion on how SPARC might influence planning and take advantage of future mission opportunities.

M. Kurylo discussed activities within NASA's Atmospheric Composition Focus Area. Five (Aura, Parasol, Calipso, Cloudsat, and Aqua) of the seven A-Train satellites have been launched and the remaining two (Glory and OCO) will be launched in 2008. Since its launch in 2004, Aura measurements have led to a number of important advances in knowledge, not only of atmospheric composition but also of features of atmospheric circulation and processes. **J. Burrows** summarised recent developments in monitoring atmospheric species with SCIAMACHY limb measurements. He also discussed aspects of validation and applications of limb products, detection of polar stratospheric clouds and analysis of BrO using comparison with model results. **S. Hayashida** discussed the future Japanese plan for remote sensing from space in relation to SPARC. The Superconducting Submillimeter-wave Limb-emission Sounder (SMILES) of the Japanese Experiment Module (JEM) on the International Space Station (ISS) will be ready in 2009. This is a space demonstration of sub-millimeter limb-emission sounding of the atmosphere, one of its objectives being to provide global observations of trace gases in the stratosphere.

M. Kurylo also reported on the NPOESS sensor plan and highlights from the September, 2006 meeting of the Steering Committee of the Network for Detection of Atmospheric Composition Change (NDACC – formerly NDSC). NDACC maintains long-term, quality-controlled records and can provide records for extra climate variables such as aerosols and ozone, and working on relevant water vapour measurements. Unfortunately, due to budget constraints, NPOESS has been reduced in scope by removing several sensors. The importance of the measurements provided by these sensors is recognised by the NPOESS IPO and it is examining ways to restore them.

G. Braathen, on behalf of IGACO and WMO, presented a rational comprehensive system for integrating, coordinating, and accessing satellite data. Provision of data to end-users involves a plethora of procedures and data centres. He reported on the status of the Integrated Global Atmospheric Chemistry Observations (IGACO) theme to address this issue.

Among issues raised in general discussion was the question of how SPARC can take advantage of mission opportunities to encourage programmes to address gaps in stratospheric measurements. While there are a plethora of satellites in various stages of planning and production, few will focus on the stratosphere. The loss of limb measurements from NPOESS is significant. Beyond the lifetime of Aura and Envisat, what measurements of ozone will be available during the crucial anticipated ozone recovery period? Identifying future measurement gaps and possible ways of addressing them was noted as a priority for SPARC. It was decided that a BAMS article, authored by prominent members of the SPARC community, would be an ideal way to alert funding agencies to the serious impact that may result from a permanent loss of key satellite measurements.

Next General Assembly: **E. Manzini** presented the local arrangements made so far for the next SPARC General Assembly in 2008 in Bologna, Italy. The facilities in Bologna will allow for a maximum of 418 people, with room for approximately 140 posters. Estimated costs for the conference, though somewhat higher than for previous SPARC General Assemblies, are reasonable for the range of services they will cover. These include conference room rentals, technical support, catering for lunch and coffee breaks on site, a conference dinner at the Palazzo Re Enzo, a shuttle bus to the conference site, on line conference registration, website creation and maintenance, and taxes and contingency funds.

It is now time to start arranging the conference website and registration, catering, funding and sponsorship strategies and other financial management plans through the SPARC IPO. It is also time to firm up plans with contracts through the Local Organising Committee (E. Manzini, C. Caganzzo, S. Corti, F. Fierli) and to begin with the scientific arrangements. The Scientific Organizing Committee will be led by Thomas Peter and Peter Haynes.

Location of the next SSG meeting: After some discussion it was decided to hold the next SSG meeting in Bremen or Berlin, Germany during late September, 2007, with the gracious help of John Burrows and Ulrike Langematz.

Closure of the Session

The 14th Session of the SPARC SSG was closed at noon on Thursday, October 12, 2006. The SSG unanimously thanked A. R. Ravishankara and LeAnn Droppleman for organising the excellent local arrangements for the session at NOAA, and Jeanne Waters, Gabriella Accatino and Victoria De Luca for support during the workshop.

Modelling of Deep Convection and Chemistry and their Roles in the Tropical Tropopause Layer: SPARC-GEWEX/GCSS-IGAC Workshop

June 12-15 2006, Victoria, BC, Canada

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Introduction

The Tropical Tropopause Layer (TTL) is an excellent example of coupling between dynamics, radiation (including cloud feedbacks) and microphysics. Convection in the tropics plays a key role in redistributing trace gases and aerosols in the upper troposphere – lower stratosphere (UTLS) region, and the interaction between cloud dynamics, radiation and microphysics is of fundamental importance in these processes. The global scale models used to study climate typically have spatial and temporal resolutions that limit their ability to properly represent many of these processes, yet a solid understanding of their effects is necessary. Cloud Resolving Models (CRMs), particularly when supported by appropriate observations, can be used to better understand the different processes and their interactions.

The TTL has received much attention within the SPARC community because of its strong link with stratospheric climate. Among the many processes operating within the TTL are those that control the amount of water vapour and trace gases entering the UTLS, important in determining greenhouse gas forcing in the tropics, and determining stratospheric chemistry and temperatures through the formation of OH, PSCs and enhanced radiative cooling.

Within the IGAC (International Global Atmospheric Chemistry) community there is considerable interest and active research in regard to the role of deep convection in transporting and processing chemical constituents and aerosols. The WCRP/IGBP Atmospheric Chemistry & Climate Initiative (AC&C), currently being developed under the joint leadership of SPARC and IGAC has the objectives of understanding and quantifying the processes that link surface emissions of constituents and precursors to atmospheric composition, and how this composition and its changes are in turn related to climate forcing and change. Modelling is a key initial component of this initiative and can address a number of issues including the identification of processes that are associated with the most uncertainty in radiative forcing and climate change, the development of metrics that provide insight into modelling of chemistry-climate interactions on a range of spatial and temporal scales, the identification of more (or less) promising approaches to representing key processes in climate models, and can contribute to the identification opportunities for programmes and projects whose goal is to improve climate models and our understanding.

Research on modelling and understanding of deep convection in the tropics has also received considerable attention within the GEWEX community. The goal of the GEWEX Cloud Systems Study (GCSS) is to support the development of cloud processes in climate and forecast models. This is accomplished by: developing the scientific basis for the parameterization of cloud processes; coordinating the acquisition and assimilation of observations; coordinating the use of CRMs to support the development of parameterization schemes in large-scale models; and promoting the evaluation and intercomparison of parameterization schemes for cloud processes.

This workshop brought together expertise from these communities, and related research activities on stratospheric processes and modelling of deep convection and chemistry in the tropics to set the stage for a better understanding of the role of convection in determining the thermal structure and composition of the TTL. The workshop involved plenary sessions, poster presentations, two sets of breakout periods in the afternoon of the third day, and final summary and discussion periods on the last half-day where future directions and actions were proposed and discussed. The plenary sessions were organised along three themes: Overviews of historical development and current TTL research (Day 1); Modelling deep convection in the tropics (Day 2); and Coupling of deep convection and chemistry (Day 3). The two very well attended poster sessions were highly complementary to the oral sessions and served to highlight new research efforts and directions. This brief report summarises key aspects of the scientific presentations, the outstanding questions and issues brought forward in breakout discussions and the actions proposed in the subsequent discussion periods.

Overview of current directions in TTL research

Research in the last decade has served to establish the nature of the TTL as a transition region in which the air has mixed stratospheric and tropospheric properties, which in turn are determined by a combination of both large-scale and convective processes. Elucidating these processes has motivated a substantial amount of research in recent years. The overall aim of the invited oral presentations on the first day was to review this research, summarise the knowledge that has been gained and provide insight into outstanding questions. These presentations, in combination with the first poster session, effectively set the stage for the more focused attention on modelling convection and chemistry in the following two days.

The vertical structure and some salient properties of the TTL were discussed in the overview presentations by **I. Folkins** and **A. Gettelman**. **Figure 1** (colour plate I) illustrates some of these properties.

Observations in the tropics indicate a trimodal structure of cloud tops associated with convection (I. Folkins). In addition to deep convection with cloud tops in the upper troposphere and shallow trade-wind boundary layer cumulus, cumulus congestus clouds with tops typically in the range of 5 km above sea level (ASL) are ubiquitous in the tropics. In regions where convection plays an important role in the time averaged large-scale energy and moisture budgets, there is typically a close balance between the net downward mass flux associated with the large-scale vertical motion in the clear areas surrounding convective regions and the net upward flux associated with convective scale motions in the enclosed cloudy areas. The radiative cooling in these clear areas in turn nearly balances the heating associated with the large-scale mean vertical motion. Thus, important features of the mean convective scale mass flux profile can be estimated using sounding data in clear areas. Such profiles reveal regions of deep convective outflow in the upper troposphere, typically between 10 km and 18 km with a local maximum typically near 12-14 km ASL. The level at which clear-sky net radiative heating vanishes ($Q_{clr} = 0$) is located near the top of the convective outflow layer but a significant amount of convection penetrates above this level.

Other defining features of the TTL region include a maximum in the temperature lapse rate in the upper troposphere, often found near the level of maximum convective outflow, and a less pronounced minimum in ozone near this level with a rapid increase above, and a more uniform vertical structure below (A. Gettelman). To first order the transition from a more uniform distribution of ozone in the troposphere to the rapidly increasing profile in the TTL is evidence for the reduced vertical mixing efficiency in that region relative to that which occurs within the tropical troposphere. However, the presence of an ozone minimum may be the result of the outflow of ozone depleted air which is transported upward from the boundary layer in deep convection. The cold point tropopause marks a sharp transition in the vertical temperature gradient (*i.e.* in static stability, poster by **T. Birner**). Although several definitions of the TTL have been proposed, a useful thermodynamic one includes the region between the maximum in the temperature lapse rate and the cold point (A. Gettelman). In view of the small vertical scales associated with the structure of salient features of the TTL, the question of whether this region can be adequately represented in AGCMs is of practical importance. However, notwithstanding the limitations imposed by the vertical resolutions of most current AGCMs there is some evidence that these models are able to simulate some of the main features of the TTL in a realistic manner (talk and poster by A. Gettelman and poster by T. Birner).

The clear-sky component of the radiative heating in the TTL region above the level of Q_{clr}=0 has both longwave and shortwave components, but it is mainly associated with shortwave absorption by CO_2 (predominantly), O_3 and H_2O. Contributions to net radiative heating in this region may also come from elevated cloud layers. In the zonal mean the radiative heating in the upper part of the TTL is partially offset by cooling associated with ascent in the Brewer-Dobson circulation which, though predominantly located in the stratosphere extends down into the TTL. However, the TTL has a 3-dimensional structure and the ascent rates required to offset the radiative heating are in general larger than those associated with the Brewer-Dobson circulation (noted in the presentation by **S. Sherwood**). In the TTL, other dynamical processes that play important roles include large-scale horizontal transport and the influence of tropical waves on various scales which may propagate into the region and, among other things, produce localised temperature and constituent fluctuations (discussed in the presentation by **W. Randel**). The temperature variance associated with these waves shows a maximum close the cold point (also W. Randel).

The magnitude and variation of water vapour in the tropical lower stratosphere is regulated within the TTL. The minimum in water vapour that is typically found in the stratosphere near the tropopause is indicative of dehydration of air ascending into the lower stratosphere. Elucidation of the processes that are responsible for this dehydration is currently the subject of active research and was discussed in several of the presentations given at the workshop. Dehydration associated with large-scale transport is a mechanism that has been explored extensively in the context of Lagrangian trajectory studies (illustrated in presentations by **P. Haynes** and **L. Pfister**), wherein possible trajectories of air parcels passing from the troposphere to the stratosphere through the TTL are determined using wind fields derived from large-scale reanalyses. In this mechanism, the net dehydration of a parcel that enters the stratosphere is determined by the coldest temperatures it encounters during the life-time of its trajectory (the Lagrangian cold point). Thus, although dehydration is associated with large-scale transport and uplifting, the three-dimensional structure of the TTL is important in this mechanism. This in turn may be affected by overshooting convection in the TTL. The results obtained in recent trajectory studies support the conclusion that stratospheric water vapour is largely controlled by large-scale transport (P. Haynes). The introduction of convective overshoots into the trajectories had an overall hydrating effect (L. Pfister). One remaining problem in these trajectory calculations is the lack of high supersaturations in the TTL, as found by recent aircraft measurements. Explaining the physical processes that lead to high levels of supersturation in upper tropospheric ice clouds is a current research challenge. Nevertheless, even rare convective overshoots may have a significant effect on constituent transport into the TTL and LS. S. Sherwood estimated that a convective cloud fraction of as little as 0.02% is sufficient to matter. Furthermore, he presented evidence that convective overshoots lower and cool the cold point, thus affecting temperatures in the TTL.

The conclusion that, to first order, stratospheric water vapour can be explained by large-scale processes does not preclude the possibility that it may be directly affected by convective processes. A plausible mechanism of dehydration could be associated with overshooting convection. Such overshooting is inevitably accompanied by entrainment of environmental air into turrets, followed by gravitational settling and mixing with the environment. If a substantial amount of the ice produced by the cooling and condensation associated with the overshooting falls out of the TTL before being detrained and mixed into the environment, this process will give rise to dehydration. The opposite effect (hydration) may occur if the ice is detrained and evaporates in the process of mixing. Strong evidence for moistening *via* this process has been found recently from aircraft measurements indicating the presence of ice particles above the tropopause close to deep convection in the TROCCINOX and SCOUT-O3 campaigns (presentation by **T. Corti**). The roles of microphysical processes and other constituents in the TTL and hydration/dehydration are currently the subjects of active research, aspects of which were presented in both oral presentations and a number of the posters.

There is currently some debate concerning the possible role of convection in the thermal structure and heat balance of the TTL. This is illustrated by the recent studies of Kuang and Bretherton (2004) and Kuepper *et al*. (2004) who used CRMs in similarly designed idealised experiments exploring a quasi-equilibrium involving a balance between radiative heating and cooling by convective overshooting and (imposed) large-scale ascent. However, they have reached different conclusions (oral presentation by **C. Bretherton**). Kuang and Bretherton concluded that radiative heating is predominantly balanced by convective cooling, while the conclusion of Kuepper is that the convective cooling contribution is relatively small. The reasons for these differing conclusions are currently not fully understood.

