SPARC

STRATOSPHERIC PROCESSES AND THEIR ROLE IN CLIMATE

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Report on the 31st Session of the Joint Scientific Committee of the World Climate Research Programme

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The 31st Session of the WCRP Joint Scientific Committee was held on 15-19 February 2010 in Antalya, Turkey, supported by the Turkish State Meteorological Service (TSMS). The WMO Permanent Representative of Turkey and Director-General of TSMS, **Mehmet Çağlar**, welcomed the participants to Turkey and Antalya. Attending on behalf of SPARC were the co-chairs, Thomas Peter and Ted Shepherd. The JSC Chair, **Anthony Busalacchi**, opened the session and noted that the meeting would focus on two major items, the WCRP visioning and the role of climate research in support of climate service. A joint session of JSC with the WMO Commission for Climatology (CCl) took place on Thursday, 18 February 2010.

A. Busalacchi acknowledged the important contributions of WCRP scientists to the World Climate Conference-3 and OceanObs'09, as well as major activities in the past year with respect to regional climate downscaling, modeling coordination and climate research in general. The vision for WCRP post-2013 would be strongly influenced by the evolution of climate science in the past decades, he said, but the future would demand more flexibility and agility to respond to stakeholder demands and the needs of society. A. Busalacchi shared his personal perspective on topics that would demand research advances from WCRP in the future. These included, among others, decadal predictability and variability, projections of future precipitation, probability of extreme events, sea ice and ice-sheet modeling, seasonal forecasting of the Arctic, aerosols and climate services.

Ghassem Asrar, Director of the WCRP, reviewed major events supported by the WCRP since the previous JSC session, including the joint GEWEX/IGBP iLEAPS Conference hosted by Australia. Cross-cutting activities have made significant progress in the last year and also the World Bank sponsored project for the Greater Horn of Africa countries will hold its first workshop in April 2010. Two important publications were the Achievements Report and the Intermediate Implementation Plan, which are currently being translated into French, Chinese, Spanish and Russian through the greatly appreciated initiatives of JSC members. G. Asrar presented an overview of the income and expenditures for the programme, noting that there had been a significant improvement in the financial status of the Programme and hence in its ability to support activities. He thanked the sponsors for their continuing confidence in WCRP.

WCRP Visioning

David Griggs gave a brief introduction to the WCRP visioning process, recalling the agreement at last year's JSC session that the way in which WCRP could most effectively carry out its activities would be if the structure was constructed along interdisciplinary scientific lines. It was proposed that the general structure of four Core Projects be retained but with revised responsibilities to facilitate climate system research at the interface of the physical Earth system components, *i.e.*, the WCRP overall activities would be based on four fundamental interactions of the physical climate system: ocean-atmosphere, land-atmosphere, cryosphere, and stratosphere-troposphere. Core Projects or similar structural elements would continue to be the main bodies through which WCRP would carry out its work program. In order to achieve this, each Core Project would be supported by an international coordination Project Office. It was agreed that within each of the four Core Projects there exist a common set of basic themes, namely: observations and analysis; model development, evaluation and experiments; process understanding; and applications and services. Members of the JSC and the community had been identified to write white papers on each of these themes, with an additional paper on capacity building, and these were presented next.

Process studies

Jochem Marotzke spoke about "processes". Understanding of processes underlies most of WCRP research and hence in discussing how to proceed, it was useful to classify these processes into three categories, namely:

1. processes underlying phenomena (*e.g.* East Asian monsoon),
2. ubiquitous processes (*e.g.* ocean diapycnal mixing), and
3. processes studied for testing parameterizations (*e.g.* cumulus convection).

The first category is usually regional in focus and its governance should therefore lie within the Core Projects. The second category would be well served within the Core Projects, too, but the challenge in both categories is how to organize studies of processes spanning several earth system domains. The third category requires engagement of and coordination amongst two very different communities, namely the observations and small-scale modeling communities, to develop and improve models. It was remarked that there exists a disconnect between small-scale process studies and global modeling, and that it was not clear how best to organize WCRP to make these interactions occur.

Observations, reanalysis

A key issue noted by **Kevin Trenberth**, is that most of the observations needed for climate research are not done by WCRP. He elaborated on three categories of observations, namely those from process studies, sustained observations, and enhanced monitoring, each with their own stewardship issues.

The role of WCRP *vis-à-vis* observations could be summarized as follows:

- Advocate improved observations and analysis
- Data set development
- Data assimilation and analysis
- Advice on best data sets
- Data sets for use in evaluating climate models
- Promote sound data stewardship
- Help to make data accessible and available.

Kevin Trenberth also advocated providing "operational attribution" through numerical experimentation in real time (*e.g.* to allow reliable statements on why the climate is the way it is and mechanisms involved). All of these activities necessitated a "climate information system". There was a call for WCRP to coordinate the distribution of *in situ* and satellite observations to the modeling community and it was suggested that WOAP might play this role. A reflection was made that there does not exist a climate observations community that parallels the modeling community and hence this is a challenging undertaking. It was pointed out that successful WCRP projects do bring together process studies, observations and models, such as the CFMIP, and hence there are precedents on which to build. It was remarked that a lot of WCRP research involves designing and building prototypes of next generation observing systems and/or identifying the necessary improvements of the existing networks, thus every effort should be made to maintain such activities.

A breakout group analyzed the WCRP roles *vis-à-vis* observations and noted that there was a need to communicate to GCOS, WMO, institutions making observations and others, the observational requirements for climate research. There was also a need to advocate and advise on data standards, ensure data availability, work to sustain existing systems and identify new data needs. Data analysis and validation and data availability for applications were also issues. The group recommended that existing structures be maintained to supervise disciplinary data stewardship (OOPC, AOPC, *etc*.), and that a pan-WCRP working group be formed to manage interdisciplinary data issues and to oversee broader data management issues.

There are many ongoing reanalysis activities but coordination amongst them is insufficient. Too few people are evaluating the reanalysis products. There is also a problem with continuity since most of the reanalyses are done in the research domain, and key personnel are lost when a particular effort is terminated. A reanalysis conference will be held in 2012 in the USA, cosponsored by NOAA and NASA. A grand science challenge could be coupled reanalysis. A task force could be required to make plans, for instance for a reanalysis intercomparison that would bring together the various communities working on reanalyses to evaluate the current state of reanalysis and to take into account land, ocean, troposphere, stratosphere, chemistry, ecosystems, etc.

In the near term, there is a need to catalyze interactions between the observations and modeling communities, including interactions with external organizations such as GEO and GCOS. It was also decided that an Observations and Analysis Council should be formed to make recommendations to JSC and that this Council would supersede WOAP.

Modeling

The authors of the white paper on modeling suggested that the key role for WCRP is to develop an integrating strategy for climate modeling that also connects models with observations and process studies. **Gregory Flato** outlined four major activities in this area:

- Promoting the confrontation of models with observations and results of process studies;
- Promoting collaboration amongst various climate science communities (includes numerical weather prediction (NWP), seasonal to interannual prediction and climate projection communities as well as those dealing with biogeochemistry, air quality, terrestrial ecology, *etc*.);
- Promoting application of models to problems of societal relevance, quantifying uncertainties and making sure they are well communicated and understood;
- Promoting the development of model improvements.

There was considerable discussion both about the function and form of the WCRP modeling efforts. In terms of organization, the authors recommended that well established panels and working groups should be maintained. It was emphasized that the WCRP modeling infrastructure should be flexible to allow focusing efforts where they were most needed, for instance for applications. There was a need to include in the framework a means to exchange learning at fine scales to determine if parameterization was the correct approach or whether these fine-scale processes needed to be resolved in climate models. The sense was that the time was right for a systematic study of the role of horizontal and vertical resolution in climate models. Model evaluation and quality assessment were also important roles for WCRP. CMIP5 would provide an ideal opportunity to assess how to best combine and evaluate these models. It was noted that confronting models with observations would be a first step in this direction.

The main recommendation from the discussion and a breakout session was the formation of a Modeling Council that would be a coordination mechanism for various WCRP modeling groups, WGCM, WGSIP and WGNE, with strong participation of JSC. The Council could meet at JSC sessions, and would make recommendations to the JSC.

Applications

Carolina Vera presented some major themes for WCRP in support of applications. These included:

- Addressing science needs for delivering more reliable predictions on all timescales,
- Provision of timely and reliable forecasts of the likelihood of hazardous weather and climate, requiring interaction between the weather and climate communities,
- Promoting more research and investment into higher resolution models,
- Exploring new forecast variables and providing more flexible formats,
- Improving communication, for instance of uncertainties, by putting information in context, and in clear language, and
- Promoting partnerships to develop meaningful two-way and sustained communication with user communities.

The WCRP should also address the need for a new generation of researchers that can conceptualize, develop and implement research that bridges the gap between science and applications. C. Vera noted that this theme depends on all other themes, involves the Core Projects, and that the scope of applications that WCRP research must support should be defined in parallel with the conceptual development of the Global Framework for Climate Services (GFCS).

Capacity building

Hasan Virji, Director of START, remarked that there seemed to be a clear consensus that WCRP should be involved in capacity building and that this was an underlying theme for all the other themes. However, most of the workshops/trainings that WCRP had co-sponsored in the past, for instance with START, had been “one-off’. H. Virji proposed that JSC reflect on how to address all capacity building requirements and include consideration of other strategic partnerships in addition to START.

A breakout group on capacity building felt that the WCRP role was to identify needs and advocate the importance of raising the capacity/capability to continue to undertake climate research, prediction and services. Two different categories of requirements existed: qualified people in the developed world, and institutional capacity in countries that cannot develop it themselves. WCRP should build on existing entities within WMO/IOC/ICSU and networks such as START and focus on creating the scientific community we need for the future. Model development and computational science were critical areas. Capacity building was the key to the success of climate services and the GFCS should take this into account. The JSC decided to develop a long-term plan of sustained WCRP capacity building activities.

Grand Challenges

Two parallel break-out groups were formed to discuss how the concept of grand challenges would fit within the proposed overall structure of WCRP, what would be their nature and how they would be selected. It was generally agreed that a grand challenge (GC) would be defined as a burning issue or barrier to progress in climate research. Implementation would involve multiple projects and/or other programmes, but an outstanding issue is the extent to which the projects would take the lead in corresponding implementation activities or whether a separate dedicated steering committee would be formed.

Initial discussions had suggested a limited lifetime for GCs of three to five years, but issues were raised as to whether this was realistic, both in terms of being able to accomplish something concrete and in terms of what would attract funding agencies to commit significant resources. Some expressed the view that climate science was moving so fast that we shouldn’t create very large long-term projects as in the past (*e.g.* TOGA or WOCE), but rather focus on shorter timescale efforts that target more specific problems of scientific, but also societal, interest.

The issue of how to select grand challenges was discussed in detail. JSC could define the issue itself, or consider suggestions submitted via white papers from the community. Once a GC had been adopted by the JSC, town hall meetings and workshops should be held to build community support, develop plans and seek funding. The Open Science Conference in 2011 could be a platform for identifying GCs. Rapid sea-ice loss could be seen as an example of GC, based on the white paper that had been presented to and endorsed by this JSC session.

WCRP future function and structure

David Griggs summarized the discussions on WCRP future function and form as follows. There would be four Core Projects working at the interfaces between the physical climate system components as agreed in Maryland. Modelling and Observations Councils would be formed to provide leadership and coordination and would report to the JSC. These Councils would not carry out activities of their own but would include representatives from the Core Projects and relevant external organizations to enable activities to be co-ordinated across the Core Projects. Councils would generally work electronically with the potential to meet for one day immediately preceding JSC meetings. While it was agreed that the idea of WCRP bringing the international scientific community together to carry out a major scientific push to address a major or grand challenge of climate science was very attractive, no decision was made pending further discussion on how these could be implemented in practice. The role of crosscuts would need to be revisited. The JSC requested the current Core Projects to consider the implications of the decisions made on future structure and come back to the next JSC with views on the implications of these decisions on the sub-structure of the Core Projects within the new structure.

WCRP Open Science Conference

Ghassem Asrar reported that the WCRP Open Science Conference (OSC) is scheduled for 24-28 October 2011 at the Sheraton Hotel in Denver, Colorado, USA. A web site is operational (**www.wcrp-climate.org/conference2011**) and a first announcement has been published. The aim is to assemble most of the WCRP research community and also to engage other key international programmes. The OSC would provide an exclusive opportunity for exchange and collaboration across diverse research communities (*e.g.* WCRP, WWRP, IGBP, and IHDP). At least 1500 participants are anticipated. The main motivations for the Conference include appraising the current state of science, identifying the most urgent scientific issues, ascertaining how WCRP can best facilitate this research, developing partnerships critical to progress in the context of the fast-emerging GFCS, and facilitating growth of the diverse workforce needed for the future. This Newsletter contains an announcement of the OSC.

Partner Presentations

Representatives of several agencies and programmes made presentations to the JSC and elaborated on how WCRP could support partner programme goals. These included the IPCC Working Groups I and II, IGBP, Earth System Science Partnership, WMO Commission for Atmospheric Sciences, GCOS, European Space Agency speaking on behalf of the Committee on Earth Observation Satellites, Group on Earth Observations, and the Integrated Research on Disaster Risk (IRDR) project. In particular, speaking on behalf of IPCC WG I Dr Stocker noted that WCRP was the most important group contributing to WG I in the past and that a lot was expected of WCRP for the next assessment. Specific areas of research that would make invaluable contributions might include:

- clouds and aerosols – processes and sensitivities,
- decadal prediction – evaluation and verification,
- multi-model ensembles using earth system models,
- regional climate change – detection and attribution and projections,
- sea level rise and ice sheet instabilities, and
- geoengineering – assessment of physical basis.

Sponsor highlights

Kari Raivio of ICSU reviewed the decision of the 29th ICSU General Assembly that led the way for the ICSU visioning exercise with the goal to engage the scientific community in exploring options and proposing implementation steps for a holistic strategy of Earth system research. **Luis Valdes** of IOC reviewed the very successful OceanObs'09 conference, which was supported by WCRP, and identified several aspects of WCRP research that were of particular interest to IOC Members. **Avinash Tyagi**, Director of the WMO Climate and Water Department, focused on the outcomes of the World Climate Conference – 3 (WCC3) held in Geneva on 31 August – 4 September 2009. He lauded the very high level of participation of WCRP scientists in the WCC3 Expert Segment that had recommended, inter alia, a strengthening of both GCOS and the WCRP in support of a GFCS. The High Level segment agreed to establish a GFCS to strengthen production, availability, delivery and application of science-based climate prediction and services and called for the formation of an independent High Level Task Force (HLTF) that would, after consultation with governments, partner organizations and relevant stakeholders, prepare a report, including recommendations on proposed elements of the Framework. In the discussion, a concern was expressed as to the mechanism for technical/scientific input to the GFCS HLTF. Despite the fact that the Conference declaration implies that the HLTF should deal with technical issues, there was limited climate science representation on the HLTF. A panel discussion on GFCS and the need for a mechanism, by which science requirements could be effectively fed into the process of defining the "Framework", ensued.

