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Report on 2010 SOLARIS Activities and Future Plans

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Group picture of the Second SOLARIS Meeting in March 2010 at the GFZ, Potsdam. Photo courtesy of Jan Dostal (GFZ, Potsdam).

This report is aimed at describing SOLARIS activities in 2010, as well as outlining future plans. It is structured as follows: First, a summary of the SOLARIS workshop and the SCOSTEP side-meeting in 2010 will be given; second, open questions that arose from those meetings will be discussed; and third, future studies will be presented. All SOLARIS activities and future plans are also available on the newly designed and regularly updated website: **http://sparcsolaris.gfz-potsdam.de/**.

Summary of the Second SOLARIS Workshop and SCOSTEP Side-meeting in 2010

The second SOLARIS (SOLAR Influence for SPARC) workshop was held from 10-12 March 2010 and was hosted by the German Center for Geosciences in Potsdam, Germany. Approximately 38 participants from 8 countries participated in the two-and-a-half day meeting to review the latest results in the field of modelling the solar influence on climate, and to decide about future coordinated SOLARIS modelling activities. Additionally, a SOLARIS side meeting was held during the SCOSTEP conference in July 2010 in Berlin, Germany, with 23 participants, some of who had been unable to attend the spring meeting at GFZ Potsdam.

The first day of the March workshop in-

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cluded a series of overview talks from invited speakers that were open to the general public. These overview talks covered a wide range of topics, including new estimates and reconstructions of solar variability in spectral and total solar irradiance going back to 1610 (**S. Solanki**), preliminary results for the irradiance reconstruction over the last 11 000 years (Holocene), and it was mentioned that the sun is leaving its grand maximum in the current solar cycle 23. **U. Cubasch** presented modelling work with coupled middle atmosphere-ocean models for selected paleoclimate events. In particular, he showed results from the start and the end of the interglacial Eemian period as an example of the transition to an ice age, as well as results for the Holocene period, a climate optimum. The model simulations combined orbital forcings with solar variability to simulate the glacial and interglacial periods. **K. Labitzke** reviewed and updated observational analysis of the solar signal in the stratosphere, focusing on the role of the QBO. Her first papers with van Loon in 1987 and 1988 are now on much firmer ground, with a gain of almost 60 years of data (QBO data have been reconstructed back to the mid-1940s). She highlighted the strong summer signal. **A. Brauer** introduced a data base of annually laminated lake sediments at GFZ Potsdam, and showed solar signals from two selected records - the Meerfelder Maar Lake in the western part of Germany, and the Lake Ammersee in Southern Germany - that confirm a sun-climate link that needs to be further investigated.

B. Funke presented results from a SOLARIS-related project, the High-Energy Precipitating Particles in the Atmosphere (HEPPA) initiative (see also the HEPPA article in this issue). A first inter-comparison between different 2D and 3D models and MIPAS observations focused on the solar proton (SPE) event in 2003, the "Halloween" storm (Funke *et al*., 2010, in prep.). Since SPEs are sporadic events and likely do not have any long-term effects on the overall climate, new inter-comparisons will investigate the effect of energetic electron precipitation (EEP) events, such as the EEP event during Northern Hemisphere winter 2009, which was a strong event in a dynamically active winter. EEP events are linked to geomagnetic activity and are modulated by the solar cycle.

L. Hood reviewed the origin of the tropical lower stratospheric ozone response to the solar cycle, currently a highly-discussed topic, since earlier 2D and 3D models have not been able to reproduce the observed vertical structure in the tropical solar signal in temperature and ozone. **K. Kodera** described some of the dynamical mechanisms through which small direct stratospheric effects can indirectly affect the lower parts of the atmosphere down to the Earth's surface, and proposed a mechanism for the modulation of the solar signal by the QBO. **J. E. Kristjansson** reviewed research on the impact of galactic cosmic rays on climate, another proposed mechanism for how solar variability could influence climate. It is now well established that electric charge can enhance aerosol nucleation, and that nucleated aerosols may eventually grow to condensation nuclei. Recent studies of Forbush decreases (rapid decreases in the observed galactic cosmic ray intensity following a coronal mass ejection) give different answers as to whether cosmic ray induced ionization influences clouds. There is no cosmic ray signal in aerosol nucleation events in Europe, little support from model studies, and global temperature is seemingly uninfluenced by cosmic rays. However, ongoing research at CERN may give new insights.

The following talks presented either observational or modelling studies on the topic of solar influence. From the extended ERA-40 reanalysis, **H. Lu** confirmed the results of Labitzke and van Loon regarding the QBO modulation of the solar cycle. **C. Blume** investigated the dependence of the occurrence of stratospheric warmings in extended ERA-40 reanalysis on different natural variability factors (solar cycle, QBO, ENSO, volcanoes) with non-linear time series analysis, using an artificial neural network. **Y. Kuroda** showed a solar cycle and QBO modulation of the southern annular mode (SAM).

A. Shapiro from the PMOD in Davos showed reconstructions of spectral and total solar irradiance variations from the Maunder Minimum to today, and came up with a much larger increase (6 W/m^2) than other estimates, *e.g.* by J. Lean or S. Solanki. **S. Oberländer** and A. Shapiro investigated the effect of different spectral solar irradiance measurements on shortwave heating rates and circulation in stand-alone radiation code calculations and online calculations with chemistry-climate models.

T. Reddmann talked about modelling of stratospheric chemistry during solar-induced NO_x enhancements, observed with the MIPAS instrument onboard ENVISAT, in the Kasima model. Using a mechanistic model, **I. Cnossen** highlighted the importance of gravity wave effects in modelling the solar signal propagation, as well as the importance of having a realistic representation of stratospheric sudden warmings.

K. Matthes presented an overview about the SPARC CCMVal (2010) report, with special focus on the natural variability chapter and the comparison of the solar signal in the different observational and chemistry climate model analyses. It is still under discussion whether the vertical structure of the tropical solar signal in ozone and temperature, especially the secondary maximum of the lower stratospheric signal, is related to non-linear effects, or aliasing of the solar cycle, the QBO, and ENSO.

A number of presentations of different chemistry-climate models focused on more detailed investigation of either the CCMVal reference simulations for the SPARC CCMVal report and the WMO ozone assessement (**A. Kubin, Y. Yamashita, G. Chiodo, K. Shibata**), or idealized solar forcing experiments (**C. Bell, S. Schimanke**), and new simulations for the next IPCC report (**S. Watanabe**). Results from coupled atmosphere-ocean models, including the middle atmosphere but not interactive chemistry, were presented by **S. Missios** and **T. Spangehl**.

The SCOSTEP conference in July 2010 in Berlin provided an ideal forum for many of the SOLARIS participants to present their latest results. Some high-lights included the first presentation of solar influence investigations in the new CMIP5 coupled atmosphere-ocean simulations from WACCM4 (**D. Marsh**), and a first comparison of the new SOLARIS-proposed filtered experiments, which are similar to the CCMVal REF-B1 simulations but including non-correlated forcings from three CCMs (EMAC, WACCM, and MRI) (A. Kubin, K. Matthes, K. Shibata, K. Kodera, and U. Langematz).

Open Questions

Fruitful discussions and exchanges took place during the workshop and the side-meeting. The following open questions emerged as prerequisites for a realistic representation of the solar signal:

- What is the role of the QBO?
- What is the role of the SSTs in the mean climate (*e.g.*, what effect do SSTs have on the occurrence of stratospheric warmings)?
- What is the role of a coupled ocean?
- What is the impact of using different spectral solar irradiance data sets?

To approach these questions, new coordinated SOLARIS model studies were discussed and are presented in the next section.

Future Studies

Proposed Coordinated Experiments

In order to approach the above questions and compare the response in different CCMs, we propose coordinated model studies designed to specifically investigate the solar cycle response. These studies will be in addition to the existing coordinated studies in the SPARC-CCMVal initiative, where natural and anthropogenic forcings have also been included to reproduce the recent past. The direct effect of the 11-year solar cycle in the upper stratosphere depends on a good representation of solar radiation processes in the radiative transfer and the photochemical parameterizations (*e.g.*, Gray *et al.*, 2010), and is reasonably simulated by the CCMs (SPARC CCMVal, 2010). However, indirect dynamical effects in the tropical lower stratosphere and the extra-tropical stratosphere, as well as the extension of the signal into the troposphere, are more difficult to reproduce and were not discussed in the CCMVal report.

The following coordinated studies are therefore proposed (further details, such as input data and a detailed experimental description, can be found at **http://sparcsolaris.gfz-potsdam.de/**):

A) Coordinated Model Runs to Investigate Aliasing of Different Factors in the Tropical Lower Stratosphere

Recently, the discrepancy between modelling studies and observations regarding the vertical structure in the tropical solar signal, as shown by the WMO (2007), has been reduced in both CCMVal-1 reference simulations (Austin *et al.*, 2008) and CCMVal-2 simulations (SPARC CCMVal, 2010, Chapter 8). Similarly, other recent simulations with CCMs reproduce the observed vertical structure in the tropical stratosphere, but only with a (prescribed) QBO, time-varying solar cycle conditions and constant SSTs (Matthes *et al.*, 2007; Matthes *et al.*, 2010), or in a CCM with fixed solar cycle conditions, with or without an internally-generated QBO (Schmidt *et al.*, 2010). It is still unclear why a vertical structure in the solar signal appears, and whether it is related to non-linear interactions or arises from contamination by other signals (QBO, tropical SSTs).

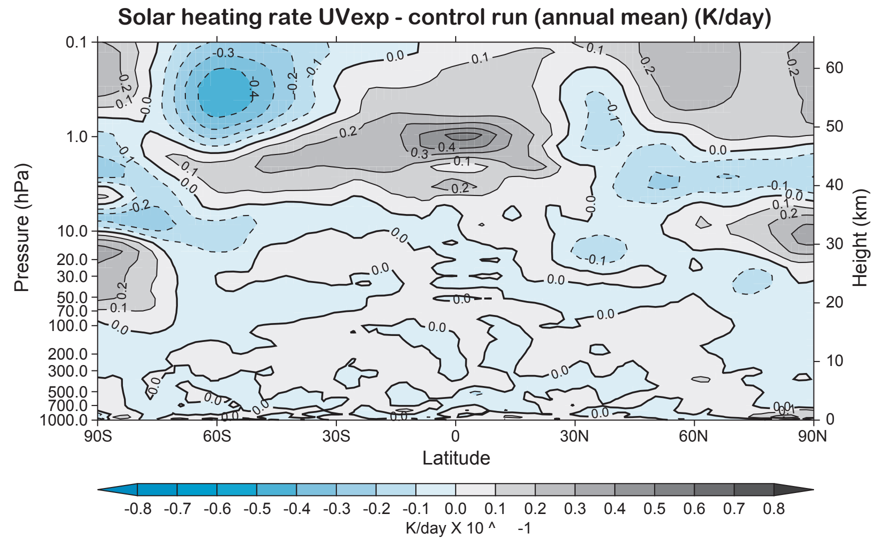

Figure 1: Annual mean short wave heating rate differences between a 7-year control run and a 7-year enhanced irradiance experiment. Note that the values have been divided by 10 for better readability (courtesy of G. Chiodo, University of Madrid).