W. Rossow gave a survey of available satellite measurements of tropical convection. The top of convection from these measurements can be deduced from brightness temperatures in relation to the cold point temperature, and therefore systems penetrating the tropical stratosphere can be inferred. He showed that larger systems are more likely to contain penetrators, and that these preferentially occur during the early stage of the lifetime of the convective system.

Modelling of deep convection and its role in the TTL

The session on modelling of deep convection and its role on the TTL aimed to provide an overview of the current research being done by those involved in the GCSS deep working group (WG). Besides a range of posters presented over the week there were several invited talks in which each speaker was asked to discuss a specific topic and describe how this work related to the issue of the TTL. The goal of these talks was to provide the workshop with details of the current state-of-the-art research into convection and to enable attendees to consider how this can be linked to problems with modelling the TTL.

The session began with **J. Petch**, the chair of the GCSS deep WG, who discussed the recent work carried out by this working group. This presentation focused on a multi-model intercomparison of simulations of the Tropical West Pacific during TOGA-COARE. Various model types were involved in this study including CRMs, single column models (SCMs), numerical weather prediction (NWP) models, and climate models run in NWP mode. An analysis of the behaviour of the models in the upper troposphere highlighted significant differences between the different model types. Deficiencies in the current experimental designs for the CRMs and SCMs for studying the TTL were discussed with suggestions for improvements.

Two talks covered aspects of observations and model evaluation. **E. Zipser** discussed microphysics observations in the tropics and how these can be used to evaluate CRM simulations. Comparing a CRM simulation of a mesoscale convective system with observations made during the KWAJEX field programme, he showed that the CRM tended to overestimate convective intensity somewhat, and graupel mixing ratios considerably. If an error in CRMs of the size shown is typical, it suggests that this would have significant implications for the use of CRMs to study transport in the TTL. He was keen to stress the difficulty and importance of assessing CRMs with observations and suggested that from the perspective of an observer of "the real world", attempting to evaluate imperfect models with imperfect data, and draw conclusions from this exercise will probably be "imperfect, squared." A further talk about available observations for the evaluation of models was presented by the chair of GCSS, **C. Jakob**. He described the Tropical Warm Pool International Cloud Experiment (TWP-ICE) which took place in Darwin in tropical North Australia during January/February 2006. The aim of the experiment was to study tropical cloud systems and their environment during monsoonal conditions in a holistic way. Implications for modelling, including the derivation of suitable forcing and validation data sets for Cloud-System-Resolving Models and Single Column Models was also discussed.

The current state-of-the-art development in convective parameterizations was presented by **L. Donner**. It was stressed that with the emergence of Earth system models there are substantial new requirements for parameterising convection. In addition to their traditional roles in providing heat and moisture sources and sinks for large-scale atmospheric flows, convective parameterizations must now treat tracer transport, in-cloud chemistry, and scavenging processes. Also, because of indirect effects on clouds by aerosols, both warm and cold microphysics must be considered within a deep convection scheme. In the latest developments of his scheme, he showed the importance of more realistic treatment of cumulus-scale vertical velocities, explicit incorporation of mesoscale circulations associated with deep convection and new insights on closures for cumulus parameterizations. The importance of the generation of upper-tropospheric ice, injection by deep convection of tracers into the stratosphere, and impact of convection on tropical transients was also discussed. In a related talk, **D. Williamson** went on to describe how parameterizations within a climate model can be tested using NWP type simulations. Short forecast errors and the balance of terms in the moisture and temperature prediction equations, which lead to errors, were compared at the ARM (Atmospheric Radiation Measurement) Southern Great Plains site for the June/July 1997 and April 1997 Intensive Observing Periods. Errors seen in the NWP forecast runs can often be linked to those seen in climate runs.

Two presentations discussed the concept of the "super-parameterization" – the use of embedded CRMs into each grid box of a larger scale model to represent a number of the sub-grid processes. **D. Randall** presented an analysis of an AMIP run with the Super-CAM showing a range of benefits to this technique, particularly in terms of capturing intraseasonal, seasonal, and interannual variability. **W. Grabowski**, the pioneer of this technique, then continued to discuss how a similar method could be applied to a mesoscale model. He discussed which processes would be resolved by which model and suggested the relevance of this for modelling tropospheric-stratospheric coupling. In a related talk, **G. Shutts** showed how a very large domain CRM had been used to study the interaction between deep convection and large-scale tropical flow. The model was configured with equatorial beta-plane geometry and used a highly anisotropic grid in the horizontal to reduce the computational burden. Characteristics of the tropical tropopause layer in the model were discussed as well as the different tropical waves produced in the model. As with the GCSS case, there were some problems in the experimental design for study of the TTL but suggestions were made on how these could be addressed.

Three talks focused on different aspects of cloud resolving modelling and how it related to the TTL. **P. Yau** provided a general discussion about simulations with a high resolution model during TOGA-COARE suggesting there is notable sensitivity to resolution with many different scales important in the convection. **E. Jensen** described the use of bin-microphysics in modelling deep convection and its importance when considering the role of microphysics in the TTL. He showed that the suggested mechanism, where extremely cold air generated in overshooting deep convection can provide a significant source of dry air to the TTL, did not occur in their simulations of updrafts penetrating the tropical tropopause. This was because the mass of ice was in relatively small crystals which did not precipitate out sufficiently. However, for a different simulation using a CRM with bulk microphysics, **D. Grosvenor** did show that overshooting convection during TOGA-COARE could lead to a significant reduction in the total water content in the TTL.

Chemistry and deep convection

The aim of the session on modelling chemistry and deep convection in the TTL was to provide an overview of current research on the topic, to describe a collaborative study that addressed midlatitude convection, and to discuss recent and upcoming observation programmes that could be used for future collaborative studies.

The overview of chemistry in the TTL, given by **M. Lawrence**, covered four topics: 1) low-ozone air masses in the TTL; 2) deep convective transport of tracers; 3) scavenging of tracers especially by ice and its role for HNO_3; and 4) extended horizontal observations of a suite of gases (ACCENT results). The challenges of observing and modelling chemical species in the TTL were introduced. One key observed phenomenon of the TTL is extremely low ozone contained in air masses which seems to be influenced by deep convective transport, but other factors, such as reactions on ice, marine boundary layer halogen chemistry, and NO_x production from lightning, may play an important role. The role of transport processes, *e.g.* deep convective transport, scavenging of gases by cloud particles especially ice, slow upwelling transport in the TTL, and exchange with the stratosphere, are found to be important factors in determining the concentrations of chemical species in the TTL.

Tropical convection and chemistry differs over the ocean and continents. The organisation and intensity of the convection over land allows for more convection reaching higher altitudes with overshooting turrets into the lower stratosphere. The higher lightning frequency in these continental storms results in more NO_x in the TTL. However, these NO_x-rich air masses chemically age while being transported to oceanic regions, resulting in air masses with increased ozone in the TTL. The emissions over land and ocean are vastly different. Continental emissions include a wide variety of non-methane hydrocarbons and volatile organic compounds, in addition to surface NO_x and carbon monoxide. Oceanic emissions include dimethyl sulfide, methyl iodide, and other very short-lived halocarbons, as well as sea-salt aerosols. **C. Mari** pointed out the importance and interaction of the diurnal cycles of oceanic convection and photochemical activity. Convection tends to peak during the nocturnal, early morning while photochemical activity is highest during the middle of the day. In severe, continental convection, **E. Riviere** pointed out the positive role of wave breaking on the ozone budget in the TTL. Both Mari and Riviere suggested the need for high resolution simulations of convection and chemistry, as well as for more measurements of chemical constituents near convection.

The effect of aerosols on deep convective clouds with their liquid and ice microphysical processes has recently become a topic of prevalent research. **C. Wang** presented results from his 3-dimensional convective-scale simulations of tropical oceanic convection with varying initial cloud condensation nuclei (CCN) concentrations. His 4 hour simulations showed the non-monotonic response of various cloud properties to increasing CCN, and that dynamics and ice microphysics both play important roles in altering these properties.

In looking toward possible future activities, **M. Barth** showed results from an intercomparison of models simulating midlatitude deep convection and chemistry. The models participating in the exercise agreed quite well with each other, and with measurements for the passive tracers CO and O_3. There was fairly good agreement of NO_x, which was produced primarily from lightning, but there was less agreement of soluble species, such as hydrogen peroxide, formaldehyde, and nitric acid.

One of the crucial components of evaluating model simulations and understanding the role of deep convection and chemistry on the TTL is a suite of chemical, physical, and dynamical measurements in and near deep convective storms. **K. Pickering** outlined the recent and upcoming field experiments of CRYSTAL-FACE, TROCCINOX, SCOUT-O3, ACTIVE, CR-AVE, AMMA, and TC4. Of the field experiments occurring before June 2006, the measurements of cloud physics, passive tracers (CO and O_3), NO_x, and lightning were quite good. It was suggested that CRYSTAL-FACE and TROCCINOX sampled primarily subtropical convection although one excellent tropical event was sampled during TROCCINOX. There were several days of sampling the HECTOR storm during SCOUT-O3 and ACTIVE and several events in contrasting regimes sampled during ACTIVE and TWP-ICE. Thus, it is promising that a tropical deep convection case can be used for future modelling studies of chemistry and thunderstorms.

Key questions and issues

Two sets of breakout sessions were held on the afternoon of the third day of the workshop, with a short plenary between them to air questions and discussion points from the first set of breakouts that would be considered in the second set. The first set of three breakout sessions were organised along thematic lines, with one devoted to a discussion of GCSS Deep Convection

Working Group case studies, a second to chemistry issues in the TTL and a third to large-scale processes in the TTL. The overarching aims of the breakout sessions were to (a) assess current knowledge and understanding, (b) identify questions and uncertainties that could be addressed through future cross-cutting and cross-programmatic collaborations, and (c) propose ways of addressing these questions and issues.

The chemistry breakout session discussed the importance of convection on chemistry with three major points. First, convection can affect the ozone production efficiency (k[NO][HO_2]) by supplying HO_x precursors to the TTL and by supplying NO_x (*via* lightning production) and removing NO_x (*via* HNO_3 uptake). Second, convection can transport Very Short Lived (VSL) halogens to the TTL, potentially altering global tropospheric photochemistry and the stratospheric halogen boundary condition. Third, while convection detraining above Q_{clr}=0 affects mostly the composition of the TTL, convection detraining at lower altitudes can affect the global troposphere.

The large-scale processes breakout session discussed a number of issues. One of the outstanding problems concerning trajectory calculations is that the transport and lifetimes appear to be wrong. These errors may be related to the absence of mesoscale dynamics (*e.g.* gravity waves, mesoscale convective systems) in the meteorological analysis fields. In addition, the absence of turbulent mixing in trajectory calculations may add some uncertainty to these Lagrangian analyses. A second issue discussed was the ability of CRMs to capture the interaction between the cloud scale and large scale given the small domain sizes used in CRMS. A third point brought forward was that it may be difficult to use tracers to distinguish between two dynamical processes, *i.e.* convective detrainment and slow uplifting, which could produce very similar tracer distributions in the TTL.

Several key questions emerged from the first set of break-out sessions:

1) How accurate are CRMs in representing key cloud-scale processes in the TTL?
2) What is the role of overshooting deep convection in setting the cold point (CP) temperature?
3) What is the role of convection in determining ozone and ozone depleting substances (ODS) in the TTL, and therefore in determining boundary conditions for ODS in the stratosphere?
4) How well do CRMs model convective outflow and the distributions (or PDFs) of detrainment?

The second set of breakout sessions discussed possible means of addressing these questions and identified some modelling and observational approaches that be necessary and/or desirable to succeed in this objective.

The accuracy of CRMs can be addressed *via* intercomparisons between models with the inclusion of observations. In this regard it will be useful to utilise the framework of GCSS which involves comparisons of several models all run for a particular case where good forcing data and observations are available; the benefits of this methodology have been well documented within GCSS. In order to evaluate both the role of convection in the TTL and the ability of models to account for it in a physically realistic way it will be necessary to include additional processes and additional observations. This is where active collaboration of experts from IGAC (chemistry) and (trop-strat exchange) SPARC communities will be critical for success. For example the use of chemical tracers such as CO and O_3 must be part of these studies.

Appropriate forcing data sets for CRMs, satellite data, and large-scale models that represent the coupling between convective and larger-scale circulations are all needed to address questions regarding the role of convection in determining ozone and ozone depleting substances (ODS) in the TTL. Mass flux analyses should be part of future intercomparison studies. A field study conducted in concert with cloud-scale and large-scale model simulations would be valuable to quantify the mass flux of key compounds from convection into the TTL.

Future directions and activities

A number of suggestions for future activities and collaborations resulted from the summary of break-out sessions and the ensuing discussion on the last day of the workshop. Several of the immediate and very near term actions suggested have been carried out, are under way, or planned:

- Posting of workshop presentations on the SPARC web site (See http://www.atmosp.physics.utoronto.ca/SPARC/TTL/Participants_Presentations.html)
- Posting of a bibliography of TTL and related literature on the SPARC web site (currently being assembled)
- Posting a list of field experiments (from K. Pickering and C. Jakob's talks) and identify contact people from these experiments for model analysis.
- Solicitation and publication of summary articles in the SPARC, IGAC and GEWEX newsletters on scientific topics and results discussed in the workshop and other related work.

Suggestions for the intermediate term (1-2 years) included organising special sessions on the role of convection in the TTL in upcoming scientific meetings and holding follow-on workshops (in 18 months to 2 years) that may deal more exclusively with some key issues that are of importance in understanding the role of convection in the TTL. These could possibly focus on results of recent field campaigns and efforts to use the results to constrain CRMs. For example, observation and modelling of short-lived chemical constiuents may provide insight and constraints on convective mass flux distributions in the TTL.