National Climate Services

The Chair introduced this topic, noting that many nations were in the early stages of formulating plans for climate services, but that it was important for JSC to hear their current or anticipated requirements from WCRP. JSC Members and meeting participants summarized in their presentations the status and development of climate services in Germany, USA, France, UK, Japan, and Canada. **Adrian Simmons** also made a brief presentation on the European Global Monitoring for Environment and Security (GMES) atmospheric environmental services. It was noted that each of the nations who presented had quite different approaches to climate services and that while some were more academic, others were based purely on operations.

A breakout group on climate information and services suggested that the WCRP should partner with institutions and projects such as IRDR, environmental agencies and START to achieve an effective dialogue with users to help drive the research priorities. WCRP should promote multi-model ensembles (MMEs) and research into how to use them. WCRP could act as coordinator across national climate services with respect to this topic. A key issue would be to manage expectations. In this respect it was important to remember that climate services are now where numerical weather prediction was 20-30 years ago. WCRP had a responsibility to communicate the credibility and skill of predictions that underpin services and promote research needed to do this better. It was noted that the best way for WCRP to engage was through national programmes and defining good measures of credibility and skill. There was also a need to recognize the diversity of delivery mechanisms. In the result JSC decided to establish a working group on science underpinning climate services.

Core Project and Working Groups Reports

A full day of the Session was devoted to reports of and discussion on activities by the WCRP Core Projects and other working bodies: SPARC, CLIVAR, CliC, GEWEX, Anthropogenic Climate Change Crosscutting Activity, Task Force on Regional Climate Downscaling (TFRCD), Working Group on Coupled Modeling (WGCM), Working Group on Numerical Experimentation (WGNE), WCRP Observations and Assimilation Panel (WOAP). Only issues of high relevance for SPARC are briefly summarized in this report.

A proposal had been put forward by WGCM for coordinated geoengineering experiments with stratospheric aerosols. There was a demonstration project, not officially part of CMIP5, conducted by a few modeling groups. Issues of particular interest included:

- Robustness of model responses to geoengineering;
- Response of the hydrological cycle;
- Response to stopping geoengineering after a few decades.

A discussion took place on observational data for model evaluation. CCMVal was noted as a good example of selecting a small subset of existing data, but for other data sets the questions remained as to which ones to select and on what basis. Besides existing data, it would be desirable to interact with space agencies to produce products/data sets that would be more suitable to compare with models. Another concern was which data sets would be used to validate the geoengineering models. A first test could be whether models correctly depicted the thermal and hydrological response to volcanoes. WGCM was recommended to work with SPARC and other projects on these issues. It was noted that climate modelers do evaluate their models by comparing with observations, and that the real challenge is not introducing metrics, but coordinating them so that they use a common means of model evaluation.

The WGNE model development effort currently involved only GEWEX, but the Group expects to widen activities on a need basis. SPARC had requested a seat at the table to bring their expertise. A major concern was the dwindling number of model developers. A WCRP community-wide consultation on model evaluation and improvement had been organized via a questionnaire. Over 100 independent responses were received from numerical weather prediction, seasonal, decadal and climate change scientists. The results were being analyzed and a workshop would be held in early 2011 to define 4-5 key areas for model development based on the survey results and to draw up an implementation plan.

SPARC report and discussion

Ted Shepherd noted that SPARC is organized along major themes with no specific associated panel structure. There are seven main activities, of which CCMVal (chemistry climate model validation) is the largest. A comprehensive peer-reviewed CCMVal report has recently been completed. It will provide critical input to the 2010 WMO/UNEP Ozone Assessment. One result of this analysis is that ranking and weighting of models is not possible in a defensible way. A super-recovery of stratospheric ozone is projected by the end of 21st century. A better assessment of uncertainties through statistical methods was carried out. A SPARC data initiative was motivated by the CCMVal report. It would include collection and some basic analysis of available chemical datasets, working closely with measurement scientists. SPARC is well represented on WCRP modeling groups (WGCM, WGSIP), but needs to be better represented on WGNE. A workshop on polar predictability on seasonal to multi-decadal timescales involving other WCRP Core Projects is planned for autumn 2010.

Thomas Peter reported that there is a risk of losing the ability to obtain ozone vertical profiles suitable for detection of long-term changes with the demise of SAGE II. This needed to be addressed if ozone recovery was to be tracked; ground based networks have improved but are not sufficiently good for the stratosphere. The Atmospheric Chemistry and Climate cross cut (AC&C) is being carried out with IGBP/IGAC. Phase I has focused on modeling but also on black carbon which is an issue for climate and air quality. First results are expected in a year. SPARC is also addressing the aerosol aspect of geoengineering. A report on stratospheric aerosol properties was issued in 2006 and a 2009 workshop on volcanoes compared geoengineering and volcanic aerosols and found that previous estimates of geoengeneering aerosol optical properties were much too optimistic. This finding greatly reduces estimates of radiative cooling by geoengineered particles.

A major concern for the immediate future is continued support for the International SPARC Office. Concerning the interaction with IGAC, the two projects had much in common and want to continue in close collaboration, but also have distinct foci and do not need to be merged. SPARC intends to expand its activities into stratosphere/troposphere interactions.

The SPARC work on aerosols was welcomed by JSC but it was noted that there are other activities on this topic within WCRP that should be coordinated. Similarly, WGCM is discussing experiments related to geoengineering and this should be coordinated with SPARC. The representative from IGBP reemphasized IGBP's desire to work together on this topic. It was suggested that WCRP could issue a short summary of the status of research on aerosols and geoengineering on a regular basis. Polar climate predictability was noted as a cross-WCRP (and WWRP) topic of interest. The question was raised as to whether AC&C was really a WCRP cross cut since most of the activity seemed to involve SPARC and IGAC and not the other WCRP projects and that perhaps this should be reviewed, especially with regard to the link to GEWEX. There was some discussion as to whether the CCMVal results should be synthesized in ensembles; it was noted that construction and interpretation of ensembles was a research challenge for all of WCRP.

Joint CCl-WCRP Session

Thursday 18 February 2010 was devoted to a session jointly organized by the WMO CCl and the WCRP. Presentations focused on observational and modeling research needs to improve seasonal to interannual predictions and research requirements for enhancing the use of climate information in impact, adaptation and mitigation studies. A joint statement on enhancing the use of climate information was agreed at the end of the session (**http://wcrp.wmo.int/documents/Resolution_CCl_WCRP_2010.pdf**).

JSC closure and the next meeting

The next JSC session will be held at the UK Met Office in Exeter, UK from April 4-8, 2011. The Chair closed the 31st session with expressions of appreciation to participants and special thanks to outgoing JSC members Guoxiong Wu and Venkatachalam Ramaswamy and retiring ICPO director, Howard Cattle.

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SPARC Report on the Evaluation of Chemistry Climate Models

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Three-dimensional climate models with a fully interactive representation of stratospheric ozone chemistry — otherwise known as stratosphere-resolving chemistry-climate models (CCMs) — are key tools for the attribution and prediction of stratospheric ozone changes arising from the combined effects of changes in the amounts of greenhouse gases (GHG) and ozone-depleting substances (ODS). These models can also be used to infer potential effects of stratospheric changes on the climate of the troposphere. In order to know how much confidence can be placed in the results from the CCMs, both individually and collectively, it is necessary to assess their performance by comparison with observations and known physical constraints. SPARC initiated the CCM Validation (CCMVal) activity in 2003 to coordinate exactly such an evaluation. The first round of CCMVal (CCMVal-1) evaluated only a limited set of key processes in the CCMs, focusing mainly on dynamics and transport. The second round of CCMVal (CCMVal-2) represents a more complete effort by the community to assess CCM performance, and is described in a recently published SPARC Report on the Evaluation of Chemistry-Climate Models. A key aspect of the model evaluation within the SPARC Report is the application of observationally-based performance metrics to quantify the ability of models to reproduce key processes for stratospheric ozone and its impact on climate. The Report is targeted at a variety of users, including: (1) international climate science assessments, including the WMO/UNEP Ozone Assessments and the IPCC Assessment Reports; (2) the CCM groups themselves; (3) users of CCM simulations; (4) measurement and process scientists who wish to help improve CCM evaluation; (5) space agencies and other bodies involved in the Global Climate Observing System.

The SPARC Report was prepared by dozens of scientists and underwent several revisions and extensive peer review, culminating in a Final Review Meeting in Toledo, Spain on November 9-11, 2009. The overall key findings and recommendations from the Report are reproduced below. (Detailed Key Findings and Recommendations by Chapter are included in the full Executive Summary which is available as part of the Report.)

Overall Key Findings

- Comprehensive process-oriented validation has led to a much better understanding of the strengths and weaknesses of CCMs. As well as identifying unphysical behaviour (*e.g.*, dehydration properties), this has led to a more precise understanding of the processes involved in CCM simulations and the connections between them. This can be used to understand some of the spread in model predictions, and will help focus model improvements.
- CCMVal-2 has provided a much more detailed assessment of model performance than CCMVal-1. For the first time, chemical and radiative processes in the CCMs have been assessed, and the upper troposphere / lower stratosphere (UTLS) has been explicitly examined. Radiation schemes have been found to be sufficient for representing the major causes of observed temperature changes in the stratosphere and the main radiative drivers of surface climate. Chemistry schemes are generally found to agree with benchmark schemes, while exceptions have been identified. Model performance in the UTLS was found to be better than might have been expected based on the spatial resolution of the models.
- The identification of model deficiencies in CCMVal-1 led to quantifiable improvements in particular models (*e.g.*, transport, Cly abundance, and tropical tropopause temperatures). CCMVal-2 has benefited from the greater number of participating models and the larger number of processes represented in those models. However, this complicates a quantitative assessment of overall model improvement between CCMVal-1 and CCMVal-2 in those diagnostics assessed by CCMVal-1.
- Compared with WRCP Coupled Model Intercomparison Project phase 3 (CMIP3) simulations, CCMVal-2 simulations have a mean stratospheric climate and variability that is much closer to that observed. In the troposphere, mean climate and synoptic variability are similarly close to the observations in both groups of simulations, while interannual variability tends to be better simulated by the CCMVal models.
- Common systematic errors in CCM results include: tropical lower stratospheric temperature, water vapour, and transport; response to volcanic eruptions; details of the Antarctic polar vortex and the ozone hole; lower stratospheric Cly; a wide variation in values of surface area density of sulphate aerosols.
- Another systematic error in CCMs concerns the representation of the quasi-biennial oscillation (QBO), which is a dominant mode of natural stratospheric variability. Most of the current models do not simulate a QBO, and the representation of the QBO in models remains a challenge. For comparison with past observations, some modelling groups therefore choose to relax tropical winds towards observed values. This technique is fully successful in reproducing the phase of the observed QBO signal in ozone, but not its amplitude.
- Models that represent solar variability only in terms of total solar irradiance cannot properly simulate the effect of solar variability on radiative heating rates, stratospheric temperature and ozone. A spectrally resolved treatment of solar variability is required.
- Use of simulations extending through the entire period of ozone depletion and recovery (1960-2100) in CCMVal-2 has allowed a more accurate estimate of the projected long-term changes in the stratosphere and the relative contributions of ODSs and GHGs to those changes, compared with CCMVal-1. This, plus the increased number of contributing models, has reduced the statistical uncertainty in the projected future ozone changes under the scenario considered.
- The multi-model trend estimates of past ozone changes are consistent with the

observed changes. Compared with CCMVal-1, the availability of model simulations from 1960 onwards together with a more robust statistical analysis has provided a more reliable estimate of the long-term ozone changes in the models.

- Widespread use of simulations beginning in 1960 has revealed that models consistently show substantial ODS-induced ozone depletion prior to 1980, especially in the SH.
- Models consistently predict an increase in tropical tropopause height and a slight warming of the tropical tropopause due to climate change. As a result, the entry value of stratospheric water vapour is predicted to increase in the future, although the magnitude of this increase is uncertain.
- Models consistently predict a strengthening of the Brewer-Dobson circulation and a decrease in mean age of air as a result of climate change, but they disagree on the relative role of resolved and parameterised wave drag.
- Models consistently predict the following changes in ozone:
  - o a partial recovery of tropical ozone followed by a decrease in the second half of the 21st century, such that tropical column ozone is predicted not even to return to 1980s values within this century; the long-term decrease is mainly found in the lower stratosphere
  - o a steady increase in NH mid-latitude and polar ozone, such that 1980s values are exceeded well before halogens return to 1980s values
  - o a slow recovery of SH mid-latitude and polar ozone, with mid-latitude ozone returning to 1980 values slightly before halogens do, and polar ozone returning roughly in line with halogens
- Major contributors to these changes include the recovery of ozone from ODS, the strengthened Brewer-Dobson circulation, and the cooling of the upper stratosphere.
- Although Antarctic ozone is expected to recover during the 21st century, a residual intermittent ozone hole may still occur at the end of the century.
- Both models and observations indicate that Antarctic stratospheric ozone loss, together with increasing GHG concentrations, has led to a poleward shift and strengthening of the SH westerly tropospheric jet during summer. CCMVal-2 models project that in the 21st century ozone recovery will largely offset the effects of increasing GHG concentrations, so that the position of the tropospheric jet will not change significantly.
- The strengthened Brewer-Dobson circulation leads to an increased stratospheric ozone flux into the NH troposphere of ~20% between 1965 and 2095. In the SH, the change is modulated by ozone depletion and recovery, and is smaller (~10%) due to the smaller predicted change in the Brewer-Dobson circulation in that hemisphere. The model range is smaller than that obtained from tropospheric models used for the IPCC assessment, which may be attributable to a more self-consistent and comprehensive representation of the stratosphere in the CCMs.
- Stratosphere-resolving CCMs continue to evolve towards more comprehensive, self-consistent stratosphere-troposphere CCMs. In this round of CCMVal, one model was coupled to an interactive ocean, while three models included comprehensive tropospheric chemistry. These developments provide a pathway for including a better representation of stratosphere-troposphere and chemistry-climate coupling in Earth System models used for ozone and climate assessments.