To eliminate possible aliasing between the solar cycle and the QBO, as well as between the solar cycle and the SSTs, and/or the QBO and the SSTs, the REF-B1 CCMVal experiments were repeated with filtered SST and/or QBO data. The QBO signal (2-3 years) and solar cycle signals (larger than 10 years) have been filtered out of the SST data set used as a lower boundary for the REF-B1 simulations. Similarly, the QBO data were filtered to retain only periods between 9 - 48 months and exclude signals related to ENSO or the solar cycle.

Currently, two CCMs with a prescribed QBO (EMAC, WACCM), and one with internally generated QBO (MRI) have finished one ensemble of the modified REF-B1 experiments.

B) Coordinated Model Runs to Study the Uncertainty in Solar Forcing

Uncertainties in the solar irradiance could have a large impact on the simulation of the climate system. The solar irradiance data compiled by J. Lean (Lean, 2000) are most frequently used for model simulations. However, in the wavelength range important for ozone chemistry (200 - 400 nm), there are differences of up to 20% to the estimate of Krivova *et al.* (2006). Further uncertainties arise from new measurements from the SIM instrument onboard the SORCE satellite, which shows a completely different spectral distribution than expected, with possible implications for solar heating and ozone chemistry (*e.g.*, Haigh *et al.*, 2010).

The proposed coordinated CCM experiments would include:

1. A control (time slice) experiment with either Lean (standard) or SIM solar irradiance data,
2. Idealized experiments with enhanced solar UV forcing in certain spectral ranges, *i.e.*, an increase of 5% between 200 and 300 nm, and an increase of 1% between 300 and 400 nm.

An example of possible implications on solar heating rates from an increase of 1% in solar irradiance data from Lean between 300 and 400 nm is shown in **Figure 1**. The annual mean difference between a 7-year control run and increased solar irradiance experiments with WACCM shows an impact on the shortwave heating rates of 0.05 K, and on subsequent variables (not shown). These differences are one third of those reported from solar cycle studies and are therefore not negligible.

It is important to investigate the reliability of current SOLARIS irradiance data recommendations for CMIP5 and CCMVal, and test the sensitivity of different radiation and photochemistry models to different spectral irradiance data sets.

CMIP5 Recommendations and Analysis

SOLARIS provided recommendations for solar irradiance data sets to be used for the CMIP5 simulations. In particular, recommendations were made for the pre-industrial control runs, as well as the future projections for models that either change total solar irradiances (TSI) only, and climate models that prescribe spectrally resolved solar irradiance variations. Since a number of long, coordinated simulations with high-top CCMs exist within CMIP5, we are planning an inter-comparison of these runs with respect to the solar signal. The tropospheric solar signal in the high-top CMIP5 simulations will be investigated in order to gain insight into typical patterns, *e.g*. the tropical Pacific response (Meehl *et al*., 2009) and sensitivity on model characteristics.

Goals

SOLARIS provides an excellent platform for the coordination and discussion of solar-related studies, as well as to provide recommendations for the solar irradiance data used to drive middle atmosphere and climate models within the SPARC CCMVal initiative and the CMIP5 simulations. The data portal will be extended and maintained, especially with methods for the inclusion of energetic particles. It will foster and initiate detailed studies on the solar UV and TSI mechanisms, as well as high energy particle events (in collaboration with HEPPA). Communication and collaboration between the SOLARIS middle atmosphere community and the climate community has begun, and will be intensified and extended, especially in light of the fact that a number of climate models that include the middle atmosphere are participating in the next IPCC scenario simulations, in support of the next IPCC report in 2013.

Acknowledgments

This article is dedicated to the memory of Christopher Bell, who had a promising career ahead of him and was unfortunately the victim of a tragic accident in June 2010. We would like to thank WCRP/SPARC for their support, as well as for the sponsorship from the Helmholtz Association in the frame of the Helmholtz-University Young Investigators Group of KM. Also, we appreciate the logistical help from Veronika Söllner from GFZ Potsdam.

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Report on the 7th SPARC Data Assimilation Workshop

21-23 June 2010, Exeter, UK

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The Seventh Stratospheric Processes And their Role in Climate (SPARC) Data Assimilation (SPARC-DA7) workshop held in Exeter, England during 21-23 June 2010 was the latest in a series of annual meetings that bring together data assimilators, users of assimilation products, and experts in modelling, measurements and process studies. Data assimilation requires knowledge of measurement and model errors, which, in turn, require knowledge of the true underlying system – the middle atmosphere. Therefore, advancement of assimilation techniques requires interaction of assimilators with dynamicists, chemists and users of assimilation products. One of the ways in which we broaden the participation in these meetings beyond data assimilators is by inviting experts (who usually are not data assimilators) to present lectures and to promote discussion along certain themes. This year the themes were: "seamless prediction", stratosphere-troposphere coupling and tropospheric constituent assimilation.

"Seamless prediction" refers to the goal of improving predictions on weather to climate time scales. It is also a focus area and common goal of both the World Weather Research Programme (WWRP) and the World Climate Research Programme (WCRP). One aspect of seamless prediction is the use of data assimilation for understanding model errors. The second theme was motivated by the fact that at operational weather centres, the importance of the stratosphere is primarily seen through its impact on the troposphere. Finally, there is increasing demand for air quality and environmental forecasting and assimilation. Thus, the last theme offered an opportunity to better connect the stratospheric chemical assimilation community with the tropospheric air quality assimilation community.

Seamless Prediction and Model Error

In addition to evaluating climate models statistically, it is also useful to consider their predictions on short time scales. A definition of seamless model assessment is the use of a wide variety of time scales to assess and improve the representation of processes within a model. The basis for the notion of seamless assessment lies in the fact that model errors on a given time scale can first appear on shorter time scales. For example, **K. Williams** showed that cloud regime properties are local but tend to appear at the first time step and persist for about 5 days, and that errors in the Madden-Julian Oscillation (MJO) can appear by day 5. For this reason, the Transpose-AMIP project (supported by the WGCM and WGNE of WCRP and WWRP, respectively and chaired by Williams) has as its goal the evaluation of climate models on short time scales. ECMWF reanalyses for 2008-9 provide the initial conditions and 64 5-day forecasts are run. By assessing model parameterizations against specific events, climate models participating in CMIP5 can be assessed in terms of their ability to depict fast processes. The short-term predictive ability of climate models can also be compared.

P. Telford discussed "nudging", or relaxation, of a CCM version of the Met Office UM to ECMWF analyses. This approach is another very effective way of identifying model biases, in this case near the tropopause. Furthermore, this approach is useful for diagnostic studies, for example in the attribution of ozone changes in the aftermath of the Mt Pinatubo eruption. Future applications might include local "nudging" to examine how reducing errors in one location (*e.g.*, European blocking) might affect model errors elsewhere.

Data assimilation can be used to infer aspects of the dynamical or chemical behaviour of the atmosphere, though it is always important to assess the limitations of such an approach. **Y. Orsolini** presented a technique based on data assimilation to estimate chemical polar ozone loss in the 06/07 Arctic winter. By comparing the results with another ozone loss estimate based on CTM simulations, he was able to show the strengths of the data assimilation approach, but also highlight issues with transport in the fields produced by data assimilation, which could largely be addressed in future by repeating the experiments using 4D-Var rather than 3D-Var.

R. Menard examined different methods of background error covariance calculation applied to chemical data assimilation. He found that the NMC method (National Meteorological Centre) works in a denser observation network and under advection dynamics only, while the forecast difference approach (sometimes know as the Canadian Quick method) can easily introduce smaller-scale variances and correlations. For the Desroziers method, the estimation of the error variances is sensitive to the mis-specification of the observation error correlation scale (much more than to mis-specification of the corresponding quantity for the background error). The representation of background errors was also a key part of the talk by **T. Milewski**, who is developing an ensemble Kalman filter for stratospheric chemical data assimilation. Using synthetic temperature and ozone observations, he showed that there were some benefits in the localization of the background error covariances, although this comes at the expense of a loss of mass/wind balance.

Of relevance to Milewski's work, but of potential importance to all areas of ensemble data assimilation, was the presentation by **C. Bishop**, in which the concept of the "outer loop" currently used for 4D-Var was derived and interpreted in the ensemble context. The outer loop in ensemble data assimilation provides an opportunity to rerun the ensemble about an ensemble mean that is closer to the truth. This might be attractive in areas of strong gradients, such as near fronts, which may be poorly represented by any of the ensemble members. Experiments with a simple soliton model showed how re-running the ensemble in the outer loop allows the ensemble covariance