In regard to coordinated modelling activities, it was suggested that it may be possible to revisit some of the case studies that have been used by the GCSS Deep Convective Working group (*e.g.* TOGA COARE) in previous CRM intercomparisons with the objective of better understanding of issues in modelling of convective scale processes of importance in the TTL. For example, an initial step could be to repeat the 2006 GCSS Deep Convection Intercomparison case of TOGA-COARE with the inclusion of 1-2 tracers. Activities are already under way (talk by P. Yau) using a multi-grid modelling approach in the context of TOGA-COARE to study the role of convection in the TTL. Future modelling intercomparison case studies to facilitate examination of TTL processes could include observations from more recent field campaigns such as TWP-ICE (talk by C. Jakob), TROCCINOX, SCOUT-O3, ACTIVE, (talk by K. Pickering) and AMMA, which took place August 2006.

It was widely agreed that an important first step toward establishing a framework for future collaborative activities is to compose a working group to build on the groundwork laid down by the workshop. This group should be comprised of researchers in the three broad communities that participated in the workshop. The working group will develop a framework for further collaborative research and plan future activities. A number of possible members for the working group were suggested. The workshop organising committee has taken on the task of bringing about this next step. It is anticipated that a small working group will correspond by email and/or meet on an *ad-hoc* basis over the coming year to develop plans for a collaborative programme that can be proposed to the IGAC, GEWEX, and SPARC projects for the endorsement that will facilitate support for future activities. At the meeting it was agreed that initially this group would include the workshop organisers (T. Birner, J. Petch, M. Barth, and N. McFarlane) with Leo Donner as the GCSS parameterization expert. It is also planned to invite others onto this group who have expertise in other relevant areas.

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Report on the SPARC Data Assimilation Workshop

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Introduction

The SPARC Data Assimilation Working Group (DAWG) was created in 2002 to address the data assimilation needs of SPARC such as (1) long term, global data sets free from trends, (2) assimilated winds with reduced transport errors, (3) help in improving model parameterization schemes, and (4) improved estimates of tracers, constituents and aerosols for process studies. **Figure 1** (colour plate I), presented by **T. Iwasaki** from the new Japanese reanalysis JRA-25, highlights the difficulty of obtaining long-term data records in the stratosphere. In the middle atmosphere, *in situ* measurements are sparse (spatially and temporally) so the primary information comes from satellites. However, temperature anomaly time series highlight the discontinuities at the start and end dates of satellite missions in reanalysis efforts, as seen in Figure 1. For example, the introduction of the AMSU instrument in 1999 coincides with a strong discontinuity in JRA-25 and a weaker one in ERA-40. Such discontinuities in the time series are unrelated to climate trends and should be removed. Clearly, SPARC continues to have a need to communicate with the Data Assimilation community and one of the main vehicles for this interaction is the annual SPARC DAWG workshop in which data assimilators, experts from the SPARC-science community, and users of assimilation products interact. The motivation and strategy for meeting the data assimilation needs of SPARC were outlined in the meeting report from the 2005 Banff workshop (see SPARC Newsletter no. 25).

While the workshops seek to address SPARC needs, the data assimilation community benefits from the interaction with the SPARC community through exposure to new physically-oriented diagnostics which can highlight where assimilated products do well and where they are lacking. The best example of this type of feedback is the identification of transport errors associated with the use of assimilated winds. Transport errors accumulate over time and affect the distribution of constituents. On the other hand, operational assimilation products are designed for optimal forecasts in the hours to 10-day range. Use of operational products for studies of the middle atmosphere provides a very stringent test on their quality, not only because of the interest in long time scales, but also because of the vertical coupling of the atmosphere through upward propagating waves and the enormous variability (and forecast error) of the mesosphere (see Polavarapu *et al*. 2005). As operational centres raise their lids to accommodate the mesosphere in order to improve the assimilation of nadir radiance measurements, the need for feedback from the SPARC community on processes such as vertical coupling and on mesospheric dynamics is becoming increasingly important.

The present workshop highlighted a few specific themes to promote exactly this kind of interaction between the different research communities (data assimilators, experts in dynamics and chemistry, and users of assimilation products). The themes chosen were: transport errors of assimilated winds, polar processes, and the tropical tropopause layer (TTL). New results from age-of-air simulations from ECMWF winds suggest considerable improvement in transport errors, making this a timely topic. The proximity of the International Polar Year (2007-8) prioritises an improved representation of polar processes in analyses. Finally, moisture is a particularly difficult variable to assimilate so the opportunity to involve TTL experts is always invaluable.

Transport errors of assimilated winds

A diagnostic typically used to assess the fidelity of transport is age-of-air. It has been a common problem that assimilated winds produce too young ages in the extratropical lower stratosphere due to excessive mixing from unphysical noise created in the assimilation process. This is reflected in poor tracer distributions with reduced horizontal gradients, and led to the statement by Schoeberl *et al*. (2003) that "current DAS (data assimilation system) products will not give realistic trace gas distributions for long integrations." While this statement seemed rather pessimistic, it has partly motivated the somewhat more encouraging results shown at this workshop.

T. Shepherd noted the value of the SPARC CCMVal transport diagnostics for assessing data assimilation products, and pointed out that the latest generation of CCMs are now producing quite a realistic representation of transport, including age-of-air (Eyring *et al*. 2006). Thus, the issue is not primarily one of spatial resolution or transport schemes, at least in the latest models.

S. Strahan showed that new age-of-air results from GEOS4-DAS are much better than those obtained with previous GEOS-DAS versions. Ages are much older but subtropical and polar gradients still tend to be too weak and vertical and horizontal transport remains too rapid, especially in the mid to upper stratosphere. The main reason for the improved results is the use of time averaged assimilated winds in the new system (Pawson *et al*. 2006). Time averaging is equivalent to applying a square filter, and therefore damps higher frequency noise. Despite the overall encouraging improvement in age-of-air, some issues remain. **Figure 2** (colour plate II) compares N_2O distributions obtained with the GCM, GEOS-DAS and MLS-Aura measurements. In December, the DAS and GCM simulations agree well with MLS up to 500K, but at higher altitudes the GCM looks much more like the observations than does the DAS. In February, the DAS does not show as much descent as the observations, nor is its vortex as isolated. The comparisons indicate that the Combo-GCM is capable of sufficient descent in the Arctic winter and of forming a strong mixing barrier at the vortex edge.

A new ECMWF reanalysis experiment (EXP471) also results in greatly improved age-of-air when compared with measurements (**Figure 3**). EXP471 is one representative experiment of a series of ECMWF experiments performed in preparation for the new ERA-Interim reanalysis. The TOMCAT (p coordinate) and SLIMCAT (theta coordinate) simulations with EXP471 winds differ by less than one year and show similar latitudinal gradients, while for the equivalent simulations using ERA-40 winds differences are between 2-3 years and the latitudinal gradient is much weaker for the TOMCAT run than for the SLIMCAT one (Chipperfield, 2006). **B. Monge-Sanz** noted that not only did the mean age improve, but more realistic age distributions were obtained when using EXP471 winds. Because numerous changes were made between the different operational systems assessed, it is difficult to pinpoint the exact reasons for the improvement. However, some attribution can be made to 4D-Var (*versus* 3D-Var used in ERA-40), improved mass-wind balance in the static background error covariances, improved ATOVS radiance assimilation, and other model improvements. The impact of 4D-Var on parcel dispersion is shown in **Figure 3b**. ERA-40 and EXP 444 used 3D-Var while the other experiments used 4D-Var. The vertical velocities in the 3D-Var runs are twice as large as in the 4D-Var ones, suggesting, therefore, that the main factor in the reduction of the excessively large vertical velocities is the use of the more sophisticated 4D-Var method in obtaining balanced tropical winds.

Age-of-air as a diagnostic in a CTM is very sensitive to the CTM system setup. For example, **B. Bregman** pointed out that not only is the assimilation method important, but that the use of forecasts instead of analyses also increases age-of-air. The advantage of 4D-Var over 3D-Var is that the analyses are in better balance. Similarly, forecasts are smoother than analyses since spurious gravity waves are dispersed within 24 hours. Also, the frequency of wind updates is just as important as the assimilation method: the use of 3-hourly wind updates produces older ages than 6-hourly updates, because the noise in the analyses is less persistent. Bregman also showed that the dispersion of parcels in the tropics in trajectory calculations is sensitive

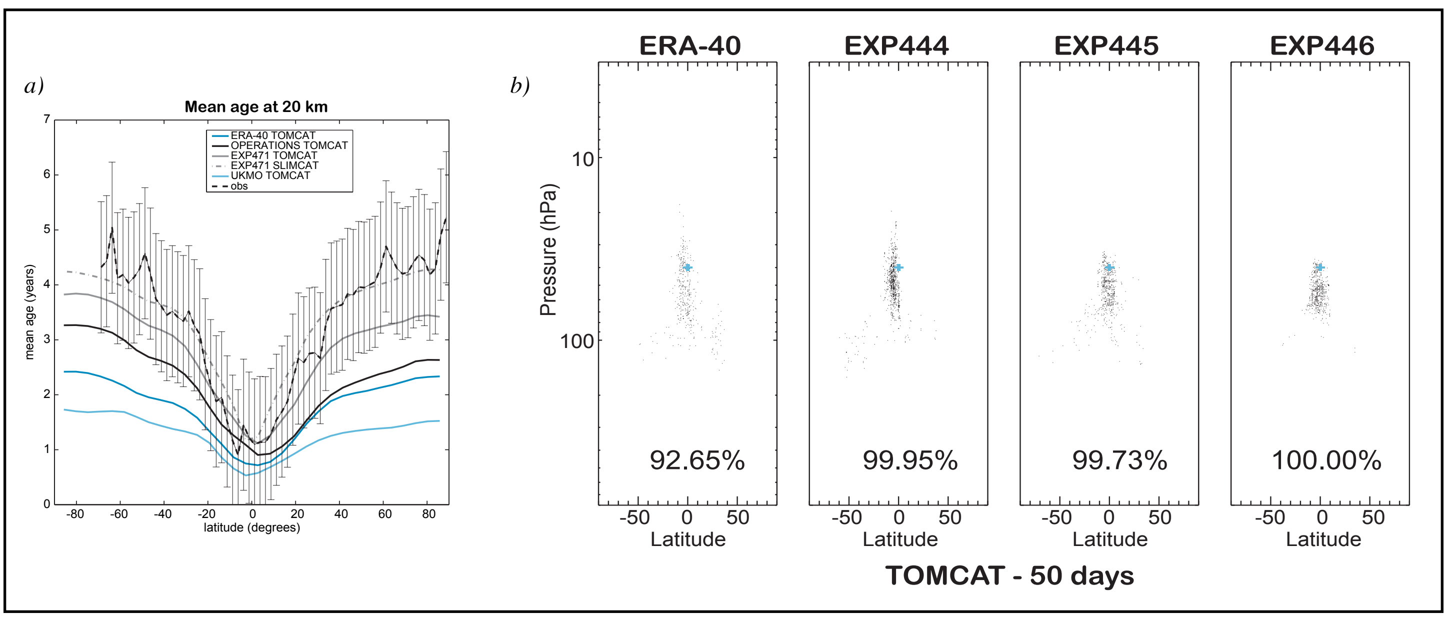

Figure 3: a) Mean age of air at 20 km altitude from TOMCAT/SLIMCAT simulations (coloured lines) using different ECMWF and UKMO analyses, compared with the mean age of air derived from in-situ ER-2 aircraft observations of CO_2 (Andrews et al., 2001) and SF_6 (Ray et al., 1999) (black dashed line). 2-sigma error bars have been included for the observations. b) Distribution of particles (black dots) after 50 days of backward kinematic trajectories with TOMCAT forced by 4 different analyses. The left-most panel is for ERA-40 winds, while the other three are for three ERA-Interim experiments produced with the same version of the model, but with differences in the assimilation method employed. For each panel the percentage of particles left in the stratosphere after 50 days is indicated. Initial position of particles is indicated by a blue cross. (Courtesy of B. Monge-Sanz.)

to the parcel release height; a small change of 2 km can greatly reduce or increase the horizontal dispersion of parcels (**Figure 4**). This is consistent with tracer diagnostics in the real atmosphere which have identified the region just above the tropical tropopause as having enhanced horizontal mixing compared with the more isolated "tropical pipe" just above. Thus, the commonly applied trajectory dispersion experiment introduced by Schoeberl *et al*. (2003) as a diagnostic to assess the quality of the assimilated winds must be interpreted with care.

Clearly, age-of-air is only one of many diagnostics that should be used to assess transport. In polar regions, p.d.f.s of N_2O were used by Strahan to assess vortex isolation and downwelling. In the upper troposphere/lower stratosphere region, distributions of CO or O_3 are useful since high CO identifies tropospheric air while high O_3 identifies stratospheric air, as illustrated in presentations by **P. Hoor** and **A. Robichaud**. **H. Bönisch** also showed how measurements of CO_2 and SF_6 can be used to estimate age-of-air in this region.

Assimilation of dynamic variables

The Met Office has a new forecast model grid which combines the high horizontal resolution of the previous weather forecast model with the high vertical resolution of the stratospheric model (50 levels with a 63 km lid). **M. Keil** noted that this single model configuration resulted in improved weather forecasts, and surprisingly 80% of the forecast improvement was due to the increased vertical domain. By improving the representation of the stratosphere the assimilation of tropospheric AMSU channels, which sense the stratosphere, was improved. In addition, more (stratospheric) channels were assimilated. (E. Holm noted that the same arguments led ECMWF to raise the lid of their operational model to 0.01 hPa (~80 km) on February 1, 2006.) The Met Office also plans to eventually raise the lid of their operational model to 80 km and assimilate mesospheric data such as SSMIS radiances.

With increasingly higher model lids, it is necessary to define background error covariances that encompass the mesosphere. **D. Jackson** reported on experiments using the "Canadian Quick" (CQ) covariance method introduced by Y. Rochon, which relies on 6-hour differences of a climate simulation (with diurnal and tidal signals removed) and can be used for new model configurations. The CQ method produced less noisy variances (and analyses) than the NMC-method, which is used for the operational system at the Met Office. It also appears to have a smaller signal associated with gravity waves. **Y. Nezlin** compared the ensemble method with the CQ method and found some surprising agreement in the middle atmosphere. In the troposphere, the ensemble method produces variances that reflect data density (as expected) and vertical correlations that are narrower and less negative than those produced from the CQ method.