Overall Recommendations

- CCM simulations of ozone depletion/recovery should be performed seamlessly over the entire 1960-2100 period, with consistent forcings, and with data produced in a standard format to allow for multi-model inter-comparison.
- A range of different scenarios should be simulated (*e.g.*, fixed GHG, fixed ODS, different GHG projections) to allow correct attribution of the predicted changes and an understanding of the sensitivity to the scenario employed.
- Models should routinely undergo tests concerning their implementation of physical processes where benchmark comparisons are available. This is especially the case for chemistry and radiation (*e.g.*, line-by-line comparisons, PhotoComp). In the case of radiation, such comparison is facilitated if the CCM radiation codes can be run in a stand-alone offline form.
- Metrics of model performance on a wide suite of diagnostics need to be made as standard practice and calculated routinely by individual model groups and through multi-model comparisons. More analysis is needed of the robustness of the application and interpretation of metrics, and their possible use to assign relative weights to ozone projections.
- More attention needs to be paid to model development to address major persistent deficiencies, *e.g.*, the late-spring breakdown of the Antarctic vortex, and simulations of the Antarctic ozone hole.
- Long-term vertically resolved data sets of constituent observations in the stratosphere are required to assess model behaviour and test model predictions. This includes ozone, but also other species that can be used to diagnose transport and chemistry. The current set of GCOS Essential Climate Variables is not sufficient for process-oriented validation of CCMs.
- More global vertically resolved observations are required, particularly in the UTLS. As CCMs evolve towards including tropospheric chemistry, lack of observations in this region will become a major limitation on model validation.
- A systematic comparison of existing observations is required in order to underpin future model evaluation efforts, by providing a more accurate assessment of measurement uncertainties.
- CCMs should use self-consistent formulations with the appropriate conservation properties (*e.g.*, primitive-equations dynamics, self-consistent treatment of chemistry, a unified treatment of photolysis and short-wave heating, a prognostic water vapour field, momentum-conserving gravity-wave drag).
- Development should continue towards comprehensive troposphere-stratosphere CCMs, which include an interactive ocean, tropospheric chemistry, a naturally occurring QBO, spectrally resolved solar irradiance, and a fully resolved stratosphere.
- The CCMVal assessment and projection process should be synchronized with that of CMIP to make the maximum use of human and computer resources, and to allow time for model improvements.

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The Extratropical UTLS: Observations, Concepts and Future Directions

Community workshop at the National Center for Atmospheric Research, 19-22 October 2009, Boulder, USA

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Introduction

An international community workshop focused on the extratropical upper troposphere – lower stratosphere (UTLS) was held in Boulder, Colorado in October 2009, sponsored by the US National Science Foundation and SPARC/WCRP. The UTLS has been a key research focus of SPARC and its collaborations with IGAC, and the Boulder 2009 workshop follows two previous SPARC-sponsored workshops in Bad Tölz (2000) (Haynes and Sheperd, 2001) and Mainz (2005) (Law *et al*., 2005). The Boulder workshop was organized in recognition of significant ongoing progress in the UTLS research community, including a wealth of new observational data focused on the extratropical UTLS (especially chemical measurements). These include data from recent research aircraft campaigns (including SPURT and START08) and in-service aircraft (MOZAIC, CARIBIC and CONTRAIL), combined with satellite, balloon and ground-based observations. In addition many global models (including models contributing to the SPARC CCMVal effort) now include a well-resolved UTLS region, so that there are renewed efforts at comparing models with observations, and improving representation of modelled physical processes in this region. Furthermore, while the UTLS has long been recognized as a key region for understanding global ozone, it is now appreciated as highly relevant for climate variability and change, so that detailed understanding and accurate modelling of the UTLS is important to a wide scientific audience. Accordingly, the Boulder workshop aimed at an updated evaluation of the state-of-the-art for observations, modelling and process understanding for the extratropical UTLS.

The Boulder workshop was attended by over 90 scientists (**Figure 1**, colour plate I), covering four days of invited overview talks, plus numerous contributed presentations and posters. A web site for the workshop (**http://www.acd.ucar.edu/utls/workshop.shtml**) includes the detailed schedule, and the archived presentations of most talks and posters. The workshop included an hour at the beginning of each day to review the highlights and discussions from the previous sessions, assembled by groups of raporteurs. Key activities included summarizing current understanding and key uncertainties regarding the UTLS, and pinpointing future research needs.

The workshop was divided into 5 interlinked sessions. It began with a session on (1) tropopause structure and dynamics, followed by (2) the chemical composition of the UTLS, (3) UTLS transport, (4) convection and microphysics in the UTLS and finally (5) long term variability and trends. The final half-day included an overall summary session, with discussion of future proposed observations and observing needs. This summary includes references to many presentations in the workshop (referenced by lead author, without a date), while references with a date refer to published work (cited at the end).

Session 1: UTLS and Tropopause Dynamical Structure

This session focused on various aspects of dynamical behavior of the UTLS and tropopause region, including new observations and modeling studies. Much current work is focused on quantifying specific dynamical aspects of the UTLS, including the tropopause inversion layer (TIL), double tropopauses (DT) and the extratropical tropopause transition layer (ExTL), with overall goals of 1) understanding these structures in the context of synoptic meteorological variability, 2) the relationships of dynamical and chemical transitions across the tropopause, and 3) their seasonal and latitudinal behavior. In particular, the global structure of static stability, structure of the TIL, connections between the TIL and the ExTL, global scale occurrence of the DT and relation to dynamical intrusions, and possible relationships between the DT and the TIL are topics of current investigation. The emerging picture is that there are connections among dynamical structures (TIL, ExTL, DT, *etc*.) and links between dynamical and chemical behavior, although the responsible mechanisms continue to be identified.

One focus in this workshop was the observational characterization of the TIL, using high vertical resolution radiosondes, aircraft measurements and GPS radio occultation data. GPS data provide characterization of the global behavior of the TIL, with new results highlighting the large-scale seasonally-varying structure of the tropical TIL, and polar TIL variability linked to stratospheric warming events (Grise *et al*., 2010). Comparisons with vertical profiles from MOZAIC aircraft data reveal good agreement with GPS measurements, and furthermore highlight sharp discontinuities in chemical tracers (O_3, CO, and H2O) linked to the thermal tropopause (Schmidt *et al*.). The high density of COSMIC GPS data also allows analysis of synoptic TIL behavior, revealing characteristic links to jet structure, Tandon *et al*. (**Figure 2**, colour plate I). The strongest climatological TIL occurs during polar summer, with a high degree of symmetry between hemispheres; Randel and Wu proposed this behavior is linked to the strong radiative effects of water vapor near the tropopause, which exhibits a strong summertime polar maximum. One novel analysis of tropopause structure using a curve-fitting algorithm to define transition layer depth (Homeyer *et al*., 2010) categorized the midlatitude tropopause as a function of transition depth. The presence of a TIL is associated with a narrow transition layer, which dominates the observed population, while no TIL is evident in the large transition case. Other novel uses of satellite data included evaluation of the space-time structure of DT occurrence frequency using high vertical resolution HIRDLS ozone and temperature measurements (Phillips and Gille), and analysis of global UTLS gravity wave characteristics using the dense sampling of COSMIC GPS data (Wang and Alexander).

Recent modeling work has focused on the evaluation of the ExTL in comprehensive global models (*e.g*. the CCMVal assessment, see summary below), in addition to more idealized studies focused on specific process understanding. Wang and Polvani have used idealized baroclinic wave cycle studies to simulate the conditions of DT formation, finding that DT occurrence is favored when the initial conditions include a strong TIL. However, their idealized model results produce DT for strong cyclonic circulations and cut-off lows, rather than for tropospheric intrusions from low latitudes, as often observed. Understanding dynamical and radiative contributions to TIL formation and maintenance continues to be an active topic. Birner used a global circulation model to quantify forcing of the global tropopause from the stratospheric residual mean circulation and radiative equilibrium calculations. The relationship between the TIL and the chemical mixing layer was examined by Kunz *et al*., (2009) using SPURT observations of UTLS ozone and water vapor and Fixed Dynamical Heating (FDH) calculations. These results demonstrated that enhanced water vapor associated with the mixing layer was a primary cause of high stability above the tropopause (strong TIL), while ozone had relatively minor influence. This finding is consistent with an evolving understanding of a key role for water vapor near the tropopause for formation and maintenance of the TIL.

Summary of CCMVal assessment of the extratropical UTLS

A comprehensive assessment of coupled Chemistry-Climate Models (CCMs) has recently been completed by the CCM Validation Project (CCMVal), and one focused activity involved evaluation of the UTLS behaviour in models. Results are described in detail in SPARC (2010), Gettelman *et al*. (2010) and Hegglin *et al*. (2010). Broadly, CCMs perform reasonably well in the UTLS with respect to the sharp dynamic and tracer gradients, given their coarse resolution. Models are able to simulate a TIL of reasonable magnitude and have distinct tracer gradients and tracer-tracer correlations across the tropopause. Deficiencies in detailed vertical structure arise from coarse resolution, along with possible problems with transport across the sub-tropical jet. Models simulate increases in tropopause height and increases in ozone in the UTLS in the 21st century future scenarios. The tropopause structure is strongly affected by Antarctic ozone depletion and recovery in the Southern Hemisphere, but trends also are predicted in the northern hemisphere. A consensus is that further global-scale observations with high vertical resolution are necessary to better evaluate models. Also, more complete representations of tropospheric chemistry will be valuable for evaluating detailed UTLS transport (which is often based on tropospheric tracers such as CO or shorter-lived hydrocarbons).

Session 2: Structure and Chemical Composition of the ExTL

This session aimed to define and characterize the ExTL and to further explain its role in the chemical, physical and dynamical structure of the extratropical UTLS. Given the complex thermodynamic and chemical structure in this region, there are many different metrics used to define the ExTL. This situation is highlighted by the fact that different vertical coordinate systems, tracer-tracer correlations, and definitions of the tropopause (thermal, dynamical, chemical) are employed in different studies. The most commonly used coordinate system remains "delta Z or delta theta from tropopause", defined using the thermal tropopause, along with O_3-CO correlations. **Figure 3**, colour plate II (from Hegglin *et al*., 2009) illustrates the use of these metrics to quantify the thickness of the ExTL mixing layer. It was noted that results based on other tracers can suggest different position and thickness of this ExTL related to the tropopause altitude, so that details depend on the definition of the tropopause itself (thermal or dynamical), and on the tracer-tracer correlation used. This situation can be partly understood by noting that different tracers are associated with different life times (in terms of sources and sinks in the UTLS), along with differences in transport pathways and time scales, and thus a different 'depth' of the ExTL is expected based on diagnoses with different tracers. Also, the thickness of the mixing layer is broader at high compared to low latitudes (Pisso *et al*.). These details emphasize the difficulty in bringing an integrated view to the broad picture of the ExTL. It is recognized that the transition layer extends on both sides of the tropopause (with a thickness of approximately 2 km on either side). Tracer structure has also been categorized by spatial location with respect to the jet position, showing systematic differences for the poleward (cyclonic) and equatorward (anticyclonic) sides of the jet (Manney *et al*.), or for the east vs. west side of cyclones (Brioude *et al*.). A newer concept is that the chemical transition layer marks a change in transport time from the lower troposphere to the lowermost stratosphere (LMS). Another important aspect is that a strong seasonality exists above the transition layer with "young" air in summer and autumn and rapid "flushing" from late spring to summer (Mackenzie *et al*.). Also, there is evidence for a strong coupling from low latitudes (the TTL and the tropical lower stratosphere) to the extratropics.

Other discussions in this session focused on the use of equivalent latitude coordinates for the UTLS (Pan *et al*.) and new ideas on defining the tropopause in 3D models (Neu *et al*.). Pan *et al*. suggested that while equivalent latitude – theta coordinates are appropriate for describing stratospheric processes, there are limitations for application near the tropopause (because of the non-conservation of PV in this region). Moreover, equivalent latitude coordinates are typically derived from meteorological analyses that have limited resolution compared to other data (aircraft or balloon). Neu *et al*. pointed out the problem that thermal, dynamical, or ozone tropopause definitions cannot simply be used for comparison with numerical simulations. It was proposed to use an "E90" tracer (an artificial tracer with a 90-day time scale) which defines the tropopause as a mixing barrier to better identify the tropopause height in CCMs. This tracer leads to good comparisons of ozone in the extratropics.

Session 3: UTLS Transport and Stratosphere-Troposphere Exchange

The workshop devoted a day to discussion of UTLS transport and Stratosphere-Troposphere Exchange (STE). Key discussions centered around several themes: (1) coupled chemical-dynamical structure of the extratropical tropopause, (2) aircraft observations of tracer correlations and mixing regions around intrusions and jet structures, and (3) the role of gravity waves and small scale processes (including deep convection).

The broad-scale structure of the extratropical tropopause and its behavior as a transport barrier are fundamental aspects of the interaction of baroclinic eddies with the background jet in the troposphere, and this behavior can be simulated in simple dynamical models (Haynes *et al*., 2001; Greenslade and Haynes, 2008). Theories for the existence, height and maintenance of the extratropical tropopause are mature, but not fully unified, and the importance of small-scale processes (gravity waves and convection) is still unclear. More recent work has highlighted the possible importance of moist processes (Frierson, 2008).

A substantial amount of effort has focused on analysis of UTLS chemical observations from recent field campaigns, with efforts to isolate transport pathways and identify mixing processes. Observations from flights during START08 (Pan *et al.*) were used to highlight the detailed structure of tropospheric intrusions, associated with the existence of air with tropospheric characteristics above the extratropical tropopause (**Figure 4**, colour plate 2); this behavior is linked to double tropopauses, potential vorticity gradients and ozone lamina. Back trajectory calculations for the air in the intrusion layer show that this air mass was transported poleward above the subtropical jet (Bowman *et al.*). These features are reasonably well simulated in chemical transport models nudged with high vertical resolution assimilated winds (Stone *et al.*). Tilmes *et al*. (2010) have developed a new seasonal climatology of tracer observations from many research aircraft campaigns (**Figure 5**, colour plate III), and further separate observations according to tropics, subtropics and polar latitudes (based on tropopause altitude). Such data provide critical comparisons for chemical structure of the UTLS in numerical models.

The use of tracer-tracer correlations from in-situ data and simulations is effective at identifying air mass origins and transport pathways, and Vogel *et al*. and Konopka and Pan have extended this concept using Lagrangian (CLaMS) model calculations to quantify the origins of air and the degree of mixing within various regions (focusing on both tropospheric and stratospheric intrusions). Konopka and Pan furthermore quantify the time history of mixing in their calculations, highlighting regions where the mixing was relatively fresh (< 72 hours) or aged (**Figure 6**, colour plate III). Hoor and Wernli used a large ensemble of trajectories to quantify the distributions of transit times (and minimum temperatures) for parcels crossing the tropopause into the extratropical stratosphere (**Figure 7**, colour plate IV), and these results can explain some of the observed differences in the mixing-layer structure of CO *vs*. water vapor. Trajectory studies by James and Legras (including diffusive effects) demonstrated the importance of two-way transport between the TTL and the extratropical lower stratosphere.