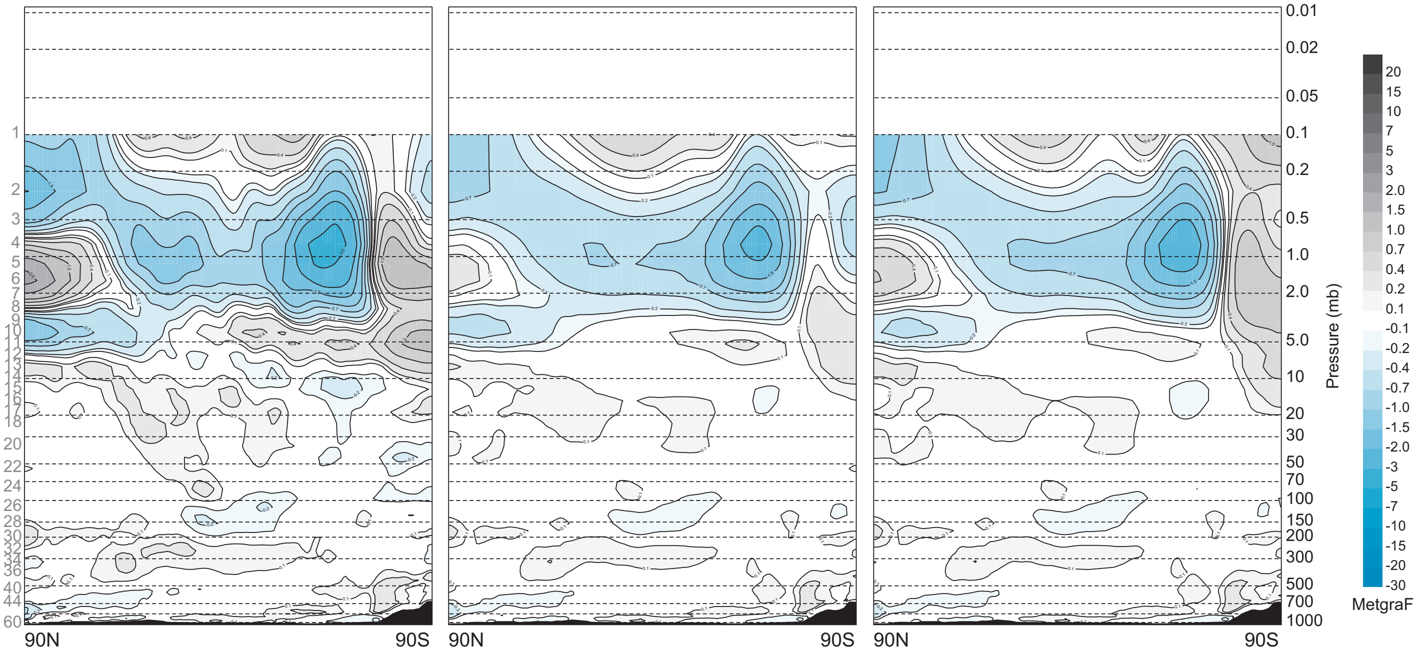

Figure 1: Monthly mean analysis increment with ECMWF weak constraint. Mean analysis increments indicate bias since random errors should average to zero. ERA-Interim (left panel) are compared to those obtained with a weak constraint (centre panel) and those obtained by removing balance operators applied to background error covariances (right panel). (Figure courtesy of Y. Tremolet, ECMWF.)

to better approximate the covariance of the distribution of historical forecasts given the truth.

If the general idea behind seamless prediction is the use of various time scales to assess and minimise model error, then data assimilation also has a role to play in seamless assessment of models. Data assimilation can be used to estimate uncertain parameters in parameterization schemes (such as gravity wave drag schemes) and thereby reduce model error. Alternatively, at ECMWF, model error is now being directly estimated along with initial conditions. **Y. Tremolet** noted that a constant model error term has been estimated operationally since September 2009. The estimated model error is largest in the stratosphere and appears to be systematic, rather than random. The addition of model error estimation to the assimilation system reduces the size of analysis increments, but the estimate does not always reflect model error. In one example, bias in aircraft observations over Denver was picked up in the model error term. In another example, deficiencies of balance operators in background error covariances were found to be similar to the model error estimate. **Figure 1** shows the monthly mean analysis increment with (centre panel) and without (left panel) a model error term. Increments are smaller with the model error term. However, the right panel shows that simply removing the balance operators from error covariances produces similar mean analysis increments to that obtained with a model error term. Thus, perhaps with the amount of observations assimilated, balance is being captured in the troposphere and there is little need for additional balance constraints. In the stratosphere, the covariance estimates are noisy and the balance operators may need improving. Future work involves allowing the model error term to be time varying, over long windows, effectively approximating a Kalman smoother. A key aspect of future improvements in NWP forecasts will rely on the accurate characterization of model error, just as it is with climate models.

New applications of data assimilation to problems of long time scales were presented by L. Neef and K. Miyazaki. **L. Neef** described the problem of assimilating Earth orientation parameters to constrain climate models since wind and mass changes influence the Earth's angular momentum which affects its wobble and rotation rate. The challenge is using a globally integrated quantity to update state variables. **K. Miyazaki** described a new way to estimate carbon fluxes at the Earth's surface using a state-augmented ensemble Kalman filter. In his scheme, meteorological variables were estimated simultaneously with CO_2 and CO_2 fluxes, improving CO_2 estimates. A variety of data sources were assimilated (from surface flask measurements, aircraft and GOSAT) making this perhaps the most advanced carbon flux estimation system in the world.

Observations and Impacts

An important role for data assimilation in climate science lies in assessing the impact of proposed Earth observations (most frequently satellite missions). As pointed out by **W. Lahoz**, the quantity of interest is the *incremental* benefit of a proposed new observation set over the existing global Earth observation network. To assess such a benefit, Observing System Simulation Experiments (OSSEs) are typically performed, and are increasingly being required of new missions early in the design phase. In OSSEs, synthetic measurements from the proposed instrument are assimilated and compared with a control cycle without the new measurements. In both cycles, the most realistic observation network (*i.e.,* most of the existing currently available observations) is used. While the results of OSSEs are not always clear because they are model dependent and because the issue of biases (from models or observations) are usually not addressed, OSSEs can still be valuable. For example, OSSEs for SWIFT (Stratospheric Wind

Interferometer for Transport Studies) found a significant benefit of SWIFT winds in the tropical stratosphere (Lahoz *et al*., 2005). Lahoz also noted that OSSEs can be used to compare the potential impact of two proposed instruments, showing that MAGEAQ (Monitoring the Atmosphere from Geostationary orbit for European Air Quality) would be more beneficial than MTG/IRS at observing lower tropospheric CO and O_3. Using an ensemble data assimilation approach, **H. Körnich** found the impact of ADM winds on zonal wind forecasts to be comparable to that of radiosondes in the Arctic, the tropics and over oceans (compare top and bottom panels of **Figure 2**). However, the impact of using different vertical sampling strategies (targeting the UTLS or the stratosphere) was unclear. Interestingly, vertical propagation of information is seen in that improved forecasts in the troposphere at day 4 lead to improved stratospheric forecasts at day 7, with this time scale being consistent with that of large scale Rossby waves (Figure 2c, top and bottom).

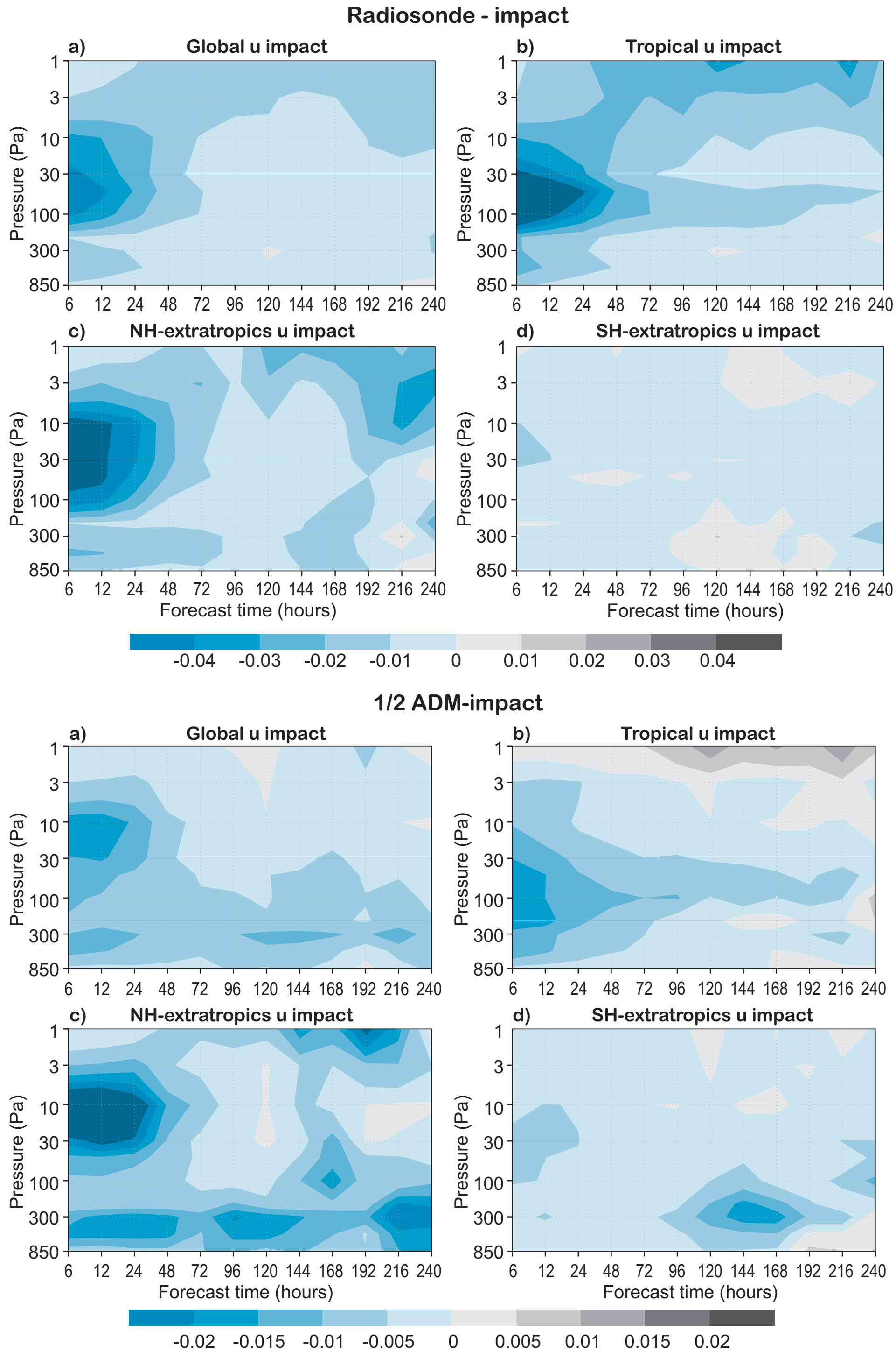

Figure 2: Zonal wind impact as estimated from the reduction of the ensemble forecast spread due to removal of radiosonde data (top 4 panels:a,b,c,d) or the addition of ADM-Aeolus data using the strato-vertical sampling (bottom 4 panels:a,b,c,d). Only half of the expected ADM-data amount was included. The area averages include only significant spread changes on a 95%-confidence level. Though the vertical sampling scenario focuses on the stratosphere, it also contains the troposphere, but with less dense sampling than the tropospheric sampling scenarios (Figure courtesy of H. Körnich, Stockholm U.)