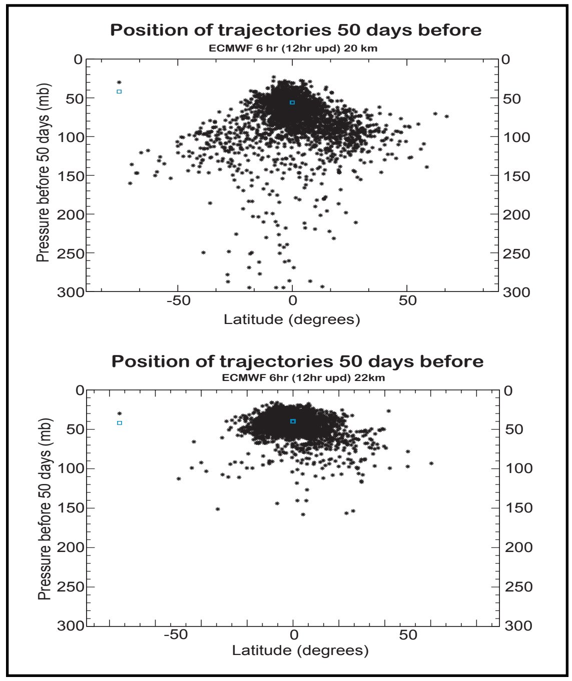

Figure 4: The end locations of 2880 air parcels after 50 days back-trajectory calculations using 6-hourly interpolated winds from the ECMWF operational analyses, starting at the equator at an altitude of 20 km (top panel) and 22 km (bottom panel). (Bregman et al., 2006.)

Not only does the mesosphere affect the definition of error covariances for the assimilation step, but it responds to the insertion of analysis increments in the tropsphere and stratosphere during the 6-hour model forecast that is used to generate a background for the next analysis step. **S. Polavarapu** showed that the vertical coupling can occur directly through resolved waves (so that different gravity wave filtering schemes result in vastly different mesospheric mean temperatures and diurnal tides) or through the filtering of parameterised gravity waves by the mean flow. Since the mesosphere is very sensitive to parameters affecting wave propagation in the lower atmosphere, it suggests the possibility that mesospheric observations can be used to constrain such parameters.

Moisture remains a difficult variable to assimilate. **E. Holm** noted that since nadir sounders (*e.g.* from METOP, GOES, HIRS, AMSU, AIRS) have weak sensitivity in the stratosphere, and since MIPAS assimilation is no longer operational, the availability of measurements of stratospheric moisture remains an issue. While MLS limb measurements are promising, they are not available in real time. When assimilating nadir soundings, realistic background error covariances can create spurious increments at 1 hPa due to the fact that moisture and temperature are coupled in the forward model. The removal of these spurious increments has required either removing channels that are sensitive to moisture, or removing the sensitivity of the forward model to moisture. Since stratospheric humidity and temperature errors are not correlated, another option is to define a new analysis variable which is normalised by the background humidity. However, at the Met Office, **H. Thornton** found that changing the moisture variable was insufficient to control spurious increments but damping correlations could be effective.

The vertical oscillation in temperature bias in various models still exists and in the case of ECMWF is believed to be associated with model biases (E. Holm). ECMWF is attempting to address the problem both by reducing model biases (*e.g.* through gravity wave drag parameterization) and by accounting for model bias in the assimilation procedure. **Y. Rochon**, however, noted that oscillating biases can be associated with the use of linear interpolation from model levels to radiative transfer (*e.g.* RTTOV) model levels. If some model levels are not involved in the mapping, the adjoint process provides no analysis increments to these levels and consistent (biased) oscillations in increments are observed. This problem is increasingly apparent as NWP models increase the number of vertical levels and reduce vertical correlation lengths which previously masked the problem. Rochon is providing an alternative interpolation scheme, which avoids this problem, to the RTTOV community.

In a poster, **N. Zagar** showed that error covariances in the tropical stratosphere, particularly the wind-mass coupling, varied with the phase of the QBO, presumably because of the different filtering of planetary-scale equatorial waves in the different QBO phases. Failure to account for this will be detrimental to assimilation in the tropics.

Tropical Tropopause Layer

The tropical tropopause layer (TTL) is an important region for SPARC science, in part because it regulates the water vapour abundance of the stratosphere. **S. Füglistaler** emphasised the challenge for data assimilation in this region, because the properties of the TTL change markedly over just a few kilometres in the vertical, and cloud radiative processes are very important. Since analysis increments tend to be of the same order as the dominant terms in the energy balance, the errors are likely to be large in this region. Yet transport studies using analyses are key to addressing many of the scientific questions associated with the TTL (see Füglistaler's article in SPARC Newsletter No. 25).

T. Birner continued this theme and focused on the temperature structure of the TTL. He noted that the sharpness of the cold-point tropopause (CPT) seen in high-resolution radiosonde measurements (collected under the SPARC GW initiative) is smoothed out in meteorological analyses. This is not simply a question of vertical resolution because the CMAM climate model, with comparable resolution, manages to capture something of the sharpness of the CPT with a layer of enhanced stability above, as seen in the radiosondes. In a recent study, Birner *et al*. (2006) showed that a similar "tropopause inversion layer" (TIL) found in the extratropics was smoothed out in CMAM by the process of data assimilation. As in the extratropics, the incorporation of coarse-resolution nadir-sounding satellite data in 1979 is clearly evident in the NCEP/NCAR reanalysis as a degradation of the tropical TIL, as can be seen in **Figure 5** (colour plate II). (A similar behaviour was pointed out for the thermal tropopause by Randel *et al*. (2000).)

There has been much interest in the subject of transport within the TTL, partly because of the dehydration problem and partly because of the chemical impact of short-lived species (including pollutants) in the TTL. One popular approach, illustrated by **M. van Weele**, uses trajectory calculations. Another approach, championed by **I. Folkins**, is to use tracers such as O_3, H_2O and CO to constrain the convective outflow. For example, the strong convective outflow at about 12 km (~ 200 hPa) is reflected in a minimum in ozone profiles at this altitude, corresponding to young boundary-layer air, yet this is not seen in all convective parameterizations. Folkins emphasised the interaction between deep and shallow convection, with the mid-tropospheric convergence from the former roughly balancing the divergence from the latter.

International Polar Year

The International Polar Year (IPY) is a period of intensive observations of the polar regions (2007-8). An introduction to IPY and to SPARC's role in IPY was described by Baldwin *et al*. in SPARC Newsletter No. 25 (July 2005). The SPARC-IPY project is entitled "The structure and evolution of the stratospheric polar vortices during IPY and its links to the troposphere" and primarily involves the collection of global assimilation products, as well as measurements from pre-existing field stations in both polar regions. During the past year, the SPARC DAWG (Data Assimilation Working Group) has obtained confirmation of participation in the SPARC-IPY project from various assimilation groups: operational weather forecast centres (ECMWF, Met Office, NCEP), operational ozone forecast groups (GMAO, KNMI), the BADC, and research groups in data assimilation (DARC, and GEM-Strato and CMAM-DAS). The products will be available at the SPARC Data Center, and the exact variables and other parameters to be saved will be determined in the coming months. It was decided to leave operational gridded products in their native GRIB format (because of its efficient compression ratio) but to provide interfaces that will make it easy for the user to extract fields from any provider. A simple user registration form will be provided to keep track of users on behalf of the data providers. Measurements taken as part of the SPARC-IPY project will be available through links on the SPARC-IPY webpage. Links to other relevant data sets and measurements from the SPARC Data Center are also planned. This archive of assimilation products and measurements will be the main legacy of this project. The SPARC community is invited to use this resource to further stratospheric science along the themes highlighted by the IPY; however, since the gridded products will be global, any applications are encouraged whether or not there is a link to polar regions.

The lifting of the lids of operational assimilation systems into the upper mesosphere is allowing the information provided in tropospheric and stratospheric measurements to propagate up into the mesosphere, as noted earlier with reference to Polavarapu's talk. A dramatic illustration is seen in the mesospheric coolings long observed in conjunction with sudden stratospheric warmings in the Arctic, as discussed by **K. Krüger** and illustrated in **Figure 6**. The phenomenon is now reflected in analyses that encompass the mesosphere. This raises important possibilities for IPY, given the extensive network of mesospheric ground-based observations. However, Krüger also highlighted the serious problem of oscillatory temperature biases (compared against radiosondes) in ECMWF analyses, illustrated by **Figure 7**, which as noted earlier is believed to result from model biases in the lower mesosphere/upper stratosphere which propagate down into the lower stratosphere through the error covariances. These oscillations lead to systematic errors in subsequent estimations of radiative cooling rates, which compromise calculations of diabatic descent in polar regions. It is thus recommended that operational centres save net model heating rates together with analyses.

An alternative way of inferring diabatic descent is directly from tracer fields. This was discussed by **J. Rösevall**, who performed a two-dimensional (isentropic) assimilation of Odin SMR N_2O data and inferred diabatic descent from the difference between observed and passive N_2O fields.

Moving down to the upper troposphere, there is considerable interest in the possibility of using special-purpose airborne observations to improve weather forecasts. **M. Weissmann** described some experiments using the DLR Falcon aircraft in the North Atlantic, using an onboard wind lidar together with dropsondes. The wind lidar observations provided a much higher impact than the dropsondes on the analysis. While the interest in this case was primarily

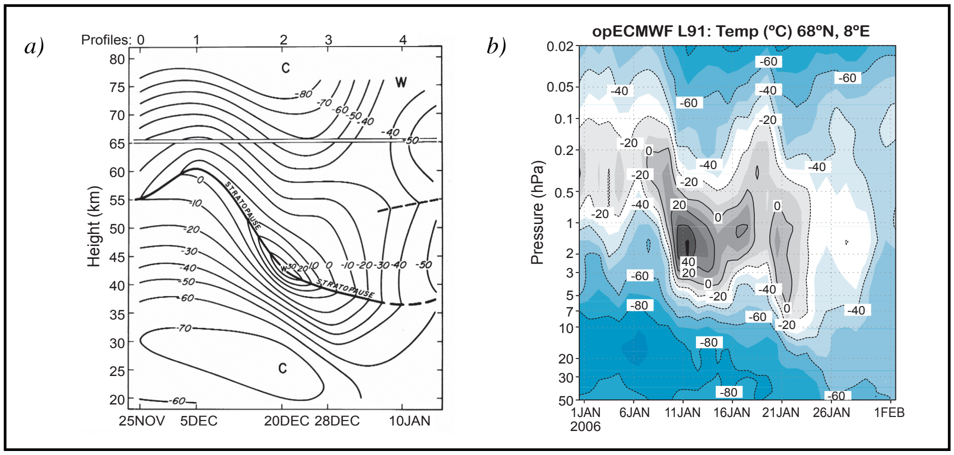

Figure 6: a) Schematic distribution of temperature at about 60°N during the development of a Major Midwinter Warming; e.g., above Scotland, between 20 and 80 km. (Labitzke, JAS, 1972). b) Vertical time section of temperature (over 68°N, 8°E) for the development of the stratopause warming and major midwinter warming during the Arctic winter 2005/06. Grey (blue) shading indicates high (low) temperatures. Operational ECMWF data (T799/L91) were used. (Courtesy of K. Krüger.)

on weather forecasts, some vertical propagation of information into the polar lower stratosphere was also seen, although its value needs to be assessed. Still, this could be an interesting link between the IPY activities planned under THORPEX and SPARC.

Chemical Data Assimilation

Assimilation of atmospheric chemistry is mainly driven by two needs: first, to improve assimilation of radiances by providing a realistic background ozone field;

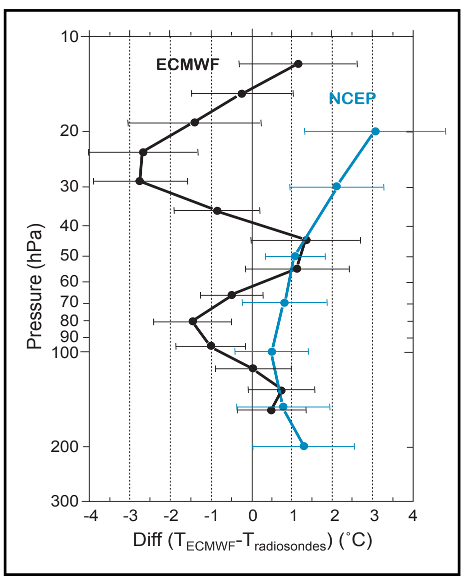

Figure 7: Comparison of ECMWF and NCEP temperatures with sondes flown during 14 June to 12 October 2003 from Antarctic stations. The ECMWF analyses are from 12 UTC for the T511 60 level operational model, cycle 25r4. The NCEP/NCAR reanalyses employed a 2.5 x 2.5 horizontal grid with 28 levels from the surface to 40 km. (From Parrondo et al., 2006.)

and second, to provide chemical analyses in both the troposphere and stratosphere. The first application requires making ozone a prognostic variable within the forecast model, and often the ozone chemistry is heavily parameterised through the so-called Cariolle scheme. The second application has up to now generally been done off-line using Chemical Transport Models (CTMs) with sophisticated chemistry, and driven by analysed winds, so that there is no coupling between the dynamical and chemical assimilation. In the future, however, these two approaches will inevitably converge. The discussion at the workshop addressed all these aspects.

Key to assimilation is the ready availability of quality-controlled observations in a standard format. For meteorological observations and operational weather forecasting this is done through the WMO, but the system does not include research observations and is not available to users outside the national meteorological agencies. For chemical observations, the situation is much worse. **G. Braathen** made the point that a rational system for integrating available atmospheric observations is missing. This involves aspects like relational data bases, easy access to meteorological data, a one-stop portal, and long-term products (**Figure 8**). Data assimilation provides an important building block in such a system, by bringing together available observations and atmospheric models to perform comprehensive analyses of the state of the atmosphere. IGOS/IGACO and GAW are international initiatives with the aim to define such information systems.