There were also discussions of several innovative observational data sets and analysis techniques. The use of tracers with multiple lifetimes with sensitivity to different altitudes (such as N_2O and CFCs) is effective for estimating transport pathways in the stratospheric overworld and 'lifetimes' of air in the UTLS between 1 month and up to several years (Ray *et al.*). Tarasick *et al.* demonstrated the use of radar observations at high latitudes to identify the tropopause and the frequent occurrence of stratospheric intrusions (associated with ozone transport to the upper troposphere). Mullendore *et al*. also highlighted the novel use of radar reflectivity as a proxy for convective detrainment in the UTLS. The important role of the lower levels of the polar vortex (the so-called sub-vortex) for transport to the midlatitude UTLS during late winter and spring was demonstrated using MLS and ACE-FTS satellite observations by Santee *et al*. MLS data were also used to document the occurrence of smoke plumes in the lower stratosphere, which originated with the large Australian wildfires during February 2009 (Massie). These remarkable features are observed at altitudes up to ~20 km, and transport to the stratosphere may be explained as a combination of upward transport within frontal systems combined with in-situ radiative heating of the smoke in the UTLS.

Results were presented from several novel high resolution modeling experiments focused on the UTLS. Miyazaki *et al*. analyzed tropopause structure in a GCM with 300 m vertical resolution (and ~50 km horizontal resolution), demonstrating that strong tracer and PV gradients near the tropopause result from the combined effects of transport, mixing and radiative effects, and they further quantified the importance of resolved small scales (gravity waves) for the mixing in this region. Mizuta and Yoshimura used simulations from an ultra-high horizontal resolution (20 km) global model to investigate the sensitivity of tropopause structure and STE to model resolution. A novel simulation of thunderstorm effects on the UTLS during the North American monsoon, using an extremely high resolution (4 km) WRF-chem model (Barth *et al.*), focused on the importance of convection on upper tropospheric ozone (including direct convective transport of ozone and ozone precursors, plus lightning-generated NO_x).

The importance of gravity waves and deep convection on the extratropical UTLS were topics of several presentations. These processes may become dominant during 'mixing events' associated with intrusions, folds and fronts, when the concept of the tropopause as a transport barrier breaks down. Several presentations focused on gravity waves, generated from topography, convection or midlatitude baroclinic adjustment processes. UTLS gravity waves observed during the START08 experiment (associated with jet-front adjustment processes) show reasonable agreement with simulations from a 5-km WRF simulation (Meng *et al.*). Also, aircraft observations of UTLS mountain waves (Moustaoui *et al.*) show complex effects on tracers (CO and ozone), which can be understood in the context of the coupling of large and small-scale waves. There were discussions that large scale features ('stirring') are well reproduced in current forecast systems (at 25 km resolution or so), and even to some extent in nudged global simulations at 100 km. However, several presentations highlighted that the mixing of chemical constituents down to the molecular level (where chemistry operates) is not being well represented, and this topic is not well understood.

Session 4 : Chemical and Microphysical Distributions

A key theme of this session was the important role of tracers with different lifetimes for deriving quantitative information on the structure of the tropopause region. Correlations of species with different photochemical lifetimes (such as various non-methane hydrocarbons, NMHC's) provides quantative information on the temporal range of tropospheric influence and mixing into the lowermost stratosphere. Examples were presented using correlations of NMHC's during START 08 (**Figure 8**, colour plate IV, Atlas *et al*.) focusing on the transport and mixing related to tropospheric as well as stratospheric intrusions. The potential of these shorter lived compounds in a more climatological context was demonstrated using acetone from regular in-flight measurements during CARIBIC, which showed an important tropospheric influence extending deep into the lowermost stratosphere from summer (June) to late autumn (**Figure 9**, colour plate V, Zahn *et al*.). Details of large-scale transport in the tropopause region were also quantified using a long record of CO_2 observations from the Japanese CONTRAIL project (**Figure 10**, colour plate V, Sawa *et al*.), focusing on propagation of the seasonal CO_2 cycle as a function of distance to the tropopause. The propagation of the CO_2 seasonal signal highlights the importance of subtropical / extratropical coupling at the location of the subtropical tropopause.

Several presentations highlighted the importance of the Asian monsoon anticyclone for transport of water vapor and other species into the LMS during NH summer. A key point is that this transport pathway can bypass the tropical tropopause, and the air in this region has distinct source regions from the deeper tropics (namely highly polluted air originating over Asia, India and Indonesia). Evidence for the importance of this transport pathway comes from recent satellite observations of CO and HCN from MLS and ACE-FTS (**Figure 11**, colour plate VI, Park *et al*). There have been relatively few in situ observations over this region (especially for trace constituents), but some exploratory observations of water vapor and ozone over Kunming (25N, 102E) were presented by Bian *et al*. showing novel and complex behavior. While the Asian monsoon shows clear influence on the lower stratosphere, it is as yet unclear to what extent monsoon circulations over other continents play similar important roles.

One further theme for this session focused on the behavior of UTLS clouds and water vapor. High resolution balloon water vapor observations in middle and high latitudes often reveal complex laminated structure, linked to vortex dynamics or transport from the TTL (Khaykin *et al*.) These observations highlight that an ExTL definition on the basis of water vapor may be confused by polar or subtropical processes, rather than by exchange across the extratropical tropopause. In addition there is evidence that cirrus clouds above the extratropical tropopause may also play a role in the water vapor budget and variability (Dessler, 2009). New aircraft remote sensing measurements from the CRISTA-NF instrument demonstrate high vertical and horizontal resolution measurements of clouds and trace gases in the UTLS (Reise *et al*.), pointing to new possibilities for untangling mechanisms and sources of variability on synoptic scales.

Session 5 : Long-term variability and Trends

The final session focused on long-term variability and trends in dynamical and chemical behavior of the UTLS. An overview of long-term measurements from the MOZAIC program (Thouret *et al*.) highlighted the availability of data from over 32,000 flights (beginning in 1994), with novel applications including quantifying quasi-global UTLS climatologies of ozone, water vapor and CO (**Figure 12**, colour plate VI), and sampling regions previously void of data (such as over Africa and China). While the long-term MOZAIC measurements are useful for studying some aspects of interannual variability (such as ENSO effects), their application to long-term trends is limited by sampling variability. Long-term changes in UTLS ozone have been examined based on aircraft measurements from the GASP program (1975-1979) and MOZAIC (1994-2001), combined with ozonesonde measurements (Staehelin *et al*.). There are substantial uncertainties in comparing data from different aircraft instruments (over different decades) when searching for relatively small ozone changes. Such uncertainties were confirmed for these data by comparisons to ozonesonde measurements, so that decadal trends cannot be confidently estimated from these aircraft data at present. A recent increase in stratospheric aerosols has been documented from lidar observations by Hoffman *et al*. (2009), and postulated to be linked to growing sulfur emissions over China. Solomon *et al*. documented a similar increase using SAGE satellite observations (which ended in 2005), and presented modeling results that highlight the importance of transport to the stratosphere through the Asian monsoon circulation.

Satellite data suggest a decrease in tropical lower stratospheric ozone over the last several decades, and similar behavior is found in many CCMVal model simulations. This modeled behavior was explored in detail by Lamarque and Solomon, who demonstrated the key mechanism was an increase in tropical upwelling, linked primarily to increasing greenhouse gases (and not to ozone depleting chemicals). It was noted that past changes in tropical upwelling may be reflected in low vs. high latitude temperature variations and trends in the stratosphere, as discussed using historical MSU and SSU data (Young *et al*.). A novel diagnostic for long-term circulation changes in the extratopical lower stratosphere based on N_2O-ozone correlations was presented by Boenisch *et al*. who noted that this region may be especially sensitive to the so-called 'lower branch' of the Brewer-Dobson circulation.

A topic of further interest was changes in the global tropopause height and possible widening of the tropics in observations and model simulations. A number of different metrics for measuring tropical width were discussed by Davis and Rosenlof, who noted their sensitivity and differences based on different observational (reanalysis) data sets. Anel *et al*. explored the use of PV gradients to quantify tropical widening. Gettelman *et al*. extended this theme by quantifying tropical width in past and future global model simulations from CCMVal, noting that for many quantities trends are difficult to quantify in the face of large natural variability.

Workshop Summary: Lessons Learned and Way Forward

The workshop focused much discussion on several key ExUTLS concepts and processes: the definition of the extratropical tropopause, the double tropopause, the TIL and the ExTL. It also focused on the role of the jet streams in transport and mixing, observations of chemical tracers and 'mixed' air, and trace gas budgets that can delineate transport pathways. The emerging trend is that these elements not only need to be described individually, but it is also key to understand their mutual connections and interactions. The relative roles of different processes are not well understood.

ExTL: Since the last major UTLS workshops (Bad Tolz, 2000 and Mainz, 2005), much progress has been made in the observational characteristics of the ExTL. The synoptic scale structure of the ExTL was targeted by research flights in the SPURT and START08 field campaigns (Engel *et al*., 2006; Pan *et al*., 2010). Trace gas budgets and transport pathways were quantified. Satellite data analyses provided global statistical behavior of the ExTL (*e.g*. Hegglin *et al*., 2009). The statistical behavior using different tracers has shown variable ExTL depth (CARIBIC, Zahn *et al*.), reflecting the underlying dynamical structure and the time scale involved in the ExTL formation.

TIL: Significant progress has been made in characterizing the global spatial temporal structure of the TIL using global GPS satellite data (Grise *et al*., 2010). Increasing evidence supports the significance of water vapor radiative effect in the formation of the TIL (Kunz *et al*., Randel and Wu). This particuar issue connects the formation of the TIL with the existence of the ExTL. In particular, enhaced water vapor in the vicinity of the tropopause, associated with the chemical mixed layer, appears to be one key mechanism for formation and maintenance of the TIL. There are also indications, using ozone data, that the strength of the TIL in turn enhances the barrier effect of the tropopause and produces a stronger chemical discontinuity between UT and LS (Tandon *et al*.).

The definition of the extratropical tropopause has often been the origin of diverse views and approaches in quantifying STE. However, a more updated perspective may be that for cases where significant differences between the dynamical and thermal tropopauses exist, this is an indication of the lack of a sharp boundary between the troposphere and stratosphere (Pan *et al*., 2007). The occurrence of the double tropopause is now recognized to be often associated with transport and intrusions from the subtropics (Pan *et al*., 2009). The mechanisms which control this process and its seasonality are far from understood, and somewhat different perspectives are given by different studies. For example, recent observations during the START08 campaign found a significant influence from these events in the lowermost stratosphere during Spring. This is consistent with the GPS analyses showing winter/spring as the high season for the double tropopause occurrence in the NH (Randel *et al*., 2007). On the other hand, trajectory based studies (*e.g*. Berthet *et al*., 2007) suggest ventilation of the layer above the subtropical jet is stronger in summer than winter. A study using HIRDLS data and the equivalent length approach found similar conclusion (Gille *et al*.). Questions also remain whether this process is a middle world process, represented as isentropic mixing between the upper troposphere and LMS, or it is part of a stratospheric process and should be considered as part of the lower branch of the B-D circulation.

The double tropopause structure also highlights the role of the jet stream in transport. The core of the sub-tropical jet forms a barrier to meridional transport, which is more vigorous below and above the jet core, and has a strong regional and seasonal component tied to the jet. The transport above the jet core is observed in aircraft and satellite data, and is consistent with the double tropopause structure. Trace gas budgets (Hoor 2005) and time scales for transport in the LMS were quantified (Boenisch *et al*., 2009). During winter and spring, the LMS above the ExTL (more than ~2 km above the tropopause) has a strong contribution from the overworld, and a tropospheric signature from the preceding autumn. From summer to autumn the UTLS is rapidly flushed with young tropospheric air. The deep monsoon anticyclones, particularly the Asian summer monsoon anticyclone, are also persistent UTLS features that strongly regulate transport, including strong meridional mixing on the east and west sides of the anticyclone (Konopka *et al*., 2009), and vertical transport deep into the stratosphere (Randel *et al*., 2010).

The workshop discussions further highlighted the wealth of available datasets for providing new insights into the ExUTLS processes. Aircraft data from research campaigns (*e.g*. SPURT and START08) provide a host of coordinated observations for studies relating the chemical behavior and meteorological/dynamical structure of the ExUTLS. The in-service flight data (MOZIAC, CARIBIC and CONTRAIL) will continue to provide a dense sampling of UTLS chemical distributions. There is increased appreciation for the high vertical resolution and accuracy of GPS temperature data. Also, satellite data continue to provide key information on large-scale chemical structure, particularly for regions where there are few aircraft measurements (*e.g*. the Asian monsoon anticyclone, and much of the tropics and SH).

Finally, there is continuing development and application of high resolution global and regional models that focus on simulation of the UTLS region, including fully coupled chemistry and climate effects. The integration of such models with current and planned observations promises significant progress for UTLS science over the next decade.

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Frierson, D. M. W. Midlatitude Static

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^ Figure 1

Participants attending the Boulder UTLS workshop, October 2009.