The assimilation of new satellite instruments requires the preparation of new forward models relating measured variables to model (or analysed) variables. For operational assimilation, common software (such as fast radiative transfer models) is often used by several forecasting centres. **H. Lewis** presented a new software package to pre-process GPS radio occultation data from levels 1a, 1b and 2 aimed at operational centres, but such software would be equally valuable for research assimilation systems. Detailed information may be found at **http://www.grassaf.org**. In addition to providing software, bending angles, refractivity, temperature, pressure and humidity profiles are available in near-real time with additional products available off-line.

When satellite retrievals are assimilated, as is often the case with observations of constituents, there is danger of assimilating *a priori* content instead of the information from the measurement. To avoid this, **A. Kaiser-Weiss** described a new method of assimilating retrievals in which an interface step is added between the retrievals and their assimilation in 4-D variational schemes. In this step, the information of observations is isolated and measurement space is transformed so errors are uncorrelated. This new method will be tested at ECMWF with real measurements.

Stratosphere-Troposphere coupling

As operational weather forecasting centres have increased model lid heights into the mesosphere, in recent years, stratospheric data assimilation has become the purview of operational centres. Since operational centres are mainly concerned with the prediction of weather in the troposphere,

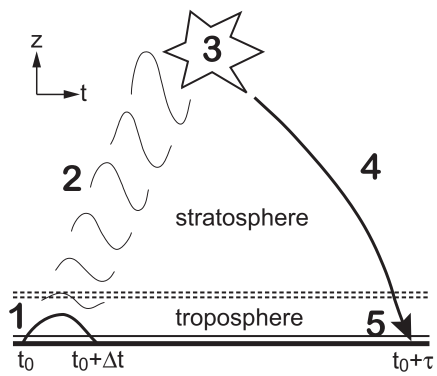

Figure 3: Schematic illustration of Troposphere-Stratosphere-Troposphere events. (1) Forced pulse of planetary waves occurring over time Δt; (2) upward-propagating waves; (3) dissipation and breaking of waves; (4) induced downward-propagating anomalies; and (5) tropospheric response at time lag $\tau > \Delta t$. (From Reichler et al., 2005.)

stratospheric data assimilation is primarily valued for its ability to impact tropospheric forecast quality. The fact that stratospheric dynamics can influence the troposphere on monthly to seasonal to decadal time scales was noted by **A. Scaife** in an overview presentation. Stratospheric events, such as sudden warmings, volcanic eruptions or ozone depletion, and signals such as the quasi-biennial oscillation can influence the extra-tropical NAO signal. Furthermore, the stratosphere can modulate tropospheric signals such as ENSO, again influencing the NAO. Thus the stratosphere effectively has a "memory" which can be exploited to enhance seasonal to decadal predictions. Nevertheless, not all models running seasonal or decadal predictions adequately resolve the stratosphere. Thus, CliVar's WGSIP (Working Group on Seasonal and Interannual Prediction) has added a new component to its international Coupled Historical Seasonal Forecasting Project (CHFP) in which the additional benefit of resolving the stratosphere is assessed in the context of seasonal forecasts. For decadal prediction, CMIP5 will have some models that resolve the stratosphere.

An overview of mechanisms that could explain the influence of the stratosphere on the troposphere was presented by **A. Charlton-Perez**. **Figure 3** (from Reichler *et al*., 2005) illustrates the various stages involved in producing a downward propagating signal from the stratosphere, such as those seen in Baldwin and Dunkerton (2001)'s dripping paint figure. In stage 1, a tropospheric wave is launched near the surface. It propagates up to the stratosphere in stage 2, increasing in amplitude as density decreases. The wave dissipates, interacting with the mean flow in the stratosphere in stage 3, leading to downward propagating wind anomalies in stage 4. Stage 5 describes the stratosphere-troposphere coupling stage, for which various mechanisms have been proposed. Charlton-Perez noted that while the mechanisms to explain stage 5 are still in dispute, none of the proposed mechanisms can be ruled out. He also wondered whether it is important to know which mechanism (*e.g.,* direct influence of stratosphere PV anomalies on the troposphere, stratospheric zonal wind shear causing reflection of planetary waves back into the troposphere, modulation by stratospheric zonal winds of baroclinic wave life cycles or eddies) explains stratosphere-troposphere coupling or whether it is sufficient to know that they all can occur.

While stratosphere-troposphere coupling is usually examined on time scales of a few weeks or longer, the influence of the stratosphere or the tropospheric medium range weather forecasts (up to 10 days) was considered by **S. Polavarapu** using the Canadian Meteorological Centre's operational forecasting system. In comparing the forecast skill of a low top system (with model lid height of 10 hPa) to a high top system (with a model lid height of 0.1 hPa), a clear downward propagation of forecast skill from day 1 to day 10 was seen in extra-tropical regions. The high-top system resulted in a dramatic 75% reduction of geopotential forecast error standard deviation (measured against radiosondes) in the lower stratosphere, with 5-10% reduction in the troposphere. Most of the improvement (in the troposphere and the stratosphere) was due to the model changes, not to the addition of extra observations in the upper stratosphere (AMSU ch. 11-14, GPS RO from 30-40 km). This result is consistent with the notion that information can propagate upward in a model that is capable of simulating realistic stratospheric dynamics. The impact of the stratosphere on tropospheric forecasts in the 5-10 day range was also seen by **S. Mahmood** when assessing the skill of the Met Office model with a 40 km top to one with an 80 km top. However, the additional benefit of increased stratospheric resolution on tropospheric forecast skill was modest, and more apparent on the 10-15 day range. Thus, once the stratosphere is reasonably simulated, further improvements may result in smaller incremental benefits on tropospheric forecasts.

N. Zagar presented an analysis of Kelvin waves in various atmospheric analyses. The normal modes method she used to perform the analysis has the advantage of being able to test impacts of changes in model physics and data assimilation on vertical energy propagation and wave properties. Here, she showed that there are large differences in the climatologies of Kelvin waves calculated from NCEP, ECMWF and other analyses, which are related to unreliable tropical circulations in these analyses. Focusing on ECMWF analyses for 2007-2009, she found evidence for stratospheric Kelvin waves, which propagate energy upward with periods about 16 days. Horizontal phase speeds are between 20 m/s and 30 m/s. Maximal Kelvin wave activity is around the tropopause region in the Pacific.

D. Jackson examined low ozone events (LOEs) in the southern summer stratosphere seen in ozone analyses based on EOS MLS data. Particularly interesting were the deep LOEs seen when tongues of low ozone at 31 and 100 hPa were superposed. The superposition is probably due to the tilt of baroclinic medium scale (wavenumbers 4-6) waves present between the two levels. Transport means that the LOEs are not simply focused over the pole, but tend to be seen preferentially over the Weddell Sea. The reason for this is unclear.

Stratosphere-Mesosphere coupling

Vertical coupling of the troposphere, stratosphere and mesosphere occurs through vertically propagating gravity waves. Liu *et al*. (2009) showed that whether perturbations were introduced to the lower atmosphere or to the mesosphere, the resulting error growth appearing after 2 days was similar. Thus, errors in the lower troposphere are connected to mesospheric errors through vertically propagating gravity waves. Since gravity waves reduce predictability decay (Ngan *et al.,* 2009) in rotating stratified turbulence, **K. Ngan** asked whether the increasing role of gravity waves in mesospheric energy spectra also leads to increased predictability (or reduced predictability decay). Using the

Met Office unified model with a lid at 60 km, Ngan showed the relative kinetic energy spectra in the troposphere, stratosphere and mesosphere. Predictability decay was found to be modestly slower in the mesosphere than in the troposphere, but numerical issues of whether gravity waves are properly resolved were raised.

Vertical coupling of the middle atmosphere is also illustrated by stratospheric sudden warming events, which are driven by planetary waves propagating up from troposphere. Manney *et al*. (2008; 2009) have shown that such events can sometimes result in large changes in stratospheric extent with the stratopause reaching heights of 75 km or more. Not surprisingly, data assimilation systems with model lids or sponge layers below 75 km have difficulty simulating such events. In an effort to improve the GMAO model's ability to fully simulate stratopause evolution, **L. Coy** and S. Pawson raised the GMAO model lid from 0.01 hPa or 80 km to roughly 100 km. The Fomichev non-LTE radiation scheme was added, background error covariances were extended to the mesopause, and other adjustments were made (such as to gravity wave drag parameters). With the assimilation of MLS temperatures, the extended GMAO system was able to better describe the January 2006 stratospheric sudden warming event. The same event was also used by **S. Ren** to assess the addition of SABER temperatures to the CMAM assimilation system. Though the CMAM had been able to capture the stratopause height changes noted by Manney (2008) without assimilating mesospheric measurements (Polavarapu *et al*., 2008, Fig. 4), Ren noticed that when mesospheric temperatures from SABER are assimilated, the simulations are less sensitive to the presence or absence of a nonorogaphic gravity wave drag scheme. In addition, **M. Keller** noted that without the assimilation of mesospheric temperatures, local instabilities such as the mesospheric 2-day wave are not captured. Keller further considered how the assimilation of mesospheric measurements is able to capture the 2-day wave, whether through direct sampling of the wave at 6-hourly intervals, or through adjustment of the zonal mean flow. While evidence pointed to the latter explanation in January 2007, a mystery remains in that the February 2007 2-day wave was absent from CMAM analyses even when SABER temperatures were assimilated.

In addition to GMAO, the Met Office is also studying the impact of raising their model lid (from 70 to 80 km). **D. Long** showed that changes to the non-orographic gravity wave drag scheme (to parameters, to make it momentum conserving) and the conversion of the turbulent dissipation of gravity waves to a heating resulted in changes to zonal mean biases of the model. Since weather forecasting model domains may now reach the mesopause, their domains can overlap with upper atmospheric physical models used for space weather. **A. Bushell** noted that space weather products and services are now being developed in Europe, and that the meteorological data assimilation community has a potential role to play in assessing upper atmosphere physical models, and perhaps in coupling the lower atmosphere to upper atmospheric models. As a first step in this direction, Bushell used SABER and MLS temperatures to assess Met Office and CMAT2 (an upper atmosphere model) fields in the region where their domains overlap (100 hPa to 80 km). Preliminary conclusions were that satellite measurements such as those from SABER and MLS were very valuable for assessing middle atmospheric and lower thermospheric model performance.