Much experience has been gained in recent years on chemical data assimilation in CTMs. Because of the tight coupling between many of the reactive gases, several groups have applied 4D-Var assimilation which ensures chemically consistent analyses and a transfer of information to unobserved species. The Belgian BASCOE 4D-Var system has been used in particular for the analysis of MIPAS observations (discussed by **Q. Errera**). The use of the relatively new SACADA 4D-Var system (**J. Schwinger, H. Elbern**) for generating long-term stratospheric composition data sets based on satellite observations was discussed by **F. Baier.**

The assimilation of ozone is so far the most studied aspect of chemical data assimilation. Because synoptic-scale variations in ozone reflect dynamics (*e.g.* total ozone is strongly correlated with tropopause height), models are able to produce ozone distributions which correlate very well with observations. This success in fact highlights the need for high-quality observations: in order to improve analyses, the observations need to have errors comparable to, or better than, the background error. This is often not the case (as discussed by R. Menard).

An extensive intercomparison of European ozone assimilation initiatives has recently been published (Geer *et al*. 2006). This work was done in the context of the EU ASSET project and was discussed by **W. Lahoz**. Eleven different assimilation setups (full chemistry *vs*. parameterised ozone chemistry, GCM *vs*. CTM) from seven different groups have been compared (**Figure 9**). By assimilating Envisat MIPAS and SCIAMACHY ozone retrievals, and using HALOE and sonde data for validation, the project was able to show that MIPAS data are 5% higher than HALOE above 30 hPa and 10% higher than ozone sondes and HALOE between 100 and 30 hPa. SCIAMACHY total columns were almost as good as MIPAS analyses but limb profiles were worse in some areas. The project also highlighted the need for full chemistry models in the representation of the ozone hole and in the upper stratosphere where chemical timescales are short.The approach of using an NWP model with on-line complex chemistry allows for the feedback of ozone analyses on other species as well on the radiation calculation. It has become clear that a detailed study of

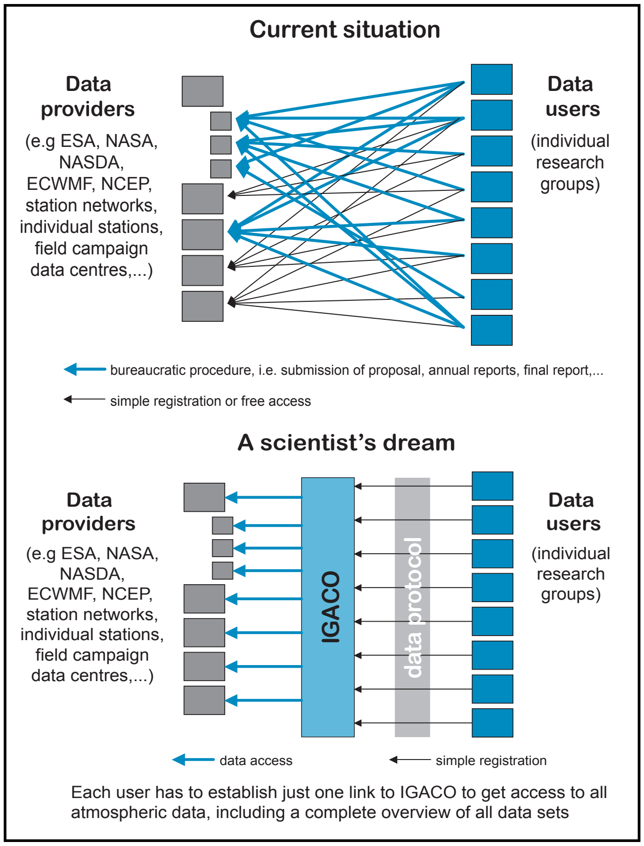

Figure 8: Schematic diagrams depicting current and ideal data access procedures. (Courtesy of M. Rex.)

model and observation biases, as well as a careful definition of the model forecast error covariance matrix, is required before meaningful results can be expected. **R. Menard** and **S. Chabrillat** showed some first results for the GEM-Strato-BIRA system in which ozone and dynamics are coupled, while the ozone-radiation interaction in GEM was further discussed by Y. Rochon. The assimilation of stratospheric temperature observations (AMSU-A in this case) induced transport biases which resulted in significant distortions of the GEM-Strato-BIRA model ozone field (see **Figure 10,** colour plate III). The level of distortion depends not only on the observations but also on the specified background error statistics and possibly as well on the response of the forecast model to the analyses. Significant model biases (transport-related) at the South Pole were also reported by several groups. One important question remaining is whether a full chemistry scheme is needed, or if the biases in a parameterised ozone chemistry would be small enough to permit meaningful ozone assimilation in a fully coupled system.

A central issue in data assimilation is the construction of the forecast covariances (B-matrix), a topic addressed in most presentations. This is especially important in multi-variate assimilation with chemisry-chemistry or chemistry-dynamics couplings. R. Menard showed that very strong correlations between temperature and ozone are found in the GEM-Strato-BIRA system while **Y. Yang** considered the tuning of observation and background errors for both dynamics and chemistry variables. In the past years, several groups have performed experiments with flow-dependent correlation models. **J. Schwinger** showed that a scheme based on gradients in PV lead to an improvement of the analysis with the SACADA system. **H. Eskes** showed that meaningful time-dependent forecast error distributions resulted from a sub-optimal Kalman filter implementation in the KNMI satellite ozone column assimilation (see **Figure 11,** colour plate III).

The assimilation of satellite data with a good quality model provides direct feedback on the quality of the measurements. Because each satellite observation is complemented by a corresponding model forecast value, the statistical significance of the results is often very high. Eskes discussed several examples illustrating how the KNMI total ozone retrieval for SCIAMACHY was validated with the ozone assimilation system, and how this has led to improvements of the retrieval code (see **Figure 12**). A routine monitoring in time of the analysis results is a useful technique to detect changes in the retrievals due to instrument changes or software updates.

EOS-Aura has acquired two years of observations, and many retrieved products have recently become available. The first assimilation results were shown for both Aura-MLS and Aura-OMI ozone (talks by **K. Wargan** and **A. O'Neill**). The first validation of the MLS/OMI analyses with sondes and with MOZAIC aircraft data showed agreement to within 10%, demonstrating the good quality of the Aura data sets (**Figure 13**). Wargan observed that only a small number (*e.g.* 15/day, occultation) of high-quality ozone profiles (as provided by *e.g.* POAM) in combination with total column observations can have a big positive impact on the analysis. Such an observation is of relevance for instrument choices on future satellite missions.

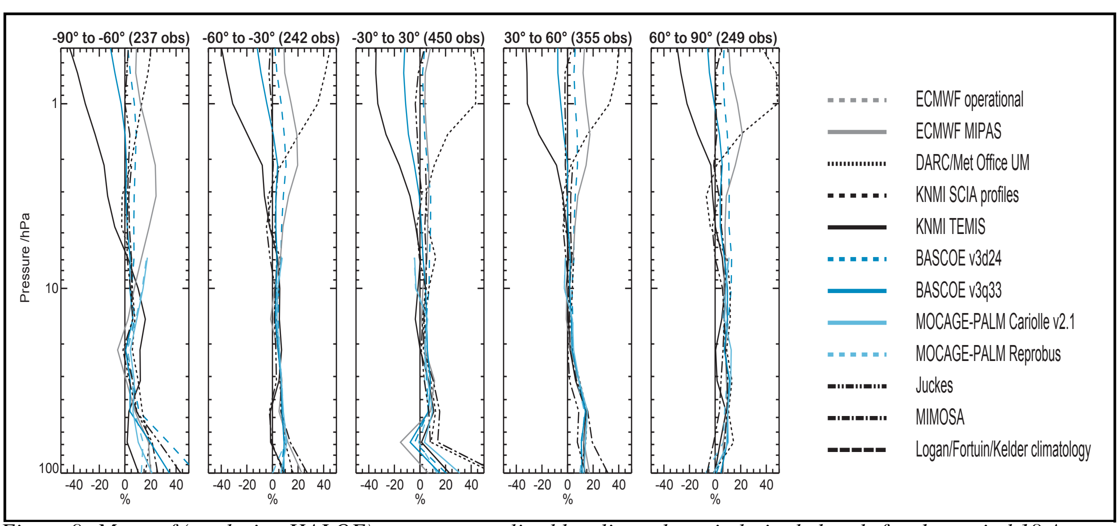

Figure 9: Mean of (analysis - HALOE) ozone, normalised by climatology, in latitude bands for the period 18 August 2003 to 30 November 2003. Statistics are shown for the ECMWF MIPAS, DARC, KNMI TEMIS, BASCOE v3d24 and v3q33, MOCAGE-PALM Cariolle v2.1 and Reprobus, Juckes and MIMOSA analyses. See colour key. (Courtesy of A. Geer and W. Lahoz; Geer et al. 2006.)

Next Workshop

The use of themes was found to be helpful in bringing together different research communities: experts in stratospheric science, data assimilators, and users of assimilation products. To con-

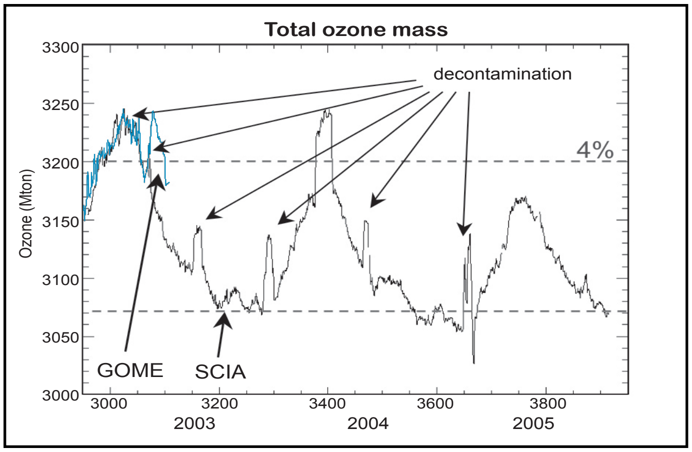

Figure 12: A time series of the total ozone mass in the atmosphere from the KNMI ozone assimilation system. Blue curve: based on GOME ozone column observations. Black curve: based on SCIAMACHY. The dashed lines show that the total mass varibability is of the order of 4%. The arrows point towards peaks with an amplitide of about 1% which coincide in time with decontamination heating periods of the SCIAMACHY instruments. (Courtesy of H. Eskes.)

tinue in this format, a number of themes were chosen for the next workshop. Firstly, as the next workshop will fall within the IPY period and because of the DAWG contribution to the SPARC-IPY project, it is natural to highlight this activity next year. Secondly, since operational weather centres are frequently judged on tropospheric weather forecasts, data assimilators are interested in better understanding the nature of stratosphere-troposphere coupling. The improvement of Met Office weather forecasts through the use of an increased vertical domain highlights the importance of the stratosphere for tropospheric assimilation problems. However, the dynamics of stratosphere-troposphere coupling is also important for improving forecasts in the medium range. As both THORPEX and WCRP have seamless prediction (from days to seasonal scales) as major objectives, this topic is very timely. Finally, with the extension of operational forecast models into the middle mesosphere (*e.g.* ECMWF, Met Office, GMAO) there is a growing need to better understand vertical coupling between the mesosphere and the lower atmosphere. Thus, the next SPARC DAWG workshop will feature invited speakers on the following topics: polar processes, strat-trop coupling, and mesospheric dynamics and observations. The usual data assimilation topics will also continue to be covered.

By alternating workshop locations between Europe and North America, we are able to include more participants from different continents. Therefore, the next workshop will be in North America, more specifically, in Toronto during 4-7 September 2007. In 2008, no DAWG workshop is planned since all participants are encouraged to attend the SPARC General Assembly in Bologna, Italy during 1-5 September 2008.

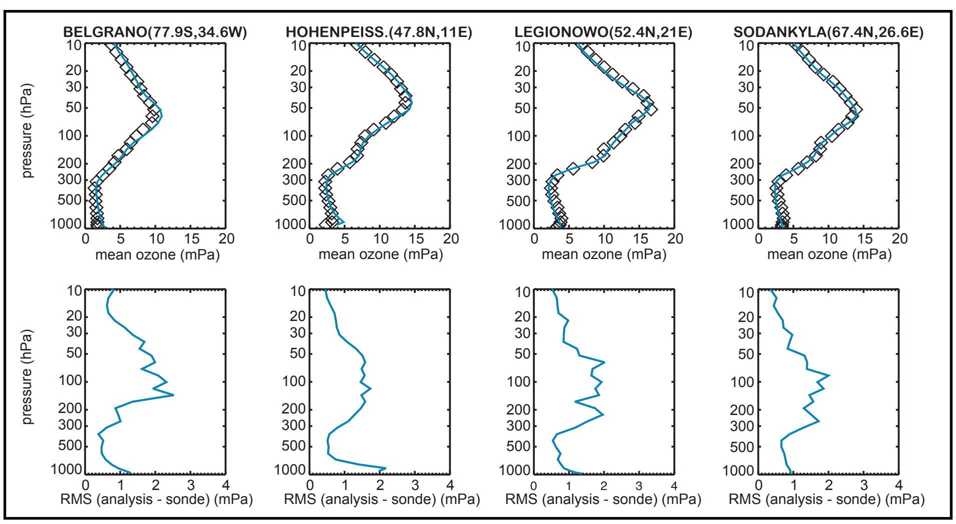

Figure 13: Top panels: the annual mean ozone from balloon sondes at four locations (diamonds) and the GMAO analysis mean (blue). Bottom panels: the corresponding root mean-square (RMS) difference. Ozone total column and profiles (216 - 0.14 hPa) from Aura's Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS) were assimilated. The analysed values closest to the sounding times were selected and interpolated to sonde locations. Vertical interpolation of all data to standard pressure levels was applied. Mean difference between the analysis and sonde data is within 10% above 300 hPa. The RMS difference is up to 50% in the upper troposphere, within 40% above 100 hPa at Belgrano, and within 20% above 100 hPa at other locations. (Courtesy of K. Wargan. Thanks to the ESA Envisat Cal/Val database team and the data originators for providing the sonde data.)