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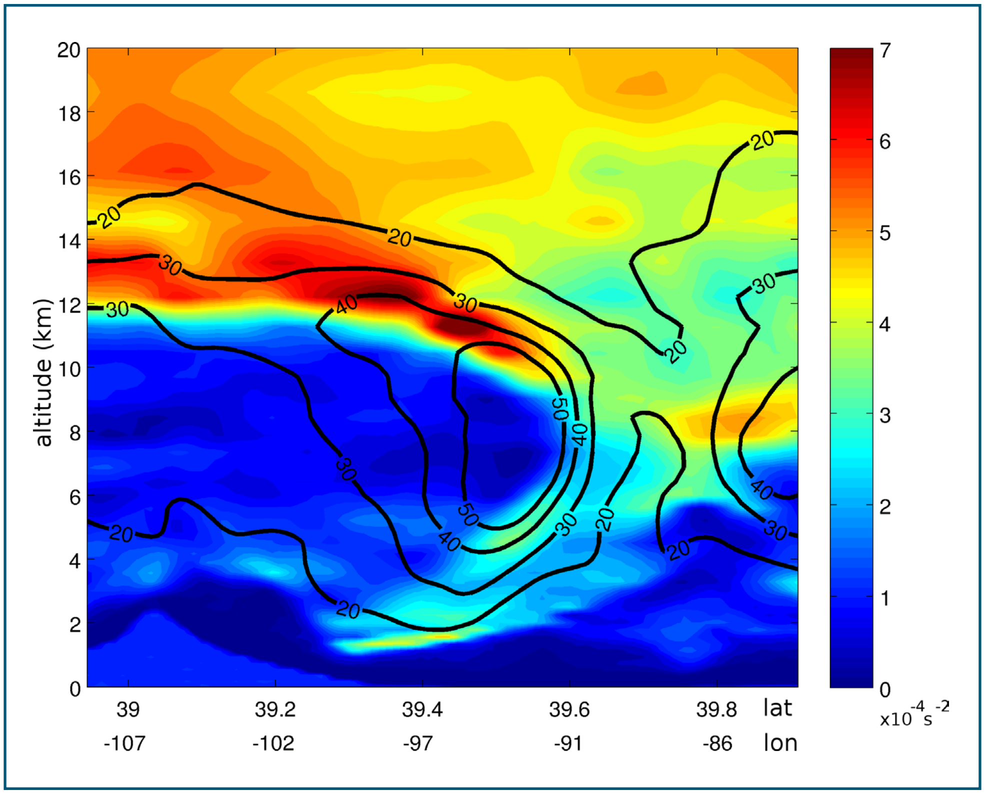

^ Figure 2

Cross section of static stability (Brunt Vaisala frequency squared, colors, contour interval of 0.2x10^{-4}*) and wind (contours, m/s), showing high resolution structure near a tropopause fold. From Tandon et al.*

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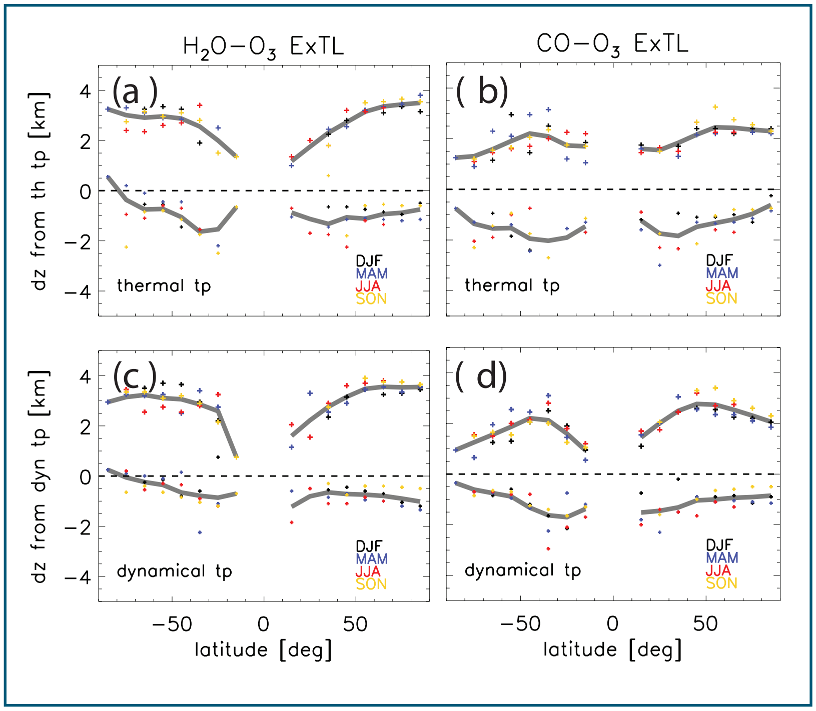

< Figure 3

Depth of the chemical mixing layer calculated from ACE-FTS data. Results are shown for calculations based on (left) H_2O-O_3 and (right) $CO-O_3$ correlations, using vertical coordinates with respect to the thermal (top) and dynamical (PV=2) tropopause (bottom). From Hegglin et al.

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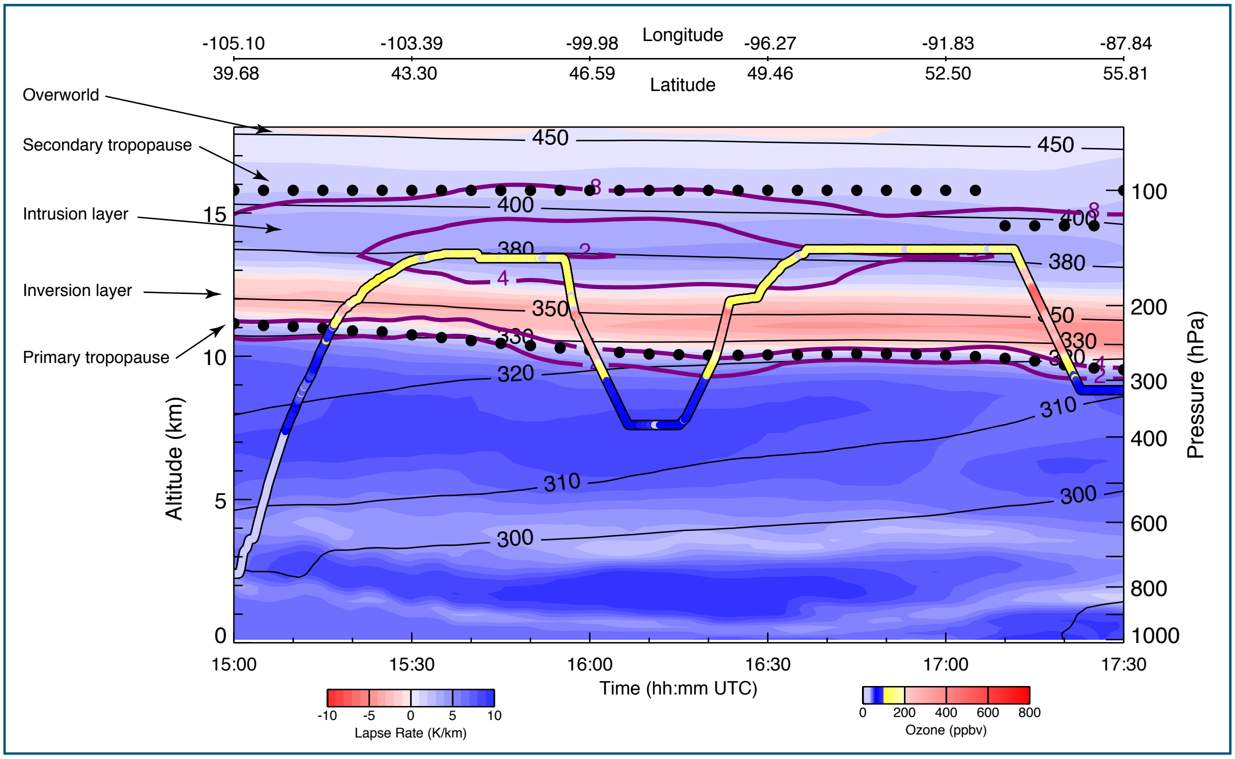

^ Figure 4

Vertical cross section along track from START08 flight 01, showing static stability, in situ ozone, PV (purple contours), and potential temperature (black contours). The stable layer in the lower stratosphere is sandwiched between the troposphere and a tropospheric intrusion from the tropics.

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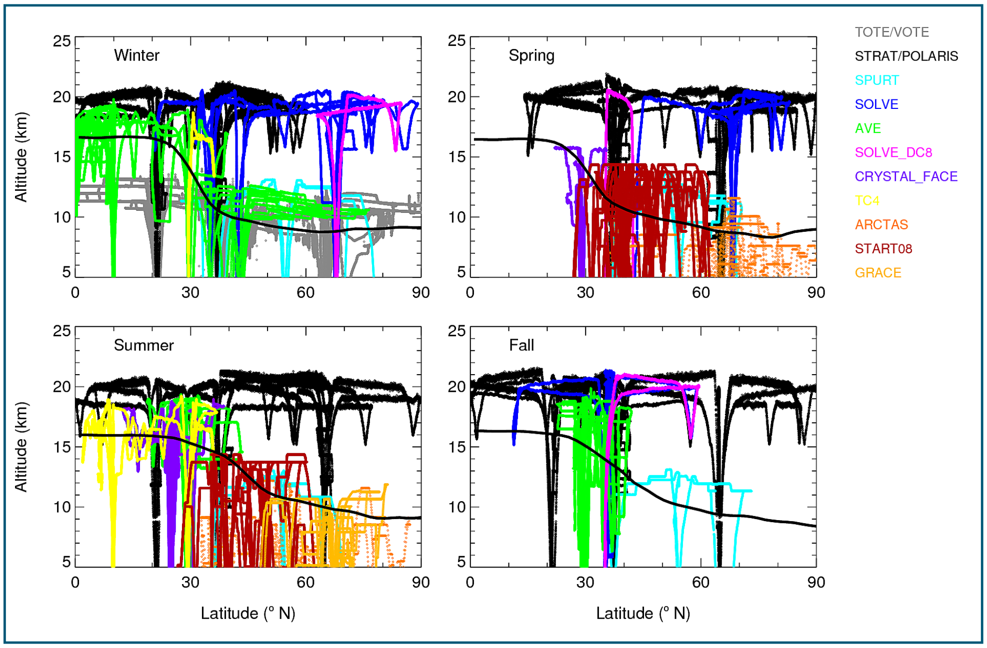
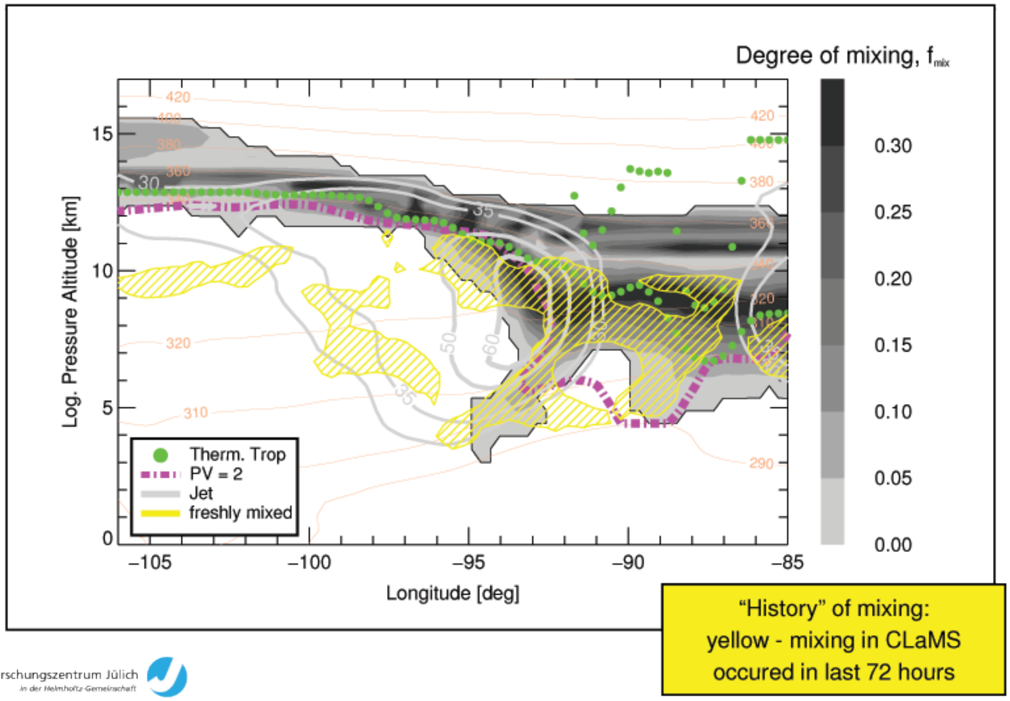


< Figure 5

Seasonal UTLS sampling over the Northern Hemisphere from numerous research aircraft campaigns (from Tilmes et al.).

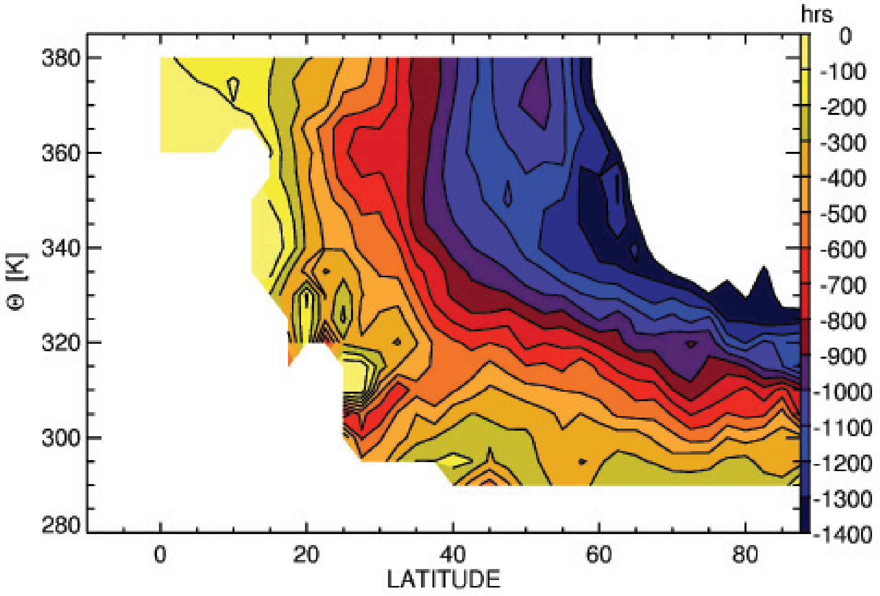


"History" of mixing:
yellow - mixing in CLaMS
occured in last 72 hours

Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft

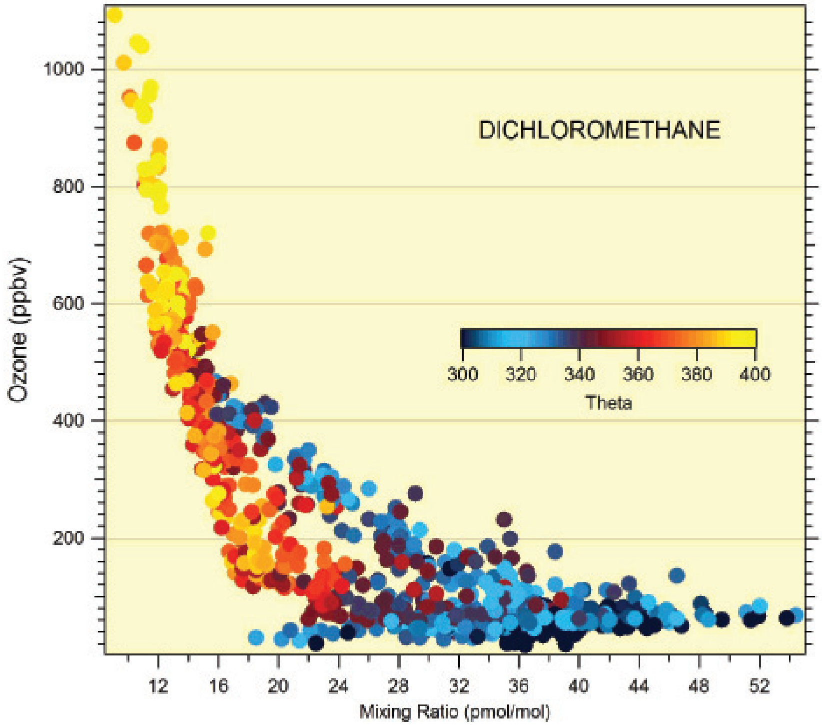
^ Figure 6

Details of mixing in a tropopause fold simulated by CLAMS. From Konopka and Pan.