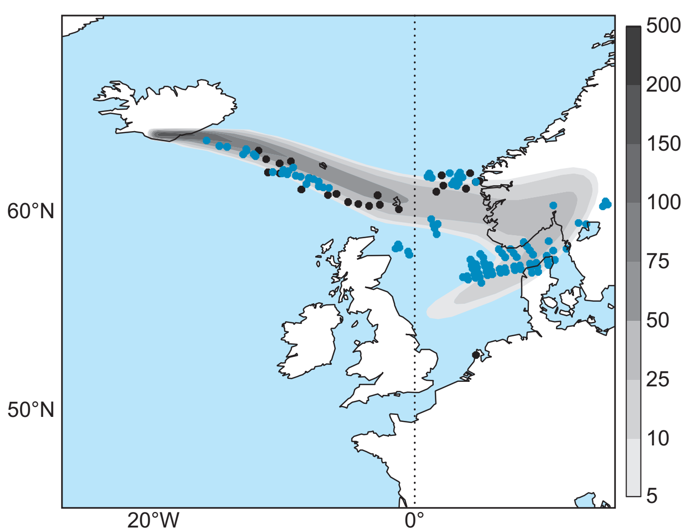

Figure 6: The locations where AIRS data (black dots) and IASI data (blue dots) have been rejected due to excessive aerosol contamination during the 12z 4D-Var assimilation window on 15th April. Superimposed is a 39-hour MACC forecast from 14th April (verifying with the centre of the same 4D-Var assimilation window) predicting the trajectory of simulated aerosol injection at 5 km. The units in the legend indicate only a relative magnitude of column aerosol tracer. (Figure courtesy of Tony McNally, Reima Eresmaa and Johannes Flemming, ECMWF.)

Constituents

D. Jones discussed the assimilation of tropospheric ozone (and precursors) in an air quality prediction system. Assimilating tropospheric ozone and CO (from TES) was generally effective in reducing the ozone bias in the analyses, but it is also a good method for pinpointing model biases. The assimilation significantly increased ozone and reduced the bias in the free troposphere, which they attributed to an under-estimate of lightning NO_x emissions, based on the CO analysis. **Figure 4** (see colour plate I) shows the impact of assimilating TES data on surface ozone over the USA. Comparison with independent observations shows that after assimilation, the bias in surface ozone was reduced in the western USA, but surface ozone was still overestimated in the eastern USA. This was attributed to an overestimate of surface emissions of NO_x in the model. Improving the representation of these emissions improved the ozone analyses (**Figure 5** - colour plate I). The speaker raised an interesting question from this result: should we use data assimilation for parameter estimation (as here), or just as a means of reducing forecast errors (as in NWP), or both? **F. Baier's** talk focused on lower stratospheric ozone and showed the benefits of assimilating ozonesonde data, at least near the sonde stations. Improved analysis may be achieved *via* further tuning of both observation and background error covariances.

The assimilation of multiple species in Jones' talk certainly highlights the benefit of complementary information, since without CO assimilation, it would have been hard to attribute model bias to the erroneous NO_x emissions. In a similar manner, **Q. Errera** aimed to assimilate stratospheric ozone to constrain inorganic Cl in the stratosphere. While it shows that the constraint of assimilated ozone on modelled HCl is weak, the constraint was found to be sufficient to allow the analyses of HCl to reproduce the observed HCl trend in the upper stratosphere lower mesosphere during the three years period of assimilation.

In the area of aerosol assimilation, **Y. Pradhan** and K. Ngan described the development of a dust assimilation scheme for the Met Office Southern Asian LAM. SEVIRI aerosol optical depths are assimilated. Initial trials using 3D-Var and run for Jan / Feb 2010, show promising results. Future work will extend the data assimilation to 4D-Var and run more extensive trials (*e.g.*, for major dust events).

A. Benedetti gave an overview of aerosol assimilation work at ECMWF (based on MODIS aerosol optical depths) with a focus on the analysis of the volcanic ash cloud from the recent Eyjafjallajökul eruption. Non-operational simulations with a simple representation of the source of the ash showed reasonable agreement against AIRS and IASI aerosol data. Most of the uncertainty in these plume forecasts is caused by the assumptions about the injection height. Further work to include aerosol optical depths from SEVIRI and AATSR is promising but biases in these products have to be identified and corrected. Operational analyses of the Eyjafjallajökul plume suffered problems because quality control rejected most of the aerosol observations in the plume (see **Figure 6**) and because there is no way of representing the source of the volcanic plume. In readiness for future eruptions, a future operational system may include the option to switch to a "volcanic eruption mode", which would incorporate relaxed aerosol observation quality control and a volcano location / plume height database.

Discussion

The SPARC data assimilation working group members are continuing to work in the areas of interest to SPARC: vertical coupling of the stratosphere with the troposphere and the mesosphere, constituent assimilation and observing system design. New applications are continuing to emerge, such as environmental prediction (*e.g.*, aerosol and dust forecasting), operational carbon flux estimation, and even extracting long time scale information about climate from Earth rotation observations. Issues that continue to be raised include the reliability of analyses in the tropics, and how to utilise assimilation techniques to improve model error. While meteorological data assimilation may be primarily used to obtain initial conditions for weather forecasting, it may be that for air quality or climate applications, data assimilation is most valuable for obtaining model parameters including constituent sources and sinks or model errors. This use of data assimilation comes under the "seamless prediction" banner and is of interest to both the WCRP and the WWRP. As the WCRP and SPARC evolve into their post-2013 form, an important question for the present is how will the data assimilation working group evolve and what role will it play?

Next meeting

The next SPARC Data assimilation workshop will be held in Brussels, Belgium during 20-22 June 2011. The local organizer is Quentin Errera. Themes and invited speakers will be announced in the next few months.

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Report on WCRP Workshop on Seasonal to Multi-Decadal Predictability of Polar Climate

25-29 October 2010, Bergen, Norway

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Background and purpose of workshop

Over the last few decades, the polar regions have exhibited some of the most striking changes in the observed climate record. Whilst the Arctic has warmed, as expected from the polar amplification of greenhouse-gas (GHG) induced warming arising from the ice-albedo feedback, the observed rate of summer-time sea-ice retreat in the Arctic is at the upper limit of climate model predictions. At the same time, Antarctic sea-ice extent is observed to be increasing, contrary to the model predictions. The clearest observed changes in the Antarctic, which are associated with the poleward shift and intensification of the summer-time mid-latitude jet, are primarily attributed to the ozone hole, which implies that the observed trends will weaken substantially or could even reverse in the coming decades as the ozone hole recovers. However, natural variability in polar regions is large, with substantial power at multi-decadal time scales, and manifests itself in large-scale "modes" whose physical nature and causality are not clear. There are even suggestions of an inter-hemispheric "see-saw". As a result, it is difficult to determine how much of the recent behaviour might be due to natural variability.

The observed and predicted changes in the polar regions have significant implications. In the Arctic, sea-ice changes will directly impact shipping, resource extraction, pollution, and coastal erosion, affecting the lives of inhabitants and those who operate in that region. In the Antarctic, ocean circulation changes will affect the rate of carbon uptake in the Southern Ocean, and could have implications for the stability of the West Antarctic ice shelf. There is, therefore, a pressing societal need to improve the reliability of climate model predictions in polar regions, including both the response to anthropogenic forcings and our understanding of the decadal time scale variability. The spatial-temporal coherence of this variability offers the hope that some component of it might actually be predictable, given knowledge of the initial state, and the initial state could also be important for the response of the polar regions to anthropogenic forcing. However, at this point we do not really know which measurements are most important for constraining that state. In addition to the societal benefits that would result from improved predictions, we would also be in a better position to explain the variability in the evolving climate record.

Because of the strong coupling that exists in the polar regions between ocean, sea ice, troposphere and stratosphere, it is necessary for all these scientific communities to work together in order to make significant progress on these problems. This was the motivation behind the WCRP Workshop on Seasonal to Multi-Decadal Predictability of Polar Climate, which brought together approximately 80 experts on polar climate variability and predictability from around the world, representing not only the above-mentioned range of physical disciplines but also observations, theory, processes, and modelling, and with a bi-polar, global perspective. The purpose of the workshop was to summarize the current state of knowledge and identify concrete steps to improve our predictive capability in polar regions[1]. The workshop was hosted by the Bjerknes Centre at the University of Bergen, and was formally opened by the Rector of the University, **Sigmund Grønmo**. JSC Chair **Tony Busalacchi** also provided welcoming remarks on behalf of the WCRP.

Reports on scientific sessions

A preliminary session provided some background context. **T. Shepherd** presented the scientific motivation for the workshop (as described above), and emphasised the role of the oceans, sea ice, land surface and stratosphere as inherently stable parts of the climate system, with significant inertia, which provide non-trivial boundary conditions (with memory) for the variability that is ultimately driven by the unstable troposphere **(Figure 1)**. This suggests that the key to improved prediction is understanding and accurately representing the sources of memory within the different climate system components, and the feedbacks between them. The stratosphere is a special case because it also represents a source of external forcing (ozone depletion, ozone changes due to solar variability, aerosols due to volcanic eruptions, and possibly geoengineering), in addition to

[1]The workshop programme and copies of the presentations can be found at http://www.atmosp.physics.utoronto.ca/SPARC/PolarWorkshop/presentations_bergen.htm

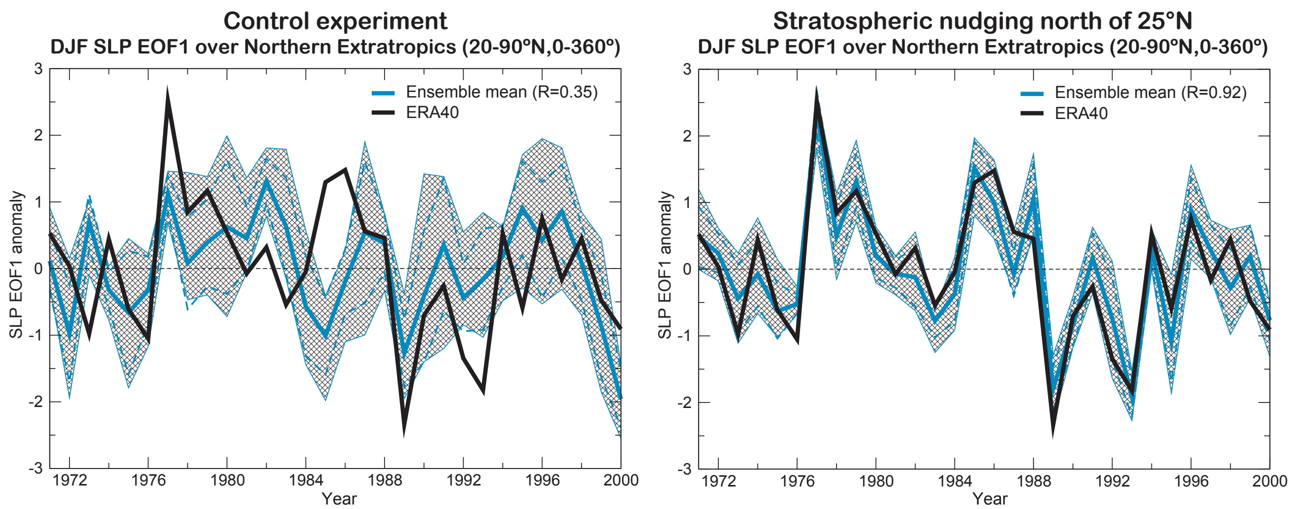

Figure 1: Evidence for the role of the stratosphere in modulating tropospheric teleconnections. A 5-member ensemble of AMIP-type simulations with the Météo-France model (shading, with the thick blue curve the ensemble mean and the dashed lines +/- 1 standard deviation) is not able to reproduce observed (black curve) interannual variations in the DJF surface Northern Hemisphere Annular Mode (NAM) over the 1971-2000 time period, represented here by the principal component of surface pressure north of 20°N, when constrained only by SSTs (left panel), but does so extremely well when the extra-tropical stratosphere is nudged to ERA-40 reanalyses (right panel). R is the ensemble mean anomaly correlation coefficient with ERA-40. From Douville (2009, GRL).