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Report on the first SOLARIS workshop

4-6 October 2006, Boulder, Colorado, USA

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The new SPARC working group on solar variability is an extension of the GRIPS solar influence intercomparison project (Matthes *et al*., 2003; Kodera *et al*., 2003). The objective of this group is "Modelling and understanding the solar influence on climate through stratospheric chemical and dynamical processes" in collaboration with working group 1 of the SCOSTEP CAWSES (Climate and Weather of the Sun-Earth System) programme.

The first SOLARIS (SOLAR Influence for SPARC) workshop was held in October 2006 and hosted by NCAR's Earth and Sun Systems Laboratory in Boulder, Colorado. This workshop was the latest in a series of meetings, beginning with the December 2004 AGU conference in San Francisco and continuing with the July 2005 IAGA conference in Toulouse that provide the middle atmospheric research community with a forum to review the latest results in the field of modelling the solar influence on climate.

Approximately 40 participants from Canada, Europe, Japan, Russia and the United States, plus local participants from Boulder (LASP/University of Colorado, NCAR) attended the workshop. The programme of the workshop and a list of participants can be found on the SOLARIS website (http://strat-www.met.fu-berlin.de/~matthes/sparc/meetingdetails.html).

The first day of the meeting included a series of overview talks from invited speakers that were open to the general public. These overviews covered topics ranging from solar variability (**T. Woods**) to new insights into dynamo theory (**M. Dikpati**), and observed solar signals in the middle atmosphere and possible transfer mechanisms. **L. Hood** and **W. Randel** presented the most up to date observational analyses of solar signals in ozone and temperature, which seem to agree better with each other than previous analyses. **K. Kodera** described some of the dynamical mechanisms through which small direct stratospheric effects can indirectly affect the lower parts of the atmosphere down to the Earth's surface. **A. Smith** talked about aliasing of the solar signal through the QBO and the problem of having data sets that are too short. **C. Randall** gave an overview about precipitating particles and their effect on stratospheric chemistry and dynamics. In the afternoon each modelling group participating in the SOLARIS project gave a summary of their current activities.

The following two days focused on the specific research activities of each group in order to determine which questions are still open and how they can be studied in more detail through the combined SOLARIS effort. These results were discussed within the context of the five coordinated research themes that comprise the SOLARIS effort (http://strat-www.met.fu-berlin.de/~matthes/sparc/goals.html):

I) Thermospheric and Mesospheric Response
II) Ozone and Temperature Response
III) Dynamical Response Including the Role of the QBO
IV) Stratosphere-Troposphere Coupling
V) Ocean Response and Paleo-Climate

Within theme I, model studies about

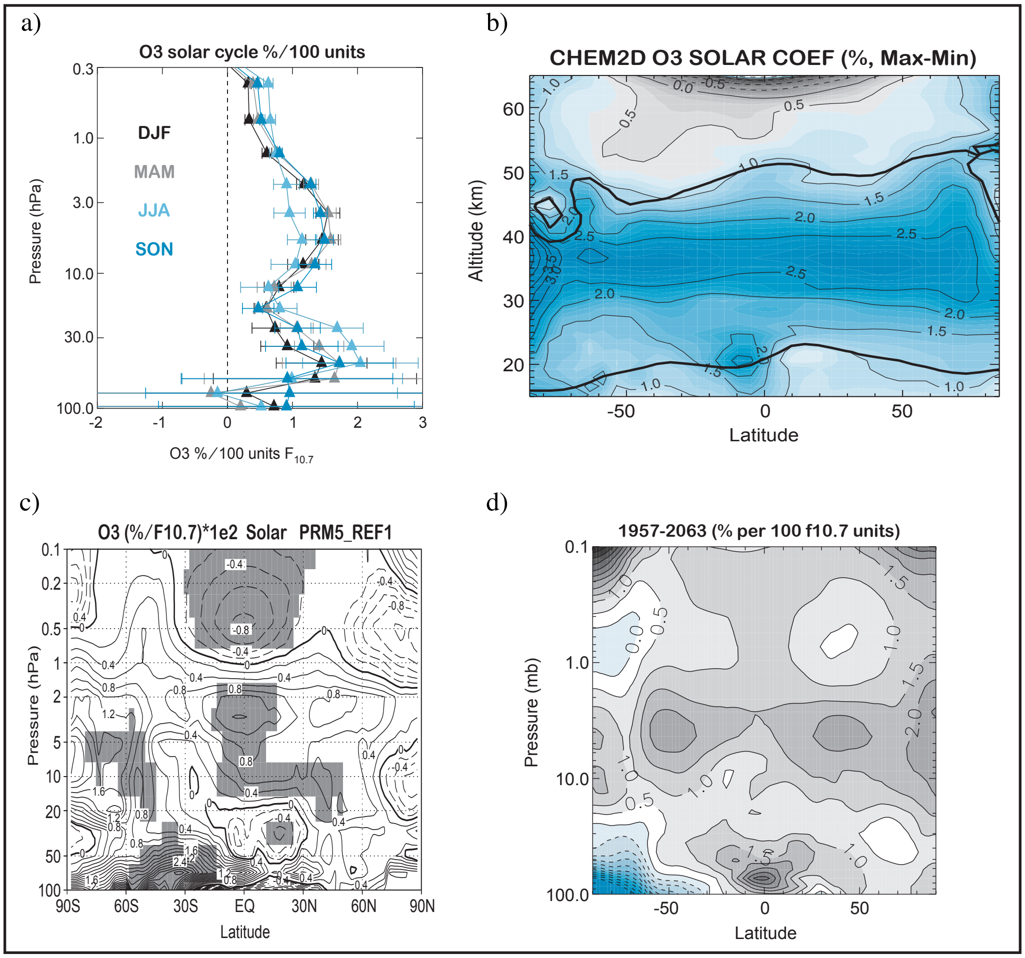

Figure 2: a) Simulated seasonal mean ozone solar response in % per 100 units of 10.7 cm flux with the CCMAMTRAC. The results have been averaged over the latitude range 25°S to 25°N and over all three ensemble members. The error bars indicate 95% confidence intervals from the linear regression analysis. (From Austin et al., 2006); b) Simulated annual mean ozone solar response in %/max-min from a 50 year simulation of the CHEM2D model. Thick black lines enclose regions where Cs is greater than 2-sigma (From McCormack and Siskind, 2006); c) Simulated annual mean ozone solar response in % per 100 units of 10.7 cm flux from the REF1 simulation of the MRI-CCM (Courtesty of K. Shibata); d) Simulated annual mean ozone solar response in % per 100 units of 10.7 cm flux from 106 years of simulations with the CCM WACCM from 90°S to 90°N and 100 to 0.1 hPa (16 km to 60 km). (Courtesy of K. Matthes.)

the influence of solar proton events on the atmosphere were shown. **Figure 1** (colour plate IV) shows one example of an experiment with NCAR's Whole Atmosphere Community Climate Model (WACCM) that incorporated solar protons during the 2003 "Halloween storm." Increased solar proton fluxes lead to increases in NO_y (see **Figure 1b,** colour plate IV) that are comparable to observations (see **Figure 1a,** colour plate IV) (presentation by **D. Marsh**). The ionization rates computed from solar fluxes for the period of 1963-2005 used in WACCM were provided by Charles Jackman and are now available on the SOLARIS website. Other studies dealt with solar influence on tides (presentation by **T. Hirooka**).

A more coherent temperature and ozone response to the 11-year solar cycle from different models came out of the discussion from themes II and III. **Figure 2** shows examples of the resulting solar signal in ozone from three different coupled chemistry climate models (CCMs) and one 2D chemistry-transport model when the 11-year solar cycle in irradiance was included. In all of the models the solar cycle was time-varying, instead of the usual constant solar min/max experiments of the past. The GFDL AMTRAC (Atmospheric Model with TRansport And Chemistry) simulations were run for 135 years (3x45 years) with observed solar cycle, SSTs, GHG, and volcanoes (REF1 simulations of CCMVal) (presentation by **J. Austin**). Note that AMTRAC does not have an internally generated QBO or a specified one. The MRI-CCM simulations are similar to the AMTRAC simulations except that the model generates a self-consistent QBO (presentation by **K. Shibata**). The NRL CHEM2D model was run for 50 years with an interactive parameterization for the QBO (presentation by **J. McCormack**). The WACCM simulations had a prescribed QBO (the observed time series were repeated in order to reach 110 years of simulation), fixed SSTs, GHGs and no volcanic aerosols (presentation by **K. Matthes**).

The discrepancy in the ozone response between observations, and 2D and 3D model simulations carried out in the 1990's seems to be reduced in the latest simulations. More models show the observed vertical structure in the tropical stratosphere, with a maximum in the upper stratosphere, a relative minimum in the middle stratosphere, and a secondary maximum in the lower stratosphere. Possible factors that may be important in obtaining the correct vertical structures are a time-dependent solar cycle, a time-varying QBO (either self-consistent or synthetic), variable SSTs, and a long enough time series (at least 50 years). Other issues that were discussed and seem to be important for producing a more realistic solar signal include a high-resolution short wave heating scheme as well as a good model climatology (presentation by **U. Langematz**). Also the question was raised of how high the top of the model has to be to simulate a realistic solar signal in the middle atmosphere. The importance of the background ozone field to the resulting temperature response was pointed out as well (presentation by **L. Gray**).

We now have a good set of model experiments with different levels of complexity that will be used to understand the relative importance of these factors in producing the solar signal in ozone. As a starting point, J. Austin, E. Rozanov and K. Tourpali have started an intercomparison of the tropical solar signal in ozone by analysing the REF1 simulations of the CCMVal SPARC initiative (Eyring *et al*., 2006).

The SOLARIS model experiments will also be used to investigate the dynamical response of QBO and solar signals. So far the observed modulation of the polar night jet and the Brewer Dobson circulation (Kodera and Kuroda, 2002), the modulation of the occurrence of Stratospheric Warmings (Labitzke and van Loon, 1988) including the importance of equatorial winds in the upper stratosphere (Gray *et al.*, 2001a, b; Gray, 2003, Gray *et al.*, 2004) have only been reproduced in a few model simulations (*e.g.*, Matthes *et al.*, 2004, 2006; Palmer and Gray, 2005). Further work is required to investigate the importance of this QBO interaction and whether it impacts the mechanism for transfer of the solar signal to the troposphere.

Within theme IV, different sensitivity studies of stratosphere-troposphere coupling were shown. A perpetual January sensitivity experiment with the ECHAM5-MESSY CCM, in which a momentum forcing was introduced in the mid-latitude stratosphere, shows a dynamically induced temperature increase in the tropical lower stratosphere (**Figure 3**) that leads to changes in vertical velocity and precipitation in the tropics, and changes in the extratropical regions with an AO-like pattern in the Northern Hemisphere troposphere (presentation by A. Kubin, U. Langematz). This idealised experiment shows that stratospheric changes can have significant effects on the tropospheric circulation and confirms earlier findings of Haigh (1996), Haigh *et al.* (2005), the presentation by **J. Haigh**, and Matthes *et al.* (2004, 2006).

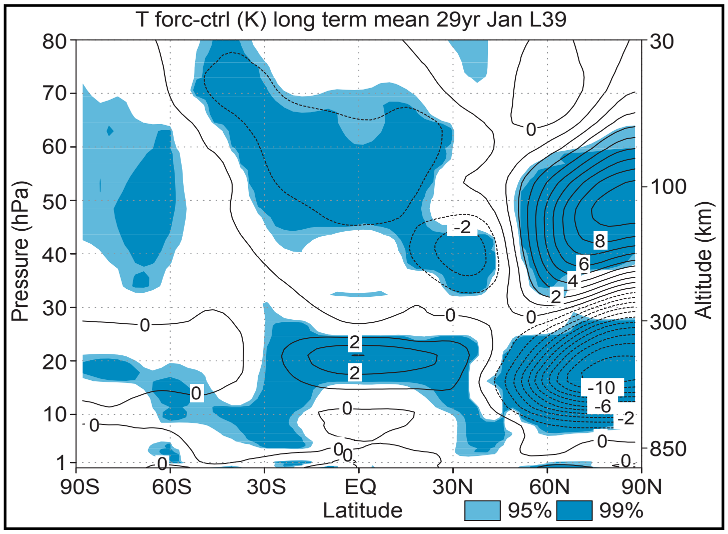

Figure 3: Zonal mean temperature differences in K between the forcing and the control run of the T42L39 perpetual January experiment with the ECHAM5-MESSY CCM. Contour interval is 2 K, light blue (blue) shading denotes statistical significance at the 95% (99%) level. (Courtesy of A. Kubin and U. Langematz.)

Within theme V, the importance of an interactive ocean was discussed. A fully interactive ocean seems to better represent the reconstructed surface temperature signal during the Maunder Minimum (**Figure 4**, presentation by **D. Shindell**). **J. Meehl** showed results from NCAR's Community Climate System Model (CCSM) in which only total solar irradiance (TSI) changes at the top (~10hPa) were introduced, and which does not have a stratosphere; these results look very similar to the changes that were achieved with a CCM that included spectrally resolved solar irradiance changes and a proper stratosphere (Matthes *et al.*, 2007). The vertical structure of the response needs to be investigated further and it needs to be clarified how much of the tropospheric equatorial signal comes from TSI and how much from spectrally resolved UV changes.