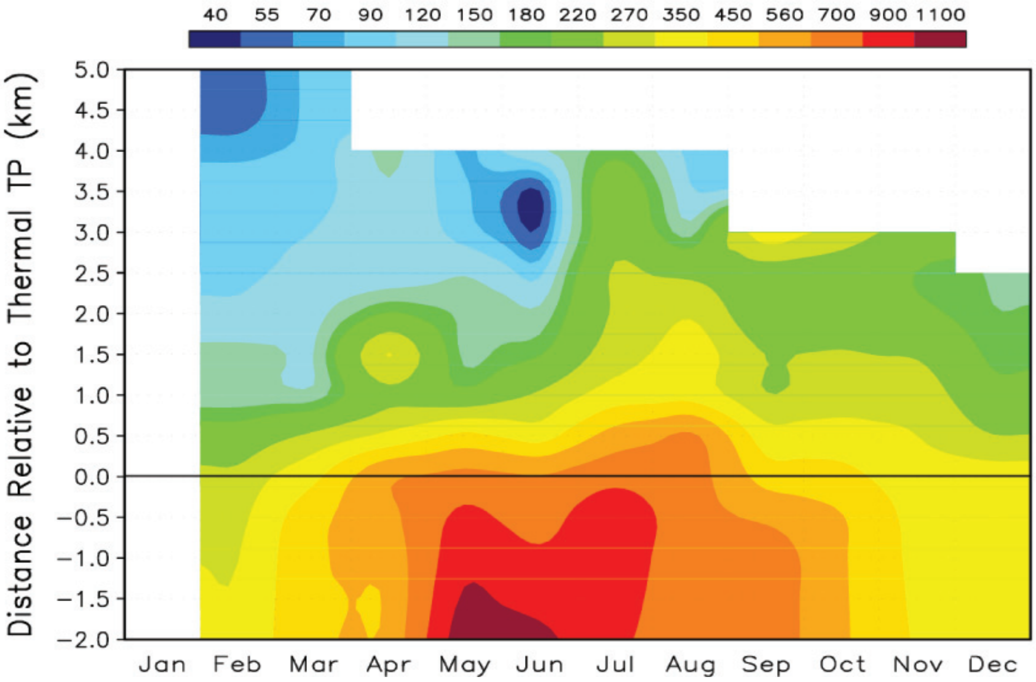
^ Figure 7

Trajectory estimates of average transport time (in hours) from the tropopause into the lower stratosphere. From Hoor and Wernli.



< Figure 8

Scatter plot of ozone vs. dichloromethane from whole air sample measurements in START08, color coded by potential temperature of the observations (from Atlas et al.).



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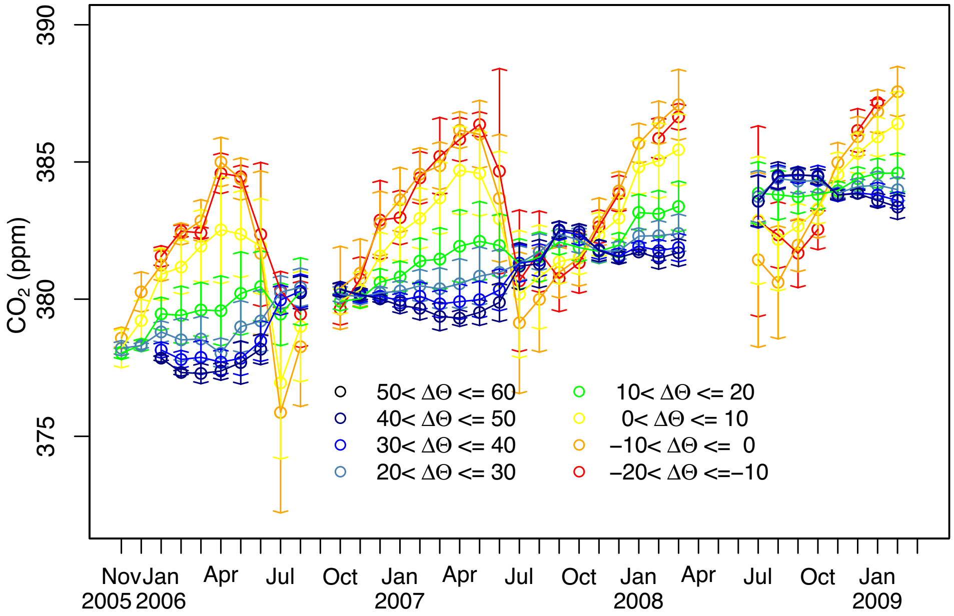
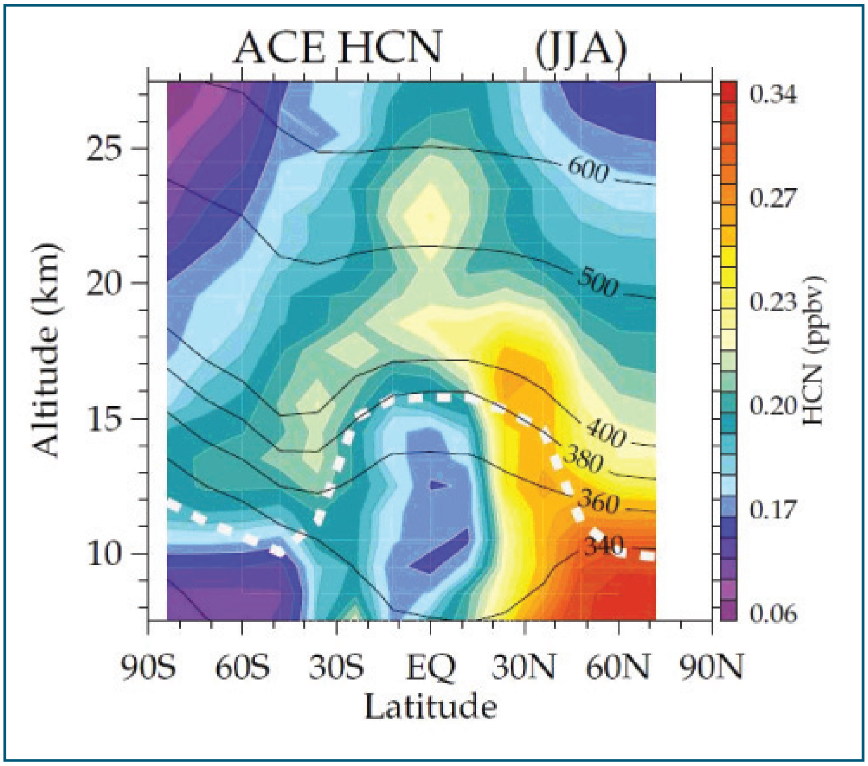
^ Figure 9

Monthly climatology of acetone mixing ratio (in units of pptv) vs. height in tropopause coordinates from CARIBIC measurements (from Sprung and Zahn, 2010). The black horizontal line denotes the 11 km level.



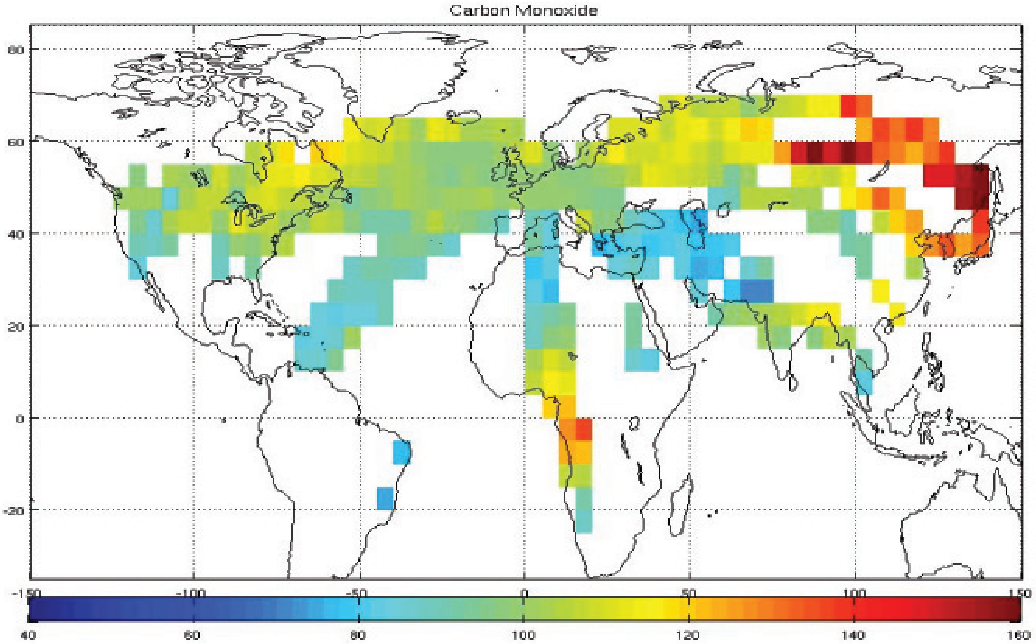
< Figure 10

Time series of CO_2 at different levels with respect to the tropopause from CONTRAIL measurements (from Sawa et al.). Note the strong seasonal cycle that varies as a function of distance from the tropopause.



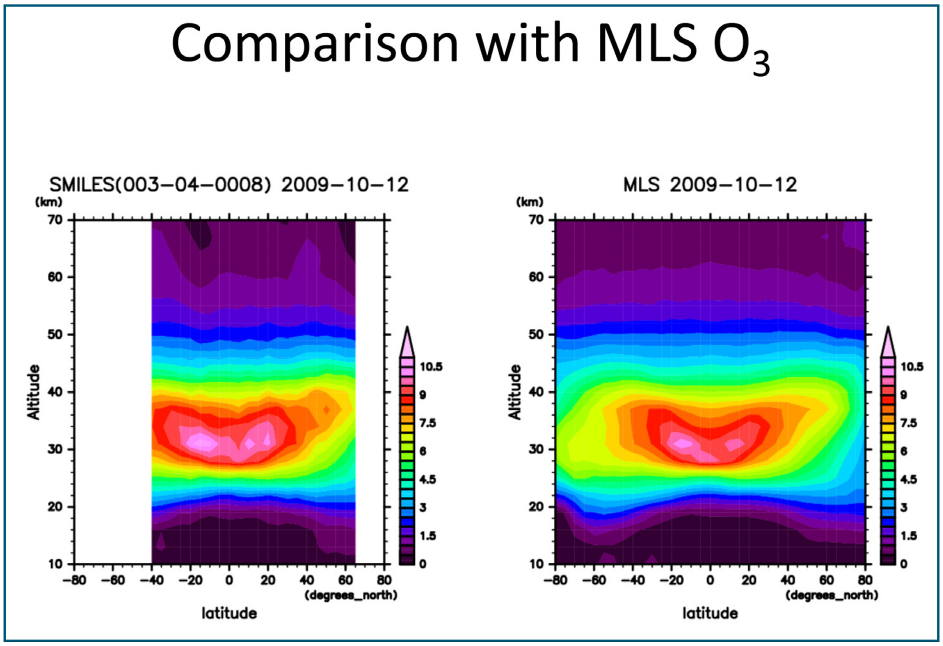
< Figure 11

Meridional cross section of HCN mixing ratio from ACE-FTS satellite observations during NH summer, showing transport into the stratosphere through the Asian monsoon. From Park et al.



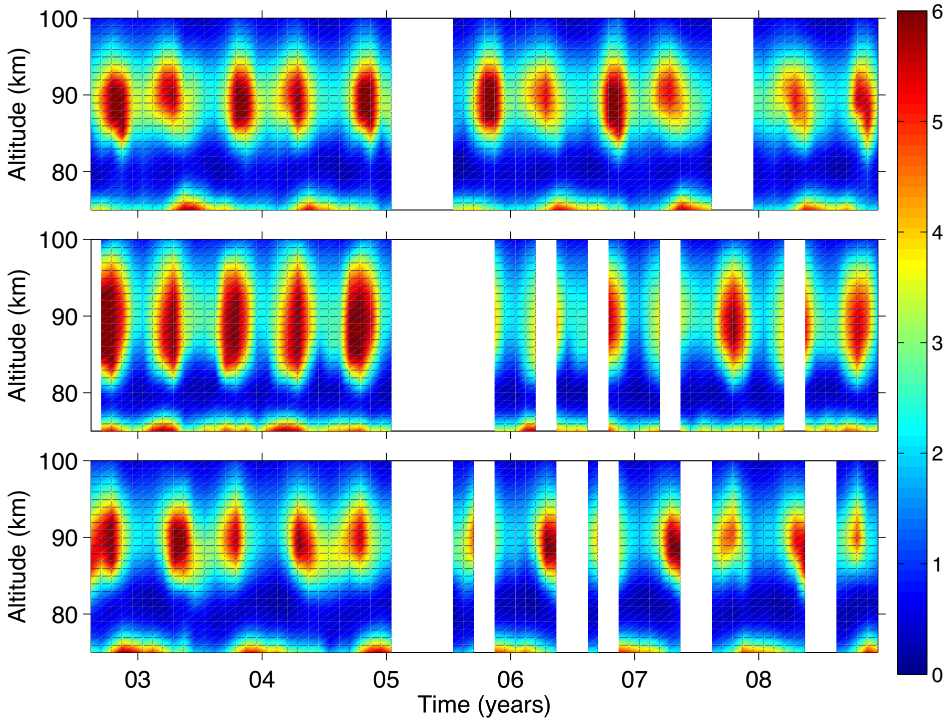
^ Figure 12

Climatology of NH summer carbon monoxide mixing ratio (ppbv) near 10 km from MOZAIC measurements (from Thouret et al.).