GHG forcing. **B. Kirtman** reviewed recent progress in seasonal to decadal prediction, which lies between the two extremes of weather prediction (dependent entirely on initial conditions, and essentially deterministic) and centennial time scale climate projections (dependent mainly on external forcings). Modern seasonal prediction relies almost entirely on the predictability of ENSO, and forecast skill is generally confined to temperate latitudes. There are believed to be untapped sources of seasonal predictability in the stratosphere, in sea ice, and in the land-surface (including snow cover), which are all operative at high latitudes — stratosphere-troposphere coupling is strongest in polar regions — so inclusion of these processes should improve predictive skill at higher latitudes. On decadal time scales, the extra-tropical ocean is also believed to represent an untapped source of predictability. **G. Boer** highlighted the rapidly growing scientific interest in decadal predictability, though noted that the decadal time scale was more of a human than a physical time scale. He reviewed recent studies of predictability in polar regions from a "potential predictability" perspective, which uses a "perfect model" framework to identify what fraction of the year-to-year changes might consist of long-time scale processes (including the forced component) that are potentially predictable given sufficient knowledge of the initial state, as opposed to unpredictable climate noise. These studies hint at some potential predictability in polar regions (**Figure 2**), but it is not yet clear how large or useful this will be. Some open issues raised in the talks by Kirtman and Boer included the use of a multi-model ensemble (which seems invariably to outperform the "best" models, even for the same ensemble size), how to best combine dynamical and statistical approaches, and how to objectively define the potentially predictable, as opposed to noisy part of the signal. In the end, predictability is a property not just of the physical system but also of the filter we apply to it, which depends on the application.

Session 1 was devoted to the mechanisms that rule sea ice variability, the way they are represented in models, and the processes that may help us in providing useful predictions. **H. Goosse** discussed the observed and simulated variations over the last centuries. He insisted that the last 30 years are not necessarily representative of the full range of variability of the system and thus collecting and analysing longer time series is needed, in particular to adequately evaluate the variability simulated by models. **R. Kwok** presented a comparison of simulated and observed ice motion and ice transport. He highlighted that many models have strong biases that need to be reduced in order to improve our ability to make good predictions. **C. Bitz** discussed different mechanisms that could lead to predictability in the

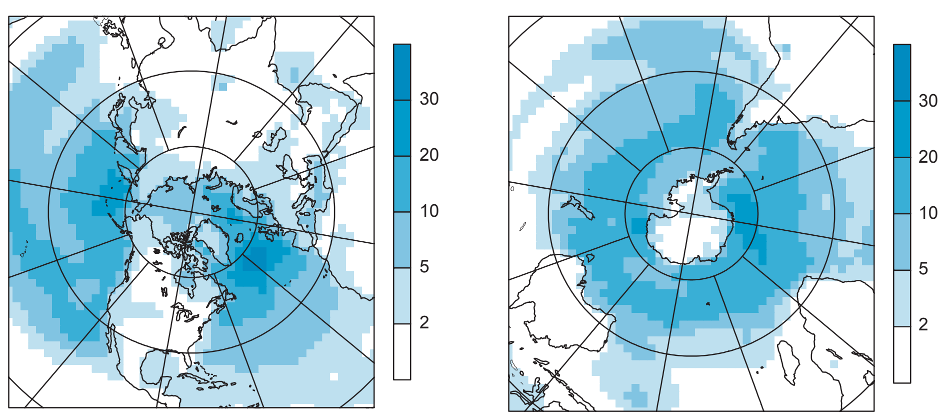

Figure 2: Evidence for decadal predictability of surface temperature at high latitudes from low-frequency internal variability, based on a "perfect model" diagnosis. The shading shows the fraction of the internally generated temperature variance accounted for by decadal and longer time scales within a multi-model ensemble of unforced control simulations in the CMIP3 archive. The presumption is that these long time scales are "potentially predictable" with sufficient information and knowledge (see also Boer and Lambert, 2008, GRL).

system, analysing ensembles of simulations with a coupled general circulation model (GCM) and observations. Re-emergence of anomalies in different seasons related to sea surface temperatures (SSTs) (linked with ice concentration changes) or changes in ice thickness appeared to be particularly promising for predictions of Northern Hemisphere sea-ice area on time scales of a few months (**Figure 3**). **J. Overland** proposed a hypothesis in which a reduced summer ice cover would lead to a warmer fall in the Arctic, inducing a decrease in atmospheric geopotential height and a large-scale reorganization of the atmospheric circulation that may be characterized by a low index of the Arctic Oscillation. If this mechanism is valid, it would have a strong impact on predictions at the seasonal scale, as well as on long term changes, because of the strong decreasing trend in Arctic ice extent projected for the next decades.

M. Raphael described sea-ice variability in the Southern Ocean and its links with atmospheric changes. Sea ice is influenced by all the known modes of atmospheric variability in the Southern Hemisphere: the Southern Hemisphere Annular Mode (SAM), the Pacific Southern America (PSA) pattern, the Semi-Annual Oscillation (SAO), and the Zonal Wave 3 (ZW3). However, none of them explains a great deal of the sea ice variance integrated over the whole Southern Ocean, probably because those modes were defined as atmospheric modes, rather than in terms of their impact on sea ice. **F. Massonnet** discussed the importance of model physics, resolution and forcing in simulations of Arctic and Antarctic sea-ice variability performed with an ocean-sea ice model driven by atmospheric reanalyses. A good forcing was found to be essential. Model physics appeared crucial in order to reproduce well the variability in the Arctic, in particular in summer, while the improvements brought by a more sophisticated model were less clear in the Southern Ocean. In the range of resolutions tested (between 0.5 and 2°), the resolution of the sea ice model was not the most critical issue.

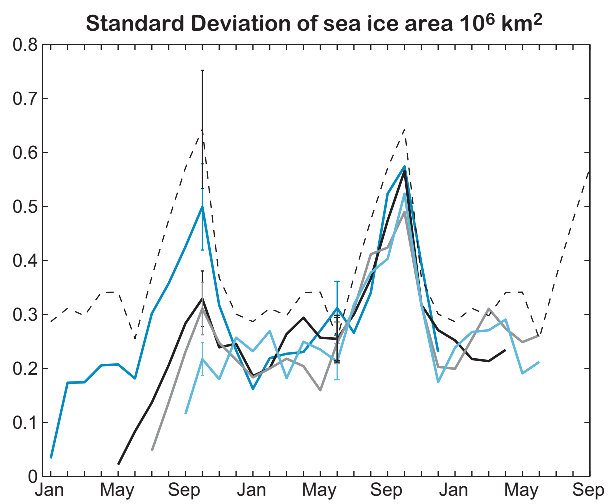

Figure 3: Evidence for seasonal predictability of summer-time sea ice based on "perfect model" experiments. The black, gray, blue and light blue curves in the figure show the growth of the standard deviation of Northern Hemisphere sea-ice area across an ensemble of model simulations where each member was initialized with identical sea-ice, ocean, and land surface conditions, starting from different points in the year. The black dashed curve is the saturation level of the standard deviation from a long control run. The solid curves lie below the black dashed curve, indicating that sea ice area is potentially predictable for up to a year in advance. The initial loss of potential predictability is faster for start dates in the summer season. Nonetheless, based on these experiments, perfect knowledge of the initial conditions in winter only offers modest predictability of sea ice area in the following summer. Figure courtesy of Cecilia M. Bitz, University of Washington.

K. Giles discussed the available satellite observations of sea-ice thickness and how they could be used to make skillful decadal predictions. Analysing observed sea-ice thickness and concentration, she showed that the summer extent is well correlated with the thickness of the following winter, but not with that of the previous winter, suggesting that summer extent could help in estimating the next winter's ice thickness.

Session 2 began with a review by **D. Holland** of challenges in understanding and modelling cryospheric processes, with an emphasis on ocean ice-shelf interactions relevant to, for example, Greenland glacial fjords and the West Antarctic ice sheet. He emphasised the key role of intrusions of warm deep water in ice-shelf melt. Unfortunately, warm deep water can neither be seen from space nor inferred from gravity. **K. Heywood** then discussed the physics and observations of Antarctic Bottom Water formation, and the extent to which global climate models are able to capture the large-scale circulation features in the Southern Ocean. She argued that while climate models seem to provide a reasonable representation of the transport of intermediate water, they are much worse at representing the transport of surface and bottom water. Moreover, climate models form deep water incorrectly through open-ocean convection.

The next two talks reviewed open ocean processes and the dynamics of the Antarctic Circumpolar Current (ACC). **S. Gille** discussed observed recent changes in the hydrographic structure (including ocean heat content) and frontal positions of the ACC (**Figure 4**), emphasising that we do not really understand the causality underlying those changes. While studies with non-eddy-permitting ocean models suggest that the shifts in the ACC front have been driven by the changes in the SAM, others have argued that ocean eddies buffer this effect and lead to a very different sensitivity. This is clearly an important issue to resolve in the future. **J. Marshall** discussed the central role of the Southern Ocean in the upwelling branch of the global overturning circulation. It is important to understand which parts of this circulation are relaxational (*i.e.*, can accommodate changes elsewhere) and which are 'choke points' that require forcing. In particular, it is not entirely clear the extent to which atmospheric wind stresses and heat fluxes, and winter sea-ice cover, may respond to as well as drive Southern Ocean upwelling.