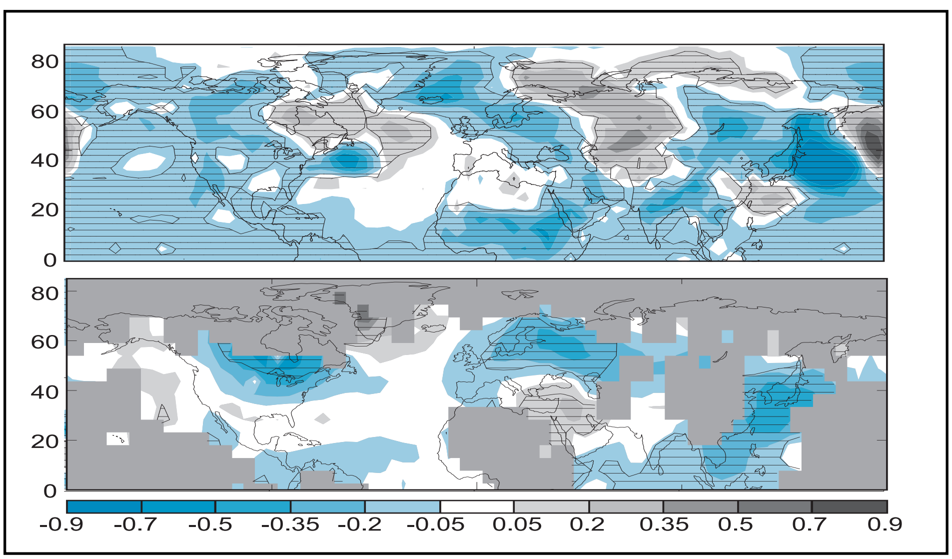

Figure 4: Annual average surface temperature change (°C) due to solar irradiance change of ~1 W/m² (top of the atmosphere, equivalent to ~0.19 W/m² at the tropopause) in the GISS ModelE (top) and the regression during the period 1650-1850 between reconstructed solar irradiance (From Lean et al., 1995) and annual average surface temperatures (bottom) (From Mann et al., 1998) filtered to only include contributions from timescales longer than 40 years, with a 20 year lag. The correlation is given in °C per change from roughly the Maunder Minimum to a century later, which is roughly 0.2 W/m² in recent reconstructions (e.g. Wang et al., 2005). Grey areas indicate no data, while hatched areas indicate statistical significance at the 90% level. (Courtesy of D. Shindell.)

The short-term (27-day) response of the middle to upper atmosphere was discussed with the Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA) (presentation by **H. Schmidt**), with the GFDL AMTRAC model (presentation by J. Austin) and with the SOCOL model (presentation by **E. Rozanov**). It was proposed to use 27-day cycle simulations to investigate the mechanisms for solar forcing in the stratosphere. For a decade or more 27-day processes have been simulated reasonably accurately whereas the response to the 11-year solar cycle is only now getting more coherent in the different model simulations. One of the main issues is whether different processes are operating on the 11-year and 27-day timescale.

Further progress and updates on our activities can be found on the SOLARIS website: http://strat-www.met.fu-berlin.de/~matthes/sparc/solaris.html.

Acknowledgments

We would like to thank Guy Brasseur, director of NCAR's Earth and Sun Systems Laboratory, for kindly hosting the workshop, and Barb Petruzzi for the help with the logistics. The support of SPARC/WCRP enabled a few students to attend. Also, the authors would like to thank R. Garcia for valuable comments on the manuscript.

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A note on an AGU spring meeting discussion of the role of atmospheric water vapour in climate and atmospheric composition

23-26 May 2006, Baltimore, Maryland, USA

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Introduction

Since the early 1970s the study of the middle atmosphere has focused on understanding the variability of its chemical and dynamical states as driven by both natural and anthropogenic processes. Concurrent with these efforts, studies have been carried out to understand both short- and long-term climatic variations that occur naturally, as well as those due to the emissions and/or alterations of optically active gases and aerosols by humanity. In these areas of study, stratospheric and tropospheric water vapour (H_2O) has been of particular interest. Water vapour is a greenhouse gas and is important for atmospheric chemistry, as it is the source of the hydroxyl radical, OH, which regulates among others the atmospheric methane lifetime and the production and destruction of ozone. Also, water vapour plays an important role in atmospheric heterogeneous chemistry, defining the aerosol effect on climate *via* formation of the stratospheric clouds. While some progress has been made in simulating the changing atmosphere, a number of observed phenomena remain unexplained, among them the reasons for the recently observed trends in upper-troposphere/lower-stratosphere (UT/LS) water vapour and temperature.

A session entitled "Role of atmospheric water vapour for climate and atmospheric composition" at the spring American Geophysical Union (AGU) meeting presented the recent state of knowledge on processes related to the UT/LS water vapour in data analysis and modelling. The atmospheric water vapour issues discussed at the session spanned from the upper troposphere to the mesosphere in the Earth's tropical and extratropical regions, and underlined the importance of coordinating water vapour research with issues related to other chemical compounds such as ozone, carbon monoxide and aerosol. The discussion converged into two main questions:

(1) What are the main mechanisms influencing the water vapour budget in the tropical tropopause layer?
(2) What are the water vapour trends?

The purpose of this note is to assess results presented at the session and to begin creating a base for the next steps of the ongoing research.

Tropical tropopause layer water vapour budget

The tropical tropopause layer (TTL) is a transition layer between the wet and turbulent troposphere and the dry and stable stratosphere, where tropospheric processes gradually decrease in importance. Two speakers (**Folkins** and **Sherwood**) emphasised that because the ambient vertical velocity vanishes near 15 km, air cannot enter the TTL from below except in vigorous convective updrafts originating in the lower troposphere. This probably limits the ability of upper-tropospheric constituents, including water vapour, to affect the lower stratosphere. Sherwood noted that observations, basic theory, and climate models all suggest that tropospheric humidity is not sensitive to microphysical forcings, even though such forcings are evidently able to change water vapour entering the stratosphere and probably account for some of the increases in water vapour between the 1950s and 1990s. Folkins underlined the major factors defining the water vapour budget in TTL. These factors are related to the processes associated with the convective detrainment. **Figure 1** shows Folkins's "TTL Virtuous Circle," which shows that to get a fair description of the water vapour evolution in the TTL, one should at least take into account (1) a vertical profile of the detrainment, (2) the water vapour mixing ratio of air parcels detraining from deep convective clouds, (3) irreversible post-convective removal of water vapour by formation and fall-out of sedimenting ice crystals, (4) the evaporation of ice crystals descending from higher altitudes, and (5) quasi-horizontal exchange with the extratropical stratosphere. He argued that a comprehensive theory of water vapour in the TTL should be based on a dynamical model that is consistent with empirical estimates of the relevant thermodynamic forcings, and should predict mean profiles of other trace species that are in agreement with observations. Since ozone affects net radiative heating in the region, the future evolution of cold point temperature will be sensitive to the convective detrainment profile.

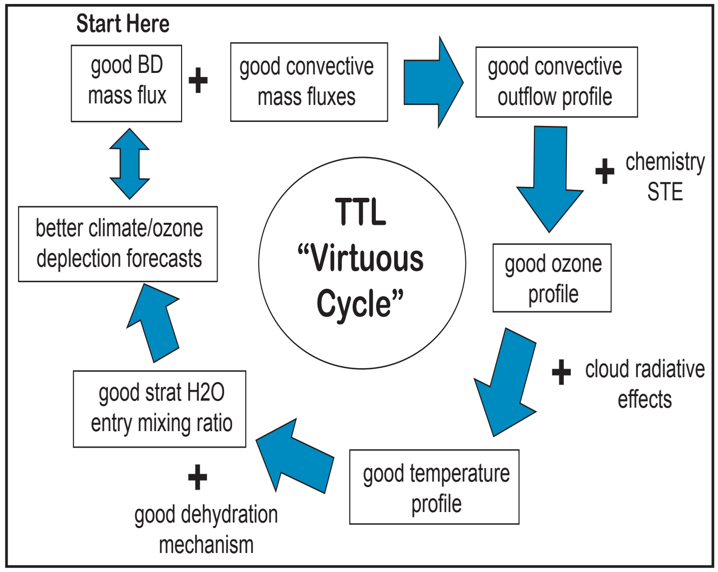

Figure 1: The TTL Virtuous Circle

Wright examined the relative roles of detrainment temperature, convective ice water content, ice cloud effective radius, and ambient relative humidity upon the efficiency of convective moistening in the tropical upper troposphere between 300 and 200 hPa by closely matching AIRS water vapour measurements with the vertical and microphysical structure of their convective sources using a trajectory model. His results show that, in a global sense, after being detrained from its convective source, water vapour is mainly controlled by temperatures during and after convective detrainment. Cloud microphysical properties appear to play a secondary role globally, although they can be more significant on regional scales. His observational results support the advection-condensation model and relative humidity control of the convective hydration/dehydration suggested by Sherwood.

John presented a method for comparing temperature and humidity profiles simulated by a dozen coupled General Circulation Models (GCMs) with observations using satellite microwave data. They showed that the models correctly predict the observed correlation between cirrus cover and atmospheric moisture, refuting a recent paper suggesting that this well-known relationship implies a missing component to the water vapour feedback.

There were a few talks at the session touching upon the question of water vapour interaction with aerosol. **Harkey** and **Hu** presented results on the role of tropical biomass burning on water vapour in the TTL. Using a regional model, Harkey predicted that changes in microphysical properties of the cirrus clouds within the TTL due to increased biomass burning caused more rapid growth of cirrus clouds and reduced water vapour content. Hu studied the influence of biomass burning aerosols on convective/cirrus cloud properties and water vapour transport to the upper troposphere. Close correlation was found among the deep/cirrus clouds, aerosols, and atmospheric constituents over these regions in the boreal summer. **Caboussat** drew attention to the role of organic aerosols in the water vapour budget of the upper troposphere. They emphasised that the chemical properties of aerosols are needed for the aerosol growth and activation and cloud formation, as illustrated in Figure 1. More precisely, organic components have an effect on the crystallization of salts in aerosols, known as the *salt-in – salt-out* effect. However, this effect is neglected in the current models and replaced by a *phase lock* between hydrophobic and hydrophilic organic components. To avoid this artifact, they proposed a model for the computation of the thermodynamic equilibrium (phase separation) and dynamics (gas-particle partitioning) of organic aerosols and the determination of the microphysical state of organic aerosols and water vapour budget. They designed an accurate method to incorporate these effects in numerical simulations of cloud formation. Results have shown that their approach is efficient and could be inserted into regional or global models. **Wang** used the CAM3 community climate model coupled to the IMPACT aerosol model to investigate how aerosol-induced increases in ice crystal number and reductions in size and settling velocity would affect water vapour in the UT/LS region. They found that a decrease in the settling velocity increased the ice flux into the stratosphere directly, but reported that a larger moistening effect occurred indirectly because the cloud cover increased, thereby increasing the radiative heating and the tropopause temperatures.

An important role of orography for the water vapour transport in the TTL region was mentioned by **Fu** *et al.* They presented evidence from multiple satellites (AURA, TRMM, AQUA) that much of the water vapour and CO entering the global tropical stratosphere in Asia is transported over the Tibetan Plateau (TP) region during the boreal summer. They showed that the tops of convection over the Asian monsoon region are mostly below the TTL (15 km), while convection over the TP can detrain water vapour directly to the tropopause level or into the lower stratosphere. In this case, the tropopause temperature is about 7K warmer and 40% less saturated than that over the Indian monsoon region. A combination of these conditions allows fast transport of water vapour into the lower stratosphere, which bypasses, or short-circuits, the "cold trap" occurring in the monsoon region.

There are three main conclusions from this part of the session:

(1) The advection-condensation model of water vapour continues to be supported in the troposphere;
(2) Model and observational studies indicate likely impacts of aerosols on TTL water vapour; and
(3) The horizontal transport is important particularly during the Asian monsoon season.

Water vapour trends

It is known that the distribution, variability, and trends of water vapour in the upper troposphere and lower stratosphere are important for understanding the Earth's climate. Trends in stratospheric water vapour, if they can be confirmed, would cause a significant change in the radiative forcing of climate. Water vapour is the dominant greenhouse gas in the atmosphere, and also can be a cooling agent in the middle and upper troposphere. Despite the stratosphere being relatively dry, small changes in the stratospheric water content can substantially alter the stratospheric chemical composition and influence surface climate.

According to the data presented by **Nedoluha** from the combination of WVMS, POAM, and HALOE measurements over the period 1991 to the present, it is difficult to gain any information about water vapour trends above 60 km due to a masking role of two major natural factors: the realization of the QBO and the variation of the solar cycle, of which the influences on the middle atmosphere are still not well understood or modelled. In the stratosphere an increase in water vapour was documented between 1990 and 1996, in spite of the fact that the interannual behaviour of the water vapour there is influenced by the QBO. After 1996 the upper stratosphere/lower mesosphere showed no trends, but starting in 2001 the water vapour in the lower stratosphere began to decrease in accordance with cooling of the tropical tropopause.

Rosenlof and **Reid** also showed that according to HALOE measurements the tropical stratospheric water vapour dropped dramatically at the end of 2001. This decrease has propagated upward, reaching 10 hPa within one to two years, and has persisted to the present (see **Figure 2a**, colour plate IV). It is directly correlated with a temperature decrease at the tropical cold point, obtained from UARS data (**Figure 2b**, colour plate IV), with a magnitude equivalent to 1/3 of the annual cycle peak-to-peak temperature differences. The cooling was confined to a narrow layer near the cold point. It also appears correlated to a change in the global sea-surface temperature pattern, including changes outside of the tropics. They hypothesised that a change in the amplitude of the tropical stratospheric QBO in temperatures occurs at the same time as the tropical tropopause temperature changes, possibly due to changes in the convective wave that forces motions in the UT/LS. They also mentioned an increase in the strength of the upper portion of the Hadley circulation, leading to an increased meridional mass flux in the lower stratosphere, peaking above 150 hPa, but below 60 hPa.

Dameris presented a modelling effort by Stenke *et al.* to simulate the historical evolution of the water vapour in the stratosphere. They ran an atmospheric GCM coupled with interactive chemistry, with all known climate system anthropogenic and natural forcings, including greenhouse gases, volcanoes, solar variability, observed changes in SST, ice coverage, and the QBO. These forcings were prescribed from the observed fields over the period from 1960 to 2000 and projected to 2020. The model simulation supports a relationship between water vapour changes and QBO variability for the observed period used in the model. It also simulated a reversal of the lower stratospheric water vapour trend with decreasing water vapour during the first 10 years and increasing values from 1980 on (see **Figure 3**). It did not show the decrease of the water vapour after 2001 reported by Nedoluha, Rosenlof and Reid; however, the forcings prescribed in the model from 2000 were not based on observations, but on future projections. The simulated water vapour variations, short- as well as long-term, are strongly linked to the temperature at the tropical tropopause, which controls the entry-level water vapour mixing ratio, and therefore all conclusions depend on how accurately the tropical tropopause is simulated.