< Figure 1

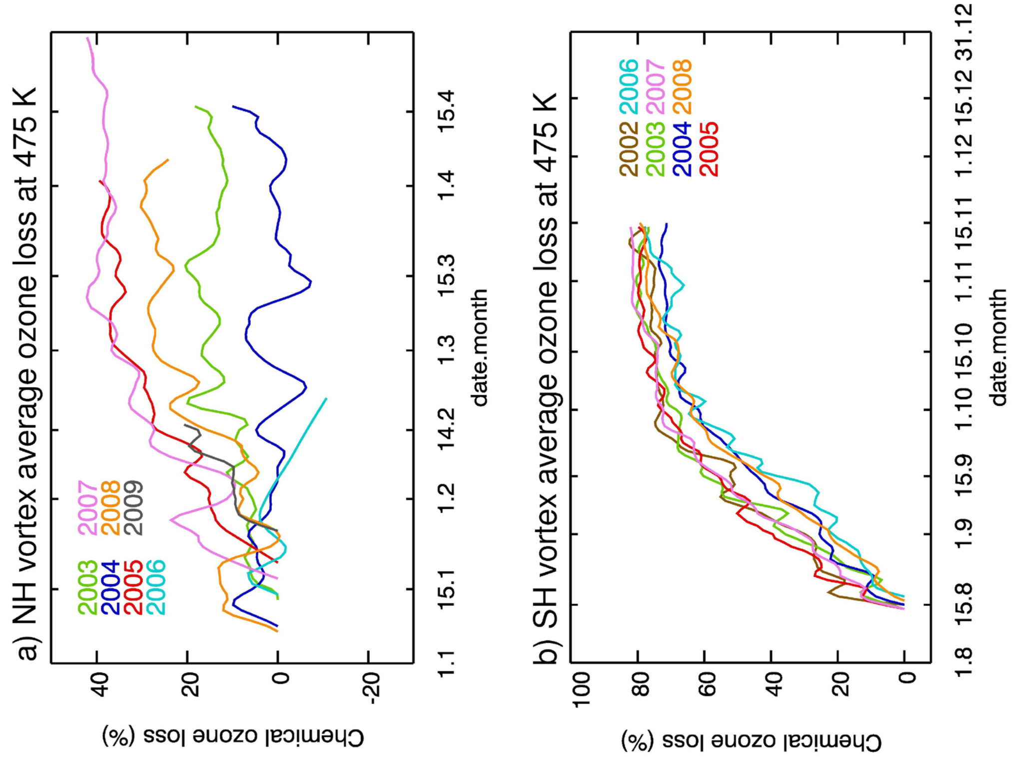
Left: Ozone retrieval from the Superconducting Submillimeter Wave Limb Emission Sounder (SMILES) onboard the International Space Station. Compared with MLS ozone data (right). (Figure courtesy of Shiotani (Kyoto University), Takayanagi (JAXA), Murayama (NICT), Koike (University of Tokyo), Kikuchi (JAXA), Kasai (NICT), Nagahama (Nagoya University), Sano (JAXA).



< Figure 2

Ozone number density in the MLT in three latitude belts as a function of time (in months) and altitude. The density is scaled by 10^8 cm^{-3}. The time covered is 1 August 2002-31 December 2008. Latitude belts: 30N-50N (top), 10S-10N (middle), 30S-50S (bottom) (figure courtesy of Erkki Kyrölä, FMI).

Report on the 5th Limb conference and workshop



^ Figure 3

Catalytic ozone loss at 475 K potential temperature (about 18 km altitude) inside the Arctic (panel a) and Antarctic (panel b) polar vortices for the period 2002 – 2009 derived from SCIAMACHY observations of stratospheric ozone profiles. The ozone loss is determined with the vortex averaging method using UKMO stratospheric analysis data (figure courtesy of Thiranan Sonkaew, IUP Bremen).

^ Figure 4

The Fifth international atmospheric Limb conference and workshop took place at Finnish Meteorological Institute, Helsinki, Finland in 16-19 November 2009. The meeting was attended by 50 scientists from 10 countries (figure courtesy of Simo Tukiainen, FMI).

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Report on the 5th Limb conference and workshop

16-19 November 16-19, 2009, Helsinki, Finland

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Christian von Savigny, University of Bremen, Germany, (csavigny@iup.physik.uni-bremen.de)
Didier Rault, NASA/Langley Research Center, USA (didier.f.rault@nasa.gov)

The fifth International atmospheric Limb conference and workshop took place in Helsinki, Finland from 16-19 November 2009. Earlier meetings in this series were in Bremen (2003), Stockholm (2004), Montreal (2006) and Virginia Beach (2007). The dates for the meeting were selected by nearly democratic Doodle-voting and the darkest month in Finland got the highest votes. The limb was bright for a few minutes during the meeting and there was only one cancellation in spite of the peak period of the H1N1 flu pandemic.

The main goal of the meeting was to bring together international scientists working on the retrieval of trace gas and aerosol information from limb observations, as well as on the validation, interpretation and usage of retrieved information for scientific analyses. With the end or failure of several satellite occultation instruments in recent years, the existing limb scatter and limb emission instruments are of crucial importance in terms of continuing stratospheric and mesospheric minor constituent time series with high vertical resolution. The fifth limb conference was also a platform to review the progress made in terms of improving the quality of limb trace gas and aerosol retrievals to a degree that makes them usable as ECV (essential climate variable) data sets.

The meeting place was the Finnish Meteorological Institute. The meeting was attended by 50 scientists from 10 countries. SPARC provided financial support for four students, which was greatly appreciated. There were 41 oral presentations and 9 poster presentations. The oral presentations and other information of the meeting are available at the meeting's web-site **http://fmilimb.fmi.fi/5thlimbmeeting/**. The sessions were: Instruments and missions, retrieval and radiative transfer, stratosphere, mesosphere and posters. The meeting was closed by the discussion session where *e.g.*, the upcoming limb missions and data initiatives were discussed. The next limb meeting was decided to take place in March 2011 in Japan.

Instruments and missions

Chris Boone presented the latest results obtained with the Atmospheric Chemistry Experiment (ACE on SCISAT). ACE is retrieving the vertical distribution of numerous trace gases, aerosols, temperature and thin clouds. A series of topics were discussed including the detection of organic molecules (formaldehyde, formic acid) in the troposphere as well as carbon dioxide profiles in both the troposphere and mesosphere. **Marty McHugh** presented results from the SOFIE (Solar Occultation for Ice Experiment) instrument on-board AIM (Aeronomy of Ice in the Mesosphere), a broadband radiometer (0.3-6 microns) measuring temperature, PMCs (polar mesospheric clouds), Carbon Dioxide, Methane, Nitric Oxide, Ozone and Aerosols in the mesosphere. SOFIE has unprecedented pointing fidelity and broadband transmission precision and is even capable of detecting cosmic dust. **Doug Degenstein** summarized the achievements of the OSIRIS instrument (Optical Spectrograph and Infrared Imager System) on the Odin spacecraft which have been made over the past nine years of operation. The current state of the operational data products (stratospheric ozone and NO_2 and stratospheric aerosols) as well as the research data products (e.g., mesospheric OH, NO_2, NO, BrO, cirrus and subvisual clouds) were presented. **Erkki Kyrölä** outlined the challenges of the stellar occultation method. With GOMOS (Global Ozone Monitoring by Occultation of Stars), he showed that it is possible to retrieve vertical density profiles of ozone, NO_2, NO_3, H_2O, O_2, and aerosols in the stratosphere as well as ozone in the MLT region. He showed GOMOS-derived climatologies for ozone, NO_2 and NO_3 for the 2002-2008 time period, as well as a series of research products such as OClO, mesopause sodium layer, PMCs, gravity waves and turbulence. **Masato Shiotani** described the Superconducting Sub-millimeter-Wave Limb-Emission Sounder (SMILES) which operates on the International Space Station. This sensor uses the limb emission in the sub-millimeter range (624.32 - 627.32 and 649.12 - 650.32 GHz). The main objectives of the mission are (1) to demonstrate the space operation of a super-conducting mixer and 4-K mechanical cooler and (2) the global observation of stratospheric trace gases (O_3, HCl, ClO, HO_2,HOCl, BrO, O_3 isotopes, HNO_3, CH_3CN). A sample ozone retrieval from SMILES limb observations is shown in **Figure 1**, colour plate VII. **Donal Murtagh** presented the PREMIER mission (PRocess Exploration through Measurements of Infrared and millimeter-wave Emitted Radiation). The main mission objective is to retrieve trace gases in the mid/upper troposphere to lower stratosphere region. The mission (planned for launch in 2016) consists of two sensors, namely (1) an infrared limb imaging spectrometer, and (2) a mm-wave limb sounder. Donal Murtagh also described the STEAM-R instrument, which uses the sub-mm limb emission technique. STEAM-R is a new generation of sub-mm limb sounders (312-324 GHz and 344-356 GHz) utilizing latest advances in receiver and spectrometer technology. The main target species will be water vapor, ozone and CO as well as biomass burning tracers. **Philippe Baron** discussed the potential of SMILES to study stratospheric dynamics and chemistry. SMILES operational products include stratospheric O_3 and HCl isotopes, ClO, HNO_3, HO_2, CH_3CN, BrO, and HOCl. Additionally, research products are investigated such as the column densities of O3, HCl, HO_2, wind in the mesosphere (up to about 90 km), as well as humidity and ice water content in the upper troposphere. **Didier Rault** described the upcoming Ozone Mapper and Profile Suite (OMPS) mission. One sensor of the suite, namely the Limb Profiler (LP), uses the Limb Scatter technique to infer the vertical distribution of ozone and aerosol from the upper troposphere up to 60 km, with along-track resolution of 150 km and a 4-day revisit time. The objective of the OMPS mission is to measure ozone distribution at sufficiently high accuracy and precision so as to allow the science community to better understand and quantify the rate of stratospheric ozone recovery. The algorithm performance is being tested with synthetic and proxy data. Since the sensor uses a novel design, alternative methods are being implemented to identify (and correct for) instrument effects and minimize data preprocessing.

Susann Tegtmeier presented the last talk of the meeting, outlining the SPARC Data Initiative on chemical observations. The main objective of the initiative is to write a SPARC report on a comprehensive comparison of vertically resolved climatologies of (mainly long-lived) chemical tracers, age of air, and aerosols from all available multi-national satellite measurements. The development of the report would follow the SPARC approach of community involvement and peer review, and is intended to provide a guide for users of chemical data sets in order to facilitate data usage for model/measurement comparisons.

Retrievals and radiative transfer

These topics were discussed in two sessions with 17 oral presentations and 4 poster presentations. In an invited talk **Alexei Rozanov** presented retrievals of water vapor in the troposphere and lower stratosphere from SCIAMACHY limb measurements. Water vapor is the most important greenhouse gas and its importance on climate change has been emphasized, for example, in a recent article by S. Solomon *et al.* (Sciencexpress, 28 Jan., 2010). The wavelength window chosen was 1353-1410 nm and the retrieval was based on SCIATRAN radiative transfer model, DOAS and optimal estimation. The SCIAMACHY retrieval results are promising and accuracy in the 12-20 km range is about 20%. **Serhiy Hrechanyy** presented differences between the operational and scientific retrieval of the SCIAMACHY limb measurements. These differences are mainly in the calculation of multiple scattering and in the regularization of the retrieval.

A two-dimensional retrieval for MIPAS measurements was presented by **Massimo Carlotti**. Based on simulations the two-dimensional retrieval seems to be better than the operational one-dimensional retrieval. **Bianca Maria Dinelli** considered a two-dimensional model for clouds (BROADBAND_CLOUDS) and how MIPAS radiances are affected by the cloud top height. **Lars Hoffman** presented tomographic retrievals for the PREMIER mission proposed to the ESA Earth Explorer program. Using a model, named JURASSIC, retrievals of data simulations were analyzed and promising results were achieved for the ability of PREMIER to map gravity wave signatures in the atmosphere. A two-dimensional approach for the SCIAMACHY limb measurements was introduced by **Sven Kühl**. The method is especially useful for measurements where large horizontal gradients occur like at the polar vortex edge.

Johanna Tamminen presented non-linear inverse problems and model selection in remote sensing problems. The focus was especially on the application of a Markov chain Monte Carlo method on data analysis. As an application she showed how the optimal aerosol model can be selected for GOMOS retrievals of aerosols. GOMOS normally works by measuring stellar light attenuation using the occultation principle. **Simo Tukiainen** then presented daytime measurements by GOMOS where the scattered solar light can be used for retrievals as done with SCIAMACHY and OSIRIS. The retrieval questions related to the proposed ALTIUS limb imaging instrument were discussed in the poster by **Emmanuel Dekemper**.

A challenging problem in the field is to properly account for multiple scattering in the retrievals using UV-visible limb measurements. **Nick Lloyd** from the OSIRIS team presented the radiative transfer model SASKTRAN. He offered to share the code with other groups and this offer was well received. **Marty McHugh** presented the SpectralCalc simulator for infrared wavelengths. **Franz Schreier** presented the TELIS data processing.

The JEM/SMILES experiment onboard the International Space Station was launched in September 2009. The talks by **Chihiro Mitsuda** and **Makato Suzuki** presented the JEM/SMILES operational level 2 data processing. Initial validation looks promising for products that will be released during 2010.

The upcoming NPOESS Preparatory Project (NPP) mission is scheduled to launch in the fall 2011 as a precursor to the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The NPP mission will be the first flight for the OMPS limb profiler, which was described above by Didier Rault. **Robert Loughman** presented the principles of the ozone and aerosol profile retrieval and **Ghassan Taha** showed retrievals studies using simulated data sets and proxy data sets based on SCIAMACHY and OSIRIS limb scatter observations.

Multi-mission validation of ozone limb sounders using the NDACC network data were presented by **Jean-Christopher Lambert**. Overall, he found a good consistency between different measurements but several interesting deviations were also revealed. BrO-retrievals from SCIAMACHY limb observations were discussed by **Justin Parella**'s talk and in a poster by **Alexei Rozanov**. **Doug Degenstein** presented **Chris McLinden**'s (absent because of H1N1) paper about BrO observations from OSIRIS. The retrieval is based on daily, zonally averaged Level 1 radiances. **Sebastian Schröder** presented a gravity wave model and its validation with SABER and future validation with PREMIER.