The focus then shifted to the Northern Hemisphere. **A. Proshutinsky** pointed to the role of the wind driven Beaufort Gyre, alternating between a strong anticyclonic regime accumulating ice and fresh water, and a weaker cyclonic regime releasing the fresh water to the North Atlantic and influencing the overturning circulation. **C. Mauritzen** emphasised the revolution that has occurred in recent years in near real time data acquisition in the Arctic and Sub-Arctic, with more than 30,000 Argo, Ice-Tethered Profiler (ITP), glider, and seal-borne CTD profiles obtained since 2001. The new data will give us the opportunity to narrow down the uncertainties in ocean heat content, fresh water content, and density both for reanalysis and operational products. **S. Østerhus** reviewed the direct measurements of mass, heat and salt exchanges between the North Atlantic and

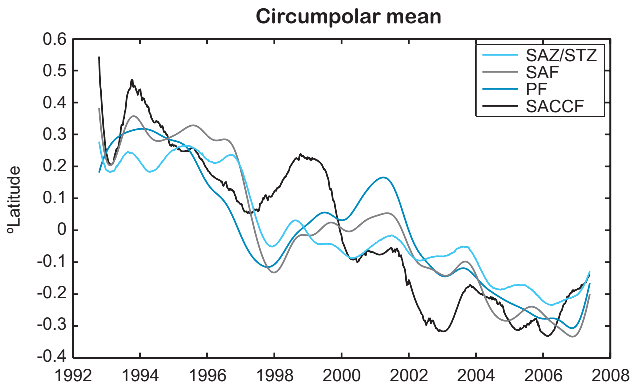

Figure 4: Evidence for decadal predictability in the Southern Ocean from long-term (presumably forced) changes. The different curves show estimates of changes in the mean latitudinal position of the fronts that comprise the ACC, as inferred from satellite altimeter measurements. (Here, SAZ/STZ is the Sub-Antarctic Zone/Sub-Tropical Zone; SAF is the Sub-Antarctic Front; PF is the Polar Front; and SACCF is the Southern ACC Front). The ACC has shifted poleward by about 60 km over the last 15 years. From Sokolov and Rintoul (2009, JGR).

the Arctic. More than 10 years of measurements show no trends in volume transports, but there has been a rapid increase in heat and salt fluxes.

T. Eldevik noted that the exchange of mass, heat and salt over the Greenland-Scotland ridge can be described mathematically by three forced conservation equations. With this approach, the sensitivity of the transports to changes in hydrography or forcing can be tested. Climate models that fail to reproduce the three distinct water masses at the ridge will respond differently to forcing perturbations. While oceanic responses to atmospheric forcing are well documented in observations and models, mechanisms for oceanic forcing of the atmosphere outside the tropics are less well understood. **A. Czaja** proposed a new mechanism for ocean-atmosphere coupling in the extra-tropics. While the textbook version is that a warmer ocean surface heats the atmosphere above and creates a baroclinic response, surface temperatures can set the atmospheric lapse rate over the warm western boundary currents and thus communicate the temperature signal throughout the entire troposphere. These moist neutrality situations are currently not parameterized in global atmospheric models, leaving a potential for prediction yet to be fully investigated.

Session 3 examined the role of the stratosphere in predictability. **P. Kushner** discussed mechanisms for coupling between the stratosphere and the troposphere. He distinguished between direct effects of stratospheric changes on the troposphere, and indirect effects whereby the state of the stratosphere affects teleconnections (*e.g.*, ENSO) within the troposphere. He also emphasised the impact of model biases, *e.g.*, models with too-long annular-mode time scales exhibit overly strong annular-mode responses to external forc-

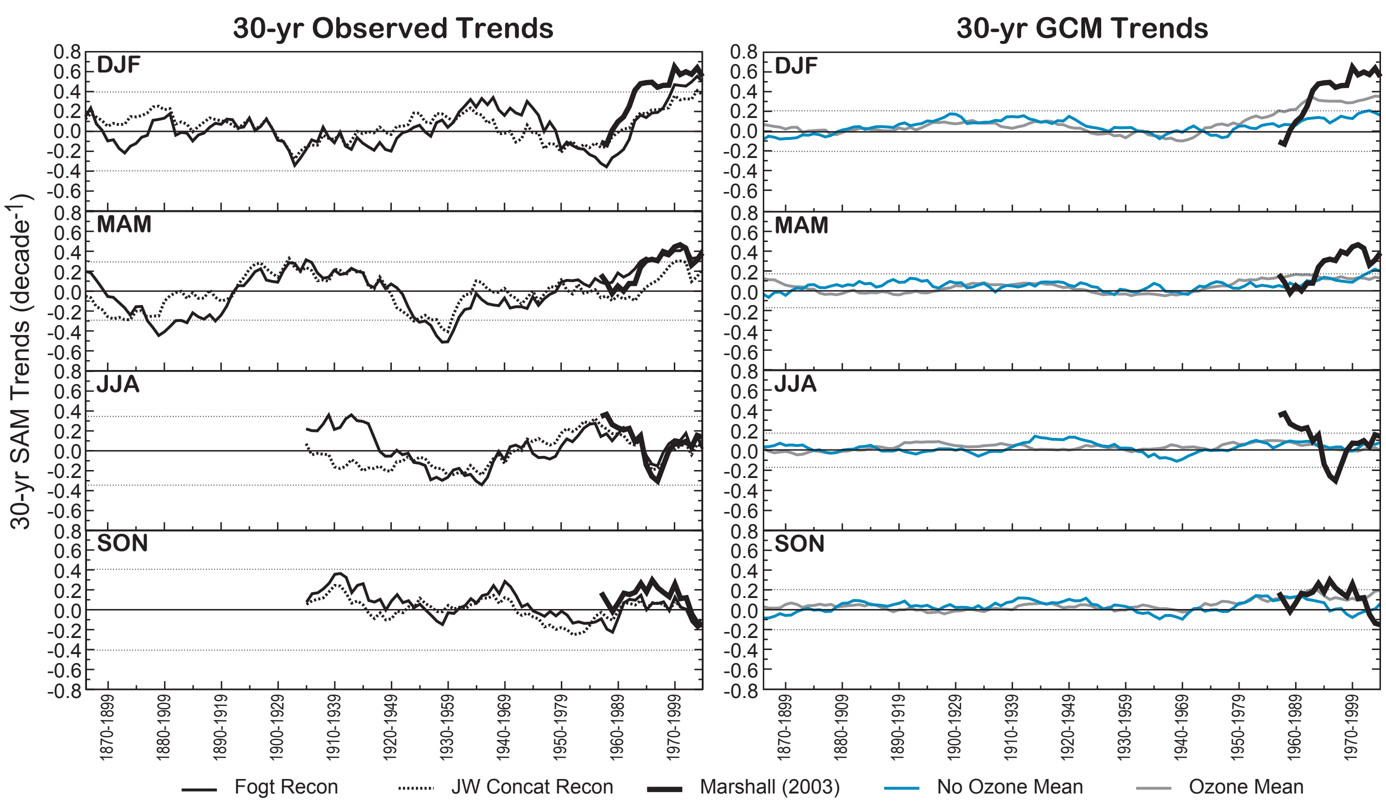

Figure 5: Evidence for decadal predictability of changes in Southern Hemisphere summer-time atmospheric circulation from ozone depletion and GHG changes. 30-year trends calculated from reconstructions of the 20th century Southern Hemisphere Annular Mode (SAM) index (left panels) show that the recent summer-time trends are unprecedented in the historical record, indicating that they are a response to external forcings. The CMIP3 model simulations (right panels) suggest that the dominant component of the forcing in this season is due to stratospheric ozone depletion. In other seasons, ozone has a negligible impact and the recent trends are just becoming significant in the fall season, but not in the spring, where the simulated trends are too strong. No significant winter trends are evident in reconstructions or simulations (not shown). The dotted lines represent the range of internal climate variability from the model's pre-industrial control simulations (left panels), rescaled by the square root of six (the number of non-ozone models) (right panels). From Fogt et al. (2009, J. Clim.).

ings. **S. Yoden** reviewed insights obtained from mechanistic models concerning internal and externally forced variability of the winter-time stratospheric polar vortex, which dominates stratospheric variability. The use of a mechanistic model permits very long simulations (*e.g.*, 15,000 years), which are needed to fully characterize the PDFs of stratospheric variability because of the large amount of decadal variability and high degree of intermittency in Stratospheric Sudden Warmings (SSWs). **T. Shepherd** reviewed basic aspects of stratospheric variability, and summarised the various physical mechanisms for memory in the stratosphere on both seasonal and interannual time scales, including tropical-polar coupling. Stratospheric models (whether simple or complex) and observations both exhibit strong decadal time scale variability, but it has yet to be determined how predictable this variability is.

J. Perlwitz discussed the impact of the Antarctic ozone hole on the Southern Hemisphere (SH) high-latitude summertime troposphere, which is by far the clearest instance of a stratospheric influence on surface climate, and is a predictable signal since it is associated with stratospheric halogen loading. The surface impact of the ozone hole involves a strengthening and poleward shift of the tropospheric jet (represented by the SH Annular Mode (SAM)), and has implications for the ocean circulation, which are beginning to be studied. The anticipated recovery of stratospheric ozone over the coming decades implies that this component of the recent climate trends will be reversed, with the latest model studies suggesting a near cancellation for summertime trends between the effects of ozone recovery and GHG forcing over the next half century. **J. Arblaster** discussed the response of the SAM, which controls much of SH climate, to future GHG and ozone forcing, emphasising that the response to ozone forcing is mostly confined to the summer season. She found that the circulation response to GHG forcing is strongly related to climate sensitivity and arises more from the warming of the tropical upper troposphere, which previous studies have shown induces dynamical (momentum flux) feedbacks through a strengthened subtropical jet, rather than from polar cooling.