Joshi presented possible consequences of the stratospheric water vapour trends for the tropospheric circulation. Based on numerical experiments with the Hadley Centre's climate model he showed that a prescribed increase in stratospheric water vapour (in accordance with observations) changes the North Atlantic Oscillation (NAO) index, which would explain a significant portion of the observed NAO trend over 1965 to 1995. This suggests a mechanism for interannual predictability of the tropospheric circulation due to effects of large tropical volcanic eruptions, ENSO events or QBO changes using information about stratospheric water vapour change.

Zveryaev and **Alan** studied trends of the tropical column integrated water vapour (CWV) over the period 1979 to 2001, and showed that the spatial distribution of CWV is strongly determined by thermodynamic constraints, while its spatial variability is dominated by changes in the large-scale dynamics, in particular those associated with the El Niño - Southern Oscillation (ENSO). They concluded that over 1979 to 2001 the CWV trends are dominated by dynamics rather than thermodynamics.

This part of the session also had three main conclusions:

(1) Upward stratospheric water vapour trends reported prior to the late 1990s are still not explained by conventional models, and have not continued;
(2) The sudden, mysterious tropopause cooling in 2001 caused a marked and persistent drying; and,
(3) Stratospheric water vapour changes are estimated to have had significant impacts on the atmospheric general circulation.

Concluding Remarks and Outstanding Questions

We believe that the Spring AGU session on water vapour had very insightful presentations and as a result raised many important questions to be answered by future research. Among the questions are:

- o Are aerosol indirect effects on water vapour significant in the stratosphere, and could they be occurring in the troposphere? If so, which aerosol types and nucleation modes are most important?
- o What will happen to methane concentrations in the future?
- o What caused the sudden 2001 cooling near the tropopause and what will happen to tropopause temperatures in the future?
- o Are there pathways around the tropical tropopause that allow significant moisture from the upper troposphere to reach the stratosphere?
- o What other natural and anthropogenic factors might have an influence on water vapour evolution in the TTL?

We are pleased that there were a few excellent student papers presented at the session (Harkey, John, Wright, Wang). Wide involvement of student research activities in these sessions guarantees that the number of atmospheric scientists studying and solving atmospheric water vapour mysteries will grow as they graduate and move forward with their own research.

List of Talks

Caboussat A., N. R. Amundson, J. He and J. H. Seinfeld: *Modeling of Organic Effects on Aerosols Growth.*

Folkins I, P. Bernath, C. Boone, and K. Walker: *Water Vapor Budget of the Tropical Tropopause Layer.*

Fu R., Hu Y., J S. Wright and J. H. Jiang: *What are the main pathways for the cross tropopause transport of water vapor and CO over the Asian monsoon/Tibetan Plateau?*

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Hu Y., R. Fu and J. H. Jiang: *Aerosol Impacts on Convective Transport of Water Vapor and Polluted Air in the Upper Troposphere Over the Asian Monsoon Region.*

John V. O., B. J. Soden and S. A. Buehler: *Comparison of UTH in IPCC AR4 coupled GCMs to microwave observations.*

Joshi M., A. Scaife, A. Charlton and S. Fueglistaler: *The influence of stratospheric water vapour changes on the extratropical tropospheric circulation on different timescales.*

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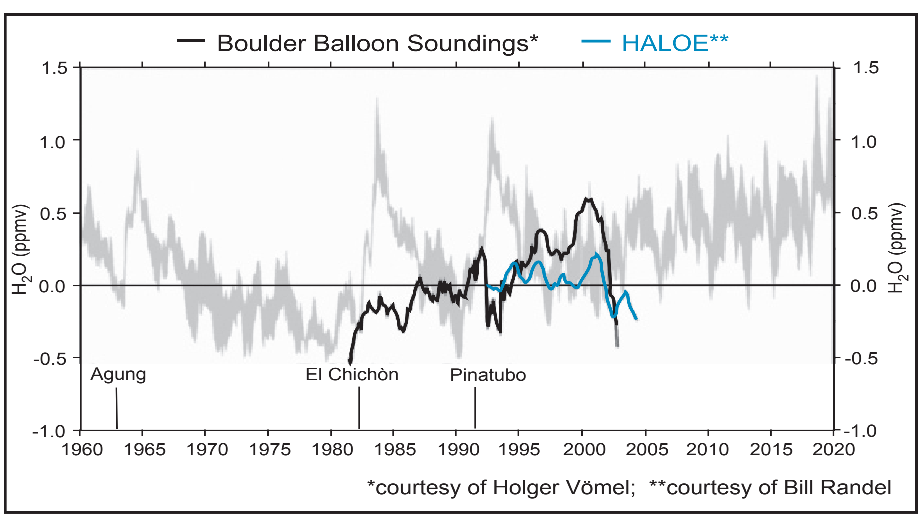

Figure 3: Deseasonalised water vapour volume mixing ratios at 40°N and 50hPa. The grey shaded area indicates the min/max values derived from three simulations for 1960-1999 and four simulations for 2000-2020. The blue and black curves show the respective time series from HALOE and Boulder balloon soundings.

Report on the Gravity Wave Retreat

26 June – 7 July 2006, Boulder, CO, USA

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Introduction

Thirty experts in atmospheric gravity wave studies were invited to participate in a Gravity Wave Retreat hosted by the Institute for Integrative and Multidisciplinary Earth Studies (TIIMES) at the National Center for Atmospheric Research (NCAR). The week of June 26th was spent on whole group interactions, whereas the other two weeks were meant for informal gatherings and scientific exchanges. A detailed agenda of the retreat and the full participant list can be found at http://www.tiimes.ucar.edu/events/gw-retreat06.htm. During the retreat, the participants presented state of the art research related to gravity waves, identified the major scientific challenges, and made recommendations for future research needs. The summary of these can be found in a White Paper posted on the retreat website entitled "Gravity Waves in Weather, Climate, and Atmospheric Chemistry: Issues and Challenges for the Community" by M. Geller (SUNY Stony Brook), H. Liu (NCAR), J. Richter (NCAR), D. Wu (JPL), and F. Zhang (Texas A & M University).

While gravity wave research has a long and rich history, there has been a recent upsurge of activity in this area because of the need to parameterise the effects of unresolved gravity waves in atmospheric general circulation models, as well as the interaction between gravity waves and convection in mesoscale systems. At the retreat, it was clear that scientific progress in these areas requires better characterization of the gravity waves launched by various sources, improved understanding of the physics of gravity wave dissipation and interaction with the mean flow, and closer collaboration between the middle atmosphere and mesoscale communities. Below, we present a short summary of these challenges and potential research avenues.

Scientific challenges

Sources

Atmospheric gravity waves have a broad spectrum of spatial and temporal scales. Horizontal wavelengths range from kilometers to thousands of kilometers, and periods range from the Brunt-Väisälä (approximately ten minutes in the troposphere) to the inertial. There is a general understanding that the spectrum of gravity waves is launched by tropospheric mechanisms such as flow over topography, convection, and frontal systems. However, the characteristics of these waves, especially the phase speed spectra of momentum flux from various sources, are not well quantified.

At the gravity wave retreat, better characterization of gravity wave sources was identified as the outstanding issue in gravity wave research. Flow over topography is the easiest gravity wave excitation mechanism to quantify, as the gravity waves generated have primarily zero phase speed relative to the ground. Convection, on the other hand, generates a broad spectrum of waves as a function of frequency (or phase speed), and hence is very difficult to characterise. Spontaneous adjustment resulting from geostrophic imbalance is another source of gravity waves; wave emissions from frontal collapse and jet streaks fall under this heading (*e.g.* Zhang 2004). *The characteristics of waves excited by unbalanced jet-front systems are poorly understood and should be a high priority in gravity wave research*. Wave characteristics from a combination of two or more of sources are even more complex and poorly described.

Gravity wave retreat participants agreed that *much could be learned about gravity wave sources and wave behaviour by having the mesoscale community interact with the middle and upper atmosphere gravity wave community*. The interactions should occur in mesoscale modelling studies as well as observational campaigns. Several mesoscale field campaigns are already being planned, and joining these efforts with instruments extending through the middle atmosphere, such as superpressure balloons, ground-based remote sensing radar, and optical techniques, would be advantageous both to the gravity wave and mesoscale communities. Mesoscale models extending from the troposphere to the lower thermosphere will be needed to support such campaign studies.

Impacts

Gravity waves are important in the atmosphere for several reasons: they can transport energy and momentum from the lower to the middle and upper atmosphere, and thus alter the large-scale circulation; upon breaking, they generate turbulence that mixes chemical species, and which can be hazardous to aviation; they can influence the generation of convection; and they can lead to the formation of clouds, such as orographic cirrus and polar stratospheric and mesospheric clouds. They may also play an important role in seeding ionospheric irregularities.

One of the basic questions in gravity wave research is how much of a global impact do gravity waves have. This question is difficult to address, as there are currently no global observations that would allow an accurate assessment. *In particular, a key question is: how much momentum do gravity waves deposit on the mean flow globally, and as a function of latitude?* A satellite campaign specifically designed to study gravity waves would be a momentous step in answering this question; however, this would require a significant commitment from funding agencies.

We can attempt to reduce the uncertainty in *our estimates of the global impact of gravity waves by intercomparing global circulation models (GCMs)*. This is a challenging task, however, as resolved waves are also a major source of momentum in the middle atmosphere in GCMs, and momentum deposition from large scale waves is poorly constrained by observations. In addition, the contribution of resolved wave drag depends on the mean flow, which itself depends on the unresolved (parameterised) drag. *One promising approach is to examine the role of gravity wave drag in the context of data assimilation and parameter estimation*, now that middle atmosphere climate models are beginning to be used in this framework (Polavarapu *et al*., 2005).

Parameterizations

Representing gravity wave effects in global climate models (GCMs) is a longstanding challenge. Typical GCM grid cells are of the order of 100 km horizontally, and these models do not resolve the excitation, propagation, or dissipation of mesoscale gravity waves. Typical GCM gravity wave parameterizations (*e.g*. Lindzen, 1981) assume fixed gravity wave source spectra launched from an arbitrarily selected altitude, usually around 100 mb. The gravity wave spectrum is then propagated through the varying winds and temperature while their influence on the momentum budget is calculated. *The largest drawback of this typical approach is that source spectra are specified independently of the characteristics of the source region. This is a particularly important shortcoming in simulations of changing climate*.

Source spectrum parameterizations for orographically generated waves have existed for almost two decades now (*e.g*. Palmer *et al*., 1986). However, there remain uncertainties in these formulations; for example, as to what fraction of the total pressure drag across complex subgrid-scale topography should be translated into a gravity wave response (see Webster *et al*., 2003). Specification of gravity waves from non-stationary sources is even more complex. Recently, based on a combination of theory and mesoscale models, a few source spectrum parameterizations for convectively generated gravity waves have emerged (*e.g*. Beres *et al*., 2004). However, there is still a lack of physically well-founded source spectrum parameterizations for processes important in mid-latitudes, such as geostrophic imbalance at jet stream levels. *Therefore, it is desirable to develop a gravity wave source specification in which different physical sources launch gravity waves in a manner consistent with the knowledge gained from field programmes and mesoscale models*. With the advent of physically based nonstationary gravity wave source parameterizations, it may also become necessary to consider the lateral propagation of gravity waves in the parameterization schemes.

Another important question regarding gravity wave drag parameterizations is how much of an effect do they have on tropospheric climate? Several authors (*e.g*. Boville 1984) have shown that changes in stratospheric gravity wave drag produce changes in the mean state and variability of northern hemisphere surface climate. Efforts should be made to evaluate this effect in general circulation models, and to develop methods to verify these findings with observations.

Need for a Community

In addition to addressing scientific challenges, the retreat participants found that there is a need for a gravity wave research community to facilitate interactions among scientists working on various aspects of gravity waves. International programmes such as SPARC have had gravity wave initiatives, but their activity has varied from year to year since SPARC's inception in 1992. Gravity waves have also been an active subject for inquiry in SCOSTEP (Scientific Committee on Solar-Terrestrial Physics) since the days of MAP (the Middle Atmosphere Program) in 1982. It is recommended that SCOSTEP, NCAR, and SPARC set up a working group that is charged with advancing the gravity wave research agenda, and that one subgroup be established to merge mesoscale, gravity wave, and middle atmosphere interests to plan, propose, execute, and analyse the data from gravity wave field programmes to improve our understanding of gravity wave sources and gravity wave behaviour in the atmosphere. Another continuing sub-group should facilitate communication between middle atmosphere modelling groups to plan and execute numerical experiments that will lead to better gravity wave parameterizations in global models.

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Future SPARC and SPARC-related Meetings

2007

14-18 January: 87th Annual Meeting, San Antonio, Texas, USA
*** 19th Conference on Climate Variability and Change,**
*** 11th Conference on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface (IOAS-AOLS),**
*** 11th Symposium on Meteorological Observation and Instrumentation,**
*** Ninth Conference on Atmospheric Chemistry**
http://www.ametsoc.org/meet/annual/index.html

12-16 February: 3rd WGNE Workshop on Systematic Errors in Climate and NWP Models, San Fancisco, CA, USA
http://www-pcmdi.llnl.gov/wgne2007/

15-20 April: EGU General Assembly, Vienna, Austria; http://meetings.copernicus.org/egu2007/

22-25 May: AGU Joint Assembly, Acapulco, Mexico; http://www.agu.org/meetings/ja07/

25-29 June : CCMVal Workshop, University of Leeds, Leeds, UK; http://www.see.leeds.ac.uk

25–29 June: AMS 16th Conference on Atmospheric and Oceanic Fluid Dynamics, Santa Fe, New Mexico, USA
http://www.ametsoc.org/meet/fainst/200716Fluid.html

2–13 July: XXIV IUGG General Assembly, Perugia, Italy; http://www.iugg2007perugia.it

20–24 August: AMS 14th Conference on the Middle Atmosphere, Portland, Oregon; USA
http://www.ametsoc.org/meet/meetinfo.html

27 -31 August: Second International Conference on Earth System Modelling, Max Planck Institute for Meteorology Hamburg, Germany; http://www.mpimet.mpg.de/fileadmin/static/icesm/

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