Stratosphere and Troposphere

Two presentations dealt with recent advances in the retrieval of stratospheric background aerosol extinction profiles from limb-scatter observations using OSIRIS (**Adam Bourassa**) and SCIAMACHY (**Florian Ernst**). Adam Bourassa presented results on the evolution of the Kasatochi aerosol plume during a 3-month period after the eruption in August 2008 – the largest volcanic eruption since Pinatubo in 1991.

A series of presentations covered different aspects of stratospheric chemical composition including satellite retrievals, comparisons with model simulations and other science applications. **Joachim Urban** reported on recent trend studies for different stratospheric minor constituents (O_3, ClO, HCl, H_2O, HNO_3) based on Odin/SMR observations in combination with several other satellite data sets. Erkki Kyrölä discussed trend analyses of stratospheric O_3 and NO_2 retrieved from both GOMOS stellar occultation and OSIRIS limb-scatter observations (see **Figure 2**, colour plate

VII). **Sven Kühl** presented stratospheric NO_2, BrO and OClO retrievals from SCIAMACHY limb observations and a comparison to model simulations with ECHAM5/MESSy1. A 7-year climatology of lower stratospheric BrO profiles also derived from SCIAMACHY limb-scatter measurements was presented by Alexei Rozanov. **Christian von Savigny** provided an overview over recent science applications based on the IUP Bremen SCIAMACHY limb ozone profile data product, including the 27-day solar cycle signature in stratospheric O_3, and the derivation of the chemical ozone losses in the Arctic and Antarctic polar vortices using the vortex average technique. **Figure 3**, colour plate VIII shows, as an example, the obtained relative chemical ozone losses in the Arctic and Antarctic polar vortices at the 475 K potential temperature level (corresponding to about 18 km altitude).

Victoria Sofieva reported on a study to quantify stratospheric gravity wave activity and turbulence using GOMOS fast photometer observations of stellar scintillations. The analysis showed enhancements in gravity wave activity and turbulence at high latitudes during winter time, likely related to the polar night jet. Finally, two presentations addressed issues related to the upper troposphere/lower stratosphere region. **Patrick Eriksson** reported on the retrieval of relative humidity and ice water content in the tropical upper troposphere using Odin-SMR microwave measurements. **Katja Weigel** discussed observations of upper tropospheric/lower stratospheric minor constituent fields (*e.g.*, O_3, H_2O, PAN, HNO_3) with very high vertical and spatial resolution using the CRISTA-NF instrument aboard M55-Geophysica. The observations clearly indicated the presence of a tropopause fold.

Mesosphere

Several contributions dealt with mesospheric composition and aerosols, as well as with solar effects on the middle atmosphere. **Annika Seppälä** provided an overview of selected aspects of the effect of energetic particle precipitation on the middle atmosphere. GOMOS stellar occultation observations provided the first polar night observations of NO_x enhancements and catalytic O_3 loss during solar proton events (SPEs). Analysis of the 2003/2004 NH winter – following the Halloween SPE – showed that different processes were responsible for the observed NO_2 abundances in the night time polar middle atmosphere, including the Halloween SPE, electron precipitation and descent of thermospheric NO of auroral origin. **Pekka Verronen** discussed the possibility of using mesospheric OH observations as a proxy for energetic particle precipitation (protons and electrons). Mesospheric OH enhancements observed during the January 2005 solar proton event with MLS/Aura were well reproduced with the SIC (Sodankylä Ion and neutral Chemistry) Model. MLS OH observations showed a good correlation with energetic electron flux measurements with MEPED (Medium Energy Proton and Electron Detector) on POES.

Jonas Hedin reported on mesospheric ozone profile retrievals from OSIRIS limb-scatter observations. He exploited the Hartley absorption bands of ozone, with the goal of filling the gap in coverage (60 – 70 km altitude) between the existing Chappuis-Huggins-retrievals and the upper mesospheric retrievals based on O_2 A-band emission observations. Combining all retrievals will allow the retrieval of ozone profiles between the tropopause and about 95 km altitude. **Stefan Lossow** provided an overview of mesospheric H_2O profile retrievals from Odin/SMR observations – using the 557 GHz emission line – with a focus on the polar summer mesopause region. The profiles show clear indications for freeze-drying due to the presence of noctilucent clouds (NLCs). Moreover, it was found that models tend to overestimate freeze-drying. Christian von Savigny reported on two different solar effects on NLCs: the first identification of a solar 27-day signature in NLCs using SCIAMACHY limb observations of NLCs, and the dynamical heating of the polar summer mesopause during solar proton events, which could be reproduced with the Kühlungsborn mechanistic general circulation model (KMCM). The reported 27-day solar cycle signature is mainly driven by a similar signature in mesospheric temperatures. The analysis indicates that the same physical process may be the driver of both the 27-day and the well known 11-year solar cycle signatures in NLCs. **Ted Llewellyn** presented night-time limb observation results using the OSIRIS instrument. The NO + O nightglow continuum (also known as air afterglow continuum) was successfully identified in the night-time OSIRIS spectra and NO profiles were derived. The vertical O profiles required for the determination of NO profiles were retrieved from simultaneous OSIRIS observations of the O_2 A-band emission. First comparisons with ACE-FTS NO retrievals show good agreement.

Discussion

In the discussion session **Claus Zehner** presented ESA's climate change initiative. There was a discussion about the future of the limb measurements. In 2010 there are several limb instruments operating like GOMOS, MIPAS and SCIAMACHY on Envisat, HIRDLS and MLS on EOS-Aura, SMR and OSIRIS on Odin, SABER on TIMED, ACE-FTS and MAESTRO on SCISAT, AIM/SOFIE and the recently launched JEM/SMILES. In the near future OMPS on NPP is the only secured limb mission. In the ESA's Earth Explorer program, the proposed PREMIER mission is an inspiring UTLS mission using mm and IR wavelengths. Presently ESA has opened a new call for Earth Explorer missions and NASA is planning to issue a new call for Explorer missions later this year. In spite of these opportunities, it seems the golden age for atmospheric limb missions will be over in the near future.

There was also a short discussion about WMO's ACSO activity for ozone cross sections in the UV-optical region led by **Johanna Tamminen** (see **http://igaco-o3.fmi.fi/ACSO/cross_sections.html**) and about radiative transfer models, especially the SASKATRAN model.

Christian von Savigny proposed a special issue of Atmospheric Measurement Techniques (AMT) on "Atmospheric Remote Sensing using Limb-observations". The special issue was opened for submissions in January 2010 and the main focus is on retrieval techniques, algorithm development and validation results related to limb observations in all spectral regions. Didier Rault promised to propose a special limb session for the AGU meeting of the Americas, taking place from August 8-13, 2010 in Foz do Iguassu, Brazil (see **http://www.agu.org/meetings/ja10/index.php**).

In summary, the fifth limb conference and workshop demonstrated that important progress has been achieved in all areas covered by the conference including algorithm development, inter-comparison and validation of retrieved data sets, as well as data usage to address scientific issues. The science issues addressed during the meeting range from solar terrestrial interactions (effects of solar particle precipitation and the solar rotational period on the middle atmosphere), long-term trend assessments of stratospheric ozone and several other relevant stratospheric species, to the evolution of the stratospheric background aerosol layer. Satellite limb instruments play an essential role for the continuation of the satellite data record of vertically resolved stratospheric minor constituent and aerosol information. The number of data products retrieved from limb instruments is continuously growing, opening exciting possibilities for future satellite missions.

The next limb meeting will take place in March 2011 in Kyoto, Japan.

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A report on the SPARC Gravity Wave Activity

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Recent intensification of effort in developing climate models with more realistic stratospheric circulations has in turn lead to an increased interest in modeling gravity wave mean-flow forcing effects in these models. SPARC hosted a small group of scientists in Toronto in 2008 with experience both in middle atmosphere climate modeling and in global observations of gravity wave momentum flux and drag to focus on the issue of how to improve the representation of gravity wave effects in climate models. A report on this meeting appeared in the July 2008 SPARC Newsletter (no. 31). The group involved in this first meeting have since prepared a review paper, which is now in press in the Quarterly Journal of the Royal Meteorological Society (Alexander *et al*., 2010). The manuscript reviews recent studies on gravity wave effects in stratosphere-resolving climate models, recent observations and analysis methods that reveal global patterns in gravity wave momentum fluxes, and results from some very high-resolution model studies capable of resolving gravity waves and their circulation effects. (A preprint of the manuscript is available at **http://www.cora.nwra.com/~alexand/publications/Alexandetal2010QJ.pdf**)

As a next step, the SPARC Gravity Wave Activity has begun an intercomparison of momentum fluxes associated with gravity waves in both observations and global models. The aim is not only to assess the degree of agreement or disagreement among the various measures of momentum flux. We also plan to eventually merge existing global observations into a coherent set of constraints that may be applied either to gravity wave parameterizations in global models or to resolved gravity waves in present and future high-resolution model simulations. With support from the International Space Science Institute (ISSI) we have assembled an ISSI International Team of scientists and have held a first meeting at ISSI in Bern, Switzerland, cosponsored by SPARC, on February 22-26, 2010. Team member expertise includes high-resolution satellite observation methods that have been used to determine global wave momentum fluxes and other global-scale observation methods, as well as climate modeling. One of the main outcomes of this meeting was preparation of a set of detailed plans for an intercomparison of gravity wave momentum fluxes and momentum tendencies organized under four scientific questions. Each question will be addressed by comparing and pooling specific sets of measurements and model output:

Question 1: What is the spectrum of absolute momentum flux carried by gravity waves in the lower stratosphere? The spectrum of momentum flux associated with gravity waves near the tropopause and in the lower stratosphere is of primary importance in determining the mean-flow forcing effects of gravity waves at higher altitudes in the middle atmosphere. Although the vector flux would be more desirable, observations can provide global estimates of the absolute value of the flux that can be used as constraints for parameterizations of gravity wave drag. Most parameterizations prescribe this flux with one or more parameter settings. Measures of the two-dimensional spectrum of momentum flux will be collected at altitude levels 20, 30, and 40 km (or pressure levels ~ 70, 10, and 3 hPa). The momentum flux spectrum will be defined either as a function of horizontal and vertical wavenumber (k,m) or horizontal wavenumber and frequency (k,ω). Spectra averaged separately in the tropics (30S-30N) and extratropics (90S-30S and 30N-90N) for each of the four seasons (DJF, MAM, JJA, SON) from both satellite and global-scale balloon measurements are planned. Some climate model parameterizations can also output these momentum flux spectra at the specified levels in the atmosphere. Knowledge of the spectra will be an important aid in the eventual merging of the various data sets (*e.g*. Preusse *et al*., 2008).

Question 2: What are the seasonal, geographical and interannual variations in momentum flux? Both observations and models show gravity wave momentum fluxes have large geographical variations that vary both seasonally and interannually (*e.g*. Ern *et al*., 2004; Gong *et al*., 2008; Sato *et al*., 2009). Geographic maps of the flux for each calendar month and year from both the observations (described above) and from climate models will be inter-compared as a first step in developing a climatology.

Question 3: How intermittent is the momentum flux? Gravity waves with their small horizontal scales and high frequencies are frequently observed in wave packets defined by a spatial and temporal envelope of finite amplitude. Conversely, the theoretical basis behind most parameterizations of non-orographic gravity waves assumes a uniformity of the wave spectrum in space and/or time, and although intermittency is recognized as important, it is generally treated by application of a scaling parameter. Is the atmospheric momentum flux delivered in a continuous stream of low-amplitude waves, or in highly sporadic large-amplitude wave packets? The answer can dramatically affect the wave breaking altitudes and the profile of the gravity wave driven force on the mean flow. Time-averaged measurements of momentum flux (such as planned in 1 and 2 above) do not address the question of intermittency, but only constrain the temporal and/or spatial integral. To assess intermittency vs uniformity, probability density functions (pdfs) of instantaneous momentum flux both from observations and from parameterized gravity waves in climate models will be intercompared. Example pdfs from satellite and balloon measurements are shown in Alexander *et al*. (2010).

Question 4: What is the zonal-mean gravity wave zonal force as a function of height and latitude? Currently, global models treat gravity wave effects on the global circulation in a variety of ways. Some models now explicitly resolve gravity waves without any parameterization (Watanabe *et al*., 2008), while in the past many climate models have treated gravity wave effects solely via parameterizations. Most models in use today will resolve some waves and parameterize the effects of others. The model used to create the MERRA analysis product (Bosilovich *et al*., 2008) falls into this last category, but residual momentum tendency increments applied at assimilation correct for remaining model deficiencies that may largely be due to deficiencies in the treatment of gravity waves. A quantitative intercomparison of the zonal-mean gravity wave driven force in these various models may show general agreement and form the basis of a climatology. Clear differences with model resolution may point toward a set of resolution-dependent constraints for parameterizations. Other differences may point to differences in the gravity wave parameterizations, model physics, or model numerics.

Attendees at the first meeting at ISSI were Joan Alexander, Julio Bacmeister, Stephen Eckermann, Manfred Ern, Marvin Geller, Albert Hertzog, Takeshi Horinouchi, Peter Love, Elisa Manzini, Peter Preusse, Kaoru Sato, Adam Scaife, Robert Vincent, and Corwin Wright. For more information on the ISSI team visit **www.issibern.ch/teams/gravitywave/**. We hope to include other participants in the intercomparison effort, and in particular we plan to present preliminary results to participants in the SPARC DynVar Activity at their meeting in Boulder 2011.

We also take this opportunity to announce plans for an AGU Chapman Conference on "Atmospheric Gravity Waves and their Effects on General Circulation and Climate" to be held at the East-West Center in Honolulu, Hawaii on February 28 – March 4, 2011. Co-conveners of the conference are Joan Alexander, Kevin Hamilton, and Kaoru Sato. This will be a meeting for the general community of scientists interested in gravity waves and in their effects on the global circulation in particular. Travel award funds will be available for qualified student and early career scientist applicants. Additional information on how to apply for these funds and further information on the meeting will be circulated later this summer, and abstracts will be due in October 2010. Please watch the Chapman Conference web page at **www.agu.org/meetings/Chapman/** for further details.

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29 September- 2 October	**The International Conference 'Deltas in Times of Climate Change',** Rotterdam, the Netherlands, http://www.climatedeltaconference.org/nl/25222734-Home.html
3-5 November	**Dyn Var workshop,** Boulder, USA, http://www.atmosp.physics.utoronto.ca/SPARC/SPARC-DynVar_Workshop_2_FA.pdf

2011

28 February- 4 March	**AGU Chapman Conference on "Atmospheric Gravity Waves and their Effects on General Circulation and Climate",** Honolulu, Hawaii, http://www.agu.org/meetings/chapman/
24-28 October	**WCRP Open Science Conference,** Denver, CO, USA, www.wcrp-climate.org/conference2011

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