M. Sigmond addressed the question of whether the ozone hole might explain the observed increase of Antarctic sea-ice extent. In his coupled model simulations, with a non-eddy-permitting ocean model, the ozone hole led, instead, to a reduced sea ice extent. This decrease is consistent with a mechanism involving enhanced offshore Ekman sea ice transport arising from the stronger westerlies. A poster by C. Bitz also found a decrease in sea-ice extent in response to the ozone hole employing a different model. However, she found that the response was significantly smaller when the ocean model resolution changed from non-eddy-permitting to eddy-permitting, owing to a significant reduction in the poleward heat transport response at higher horizontal resolution. This result is consistent with the 'buffering' effect of eddies that was discussed by S. Gille (see above). **J. Jones** presented a reconstruction of the SAM index over the entire 20th century. This record is important because there is a paucity of long data sets for SH high latitudes. She found that in DJF the recent increase of the SAM index was unprecedented in the historical record, so presumably a response to forcing (which models suggest has mainly come from the ozone hole), whereas in MAM the recent increase was large but still within the range of natural variability (**Figure 5**). No SAM trends were identified in either JJA or SON.

Session 4 focused on predictability of the Arctic climate system, and covered ocean-atmosphere exchanges, mid-latitude-Arctic coupling, high-latitude-terrestrial predictability, sensitivities and feedbacks in the Arctic system, and the use of models for prediction. **X. Zhang** showed how an observational constraint (the sensitivity of Arctic sea-ice extent to air temperature) could be used to narrow the range of future sea-ice projections obtained from global climate models. Zhang also showed how the recent loss of summer Arctic sea ice is part of a broader Rapid Change Event involving a shift of the atmospheric circulation. **H. Tanaka** discussed the role of the Arctic Oscillation (AO), which explained about half the Arctic warming from the 1960s to the 1990s. He showed that the AO is almost dynamically orthogonal to the "global warming" component of the recent Arctic change.

M. Karcher documented the variability of the Atlantic Water inflows and outflows, for which the Arctic Ocean acts as a switchyard (**Figure 6** - colour plate II). While these inflows have subpolar origins, the Nordic Seas impose their imprint. Karcher showed that North Atlantic inflow anomalies may impact the deep water overflows about 10-15 years after entering the Arctic Ocean, implying some potential predictability of overflow variability. **K. Shimada** showed that the recent reduction of sea ice in the western Arctic Ocean is

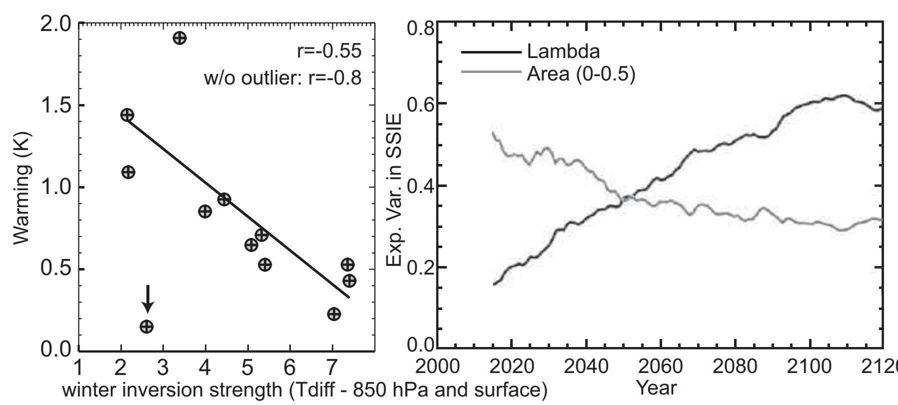

Figure 8: Mechanisms controlling spread in the Arctic climate change predictions of the CMIP3 models. Left: Relationship between winter inversion strength and annual-mean Arctic warming by the 22nd century (A1B emissions scenario). The stronger the inversion, the more heat is lost by cooling to space (mainly from clear-sky conditions), and the smaller the overall annual-mean warming. The observed inversion strength lies at the left end of the model range, suggesting the models may have unrealistically high levels of negative long-wave feedback. Right: Fraction of explained variance in Arctic sea-ice extent changes in CMIP3 models from present day to the indicated year, from the radiative feedback parameter λ (mainly related to inversion strength) (black) and the climatological extent of thin sea ice (grey). These two parameters, which can both be constrained by observations, account for nearly all the predicted changes in sea-ice extent, with the latter dominating in the first few decades and the former dominating later in the century. From Boé et al. (2009, J. Clim.; 2010, Clim. Change Lett.).

due to a combination of three factors: heat, preconditioning, and winds. The inflowing Pacific Summer Water is a source of heat, but its impact on sea ice is amplified by wind-driven changes in the Beaufort Gyre dynamics and the interplay with reduced ice concentrations, Ekman pumping, and topography. **M. Serreze** discussed the broader issue of polar amplification, and showed that its strongest manifestation in the cold season and the marginal ice zone is indicative of a contribution of a feedback arising from the reduced sea ice. There is a need for coordinated model experiments to assess the impacts of the reduced sea-ice extent on the atmospheric circulation elsewhere in the Northern Hemisphere.

In the first of the "terrestrial" presentations, **D. Lawrence** showed that in CCSM3 21st century A1B simulations, the rate of warming over Arctic land areas is enhanced by 1-2°C/decade in autumn and winter during periods of rapid sea-ice loss (**Figure 7** - colour plate II). He showed that the same seasonality and spatial pattern of Arctic land warming was also found in AMIP-type experiments forced by the sea-ice loss projected by CCSM3 by the end of the 21st century. Lawrence also showed that 21st century simulations are accompanied by substantial changes in permafrost, as defined by the ground temperature at 3 m depth. **A. Slater** addressed the simulation of snow and soil temperature within a data assimilation framework. There are severe problems with the available data coverage for these variables, especially in the case of snow water equivalent and depth, despite the potential importance of these variables for predictability on seasonal time scales. Finally, **H. Morrison** showed that climate models poorly simulate Arctic clouds, especially the partitioning of condensate into the liquid and ice phases. A key question is whether the frequency of occurrence of different cloud states can be related to certain parameters available at the grid-cell scale. Large-Eddy-Simulation experiments can be exploited for this purpose.

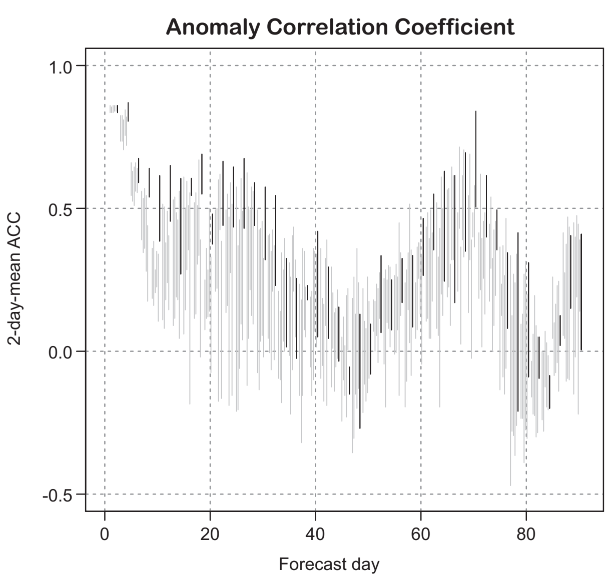

Figure 9: Evidence for enhanced seasonal predictability of Arctic surface air temperature during fall and early winter 2007 from prescribing sea-ice extent in ensemble hindcasts based on the ECMWF coupled seasonal prediction system. Record low summer-time sea-ice extent occurred in 2007. The 2-day mean anomaly correlation coefficients are shown as a function of forecast day (starting October 1, 2007), and calculated over high latitudes (60°N-90°N). Each black vertical bar is the envelope of the 5-member hindcasts using the prescribed 2007 sea ice, while the five grey vertical bars on its left are the envelopes of the 5-member hindcasts using prescribed, but "erroneous" or scrambled, sea-ice extent from the five preceding years (2002 to 2006). From Orsolini, Senan, Benestad and Melsom, to be submitted.

A. Hall used a suite of CMIP3 simulations to assess the predictable component of Arctic change that is anthropogenically driven. Polar amplification is seen in the surface air temperature, but not in the heat content of the upper ocean, pointing to atmospheric processes as the key to the large spread in the models' polar amplification. The main predictor of a model's response to GHG forcing is the longwave feedback parameter under clear-sky conditions. The models' low-level stratification is closely tied to this feedback, and the models with strong near-surface stratification show relatively little warming because of strong longwave cooling. In general, the models' surface-based inversions are too strong. Hall further showed that the spread in models' rates of sea-ice loss is related to two factors: the initial area of thin (<0.5 m) sea ice, and the longwave feedback parameter (**Figure 8**). **J. Christensen** raised the issue of potential nonlinearity in the systematic errors of regional climate models, identifying cases where systematic errors in surface temperature had a strong dependence on temperature over particular European regions. Further work is needed to place these dependences into a framework of GHG-induced warming. **A. Rinke** reported on an ensemble of 15-month hindcast simulations starting in March and September of various years of the 1979-2009 period. The experiments included various combinations of atmospheric, sea ice/SST, and snow initializations. One of the key findings was that certain atmospheric conditions are more predictable than others.

Session 5 consisted of two parts: one on seasonal predictability involving sea ice or snow as predictors, and one on seasonal to decadal predictability involving fully coupled global climate models. **M. Baldwin** reviewed the evidence for the influence of stratospheric winter-time variability on surface weather regimes. Weak and strong stratospheric vortex events have been shown to influence the frequency distribution of AO/NAO conditions up to 60 days after the events. Unfortunately the seasonal forecast models all under-estimate stratospheric variability, indicating that there is still a way to go before the maximum forecast skill from stratospheric effects is realised. **Y. Orsolini** used the coupled ECWMF seasonal prediction system to show that sea-ice anomalies provide some predictability of Arctic surface air temperature during autumn and early winter (**Figure 9**), consistent with Lawrence's inferences (see above) using GCM studies, and also that autumn sea ice variability can induce deep temperature anomalies throughout the troposphere and circulation changes influencing East Asia early winter climate. Orsolini also used an atmospheric GCM to show that Eurasian autumn snow cover can influence atmospheric wave trains over the North Pacific and eventually over the North Atlantic. **J. Cohen** pointed to autumn snow cover over Eurasia as a precursor for stratospheric variability. More snow and a strengthened Siberian High appear to strengthen the Rossby-wave flux into the stratosphere, weakening the polar vortex and thus favouring negative AO situations. Cohen also presented an experimental prediction of the winter 2010/2011 conditions based on his approach.

In parallel with such observational and reanalysis studies, efforts are being made

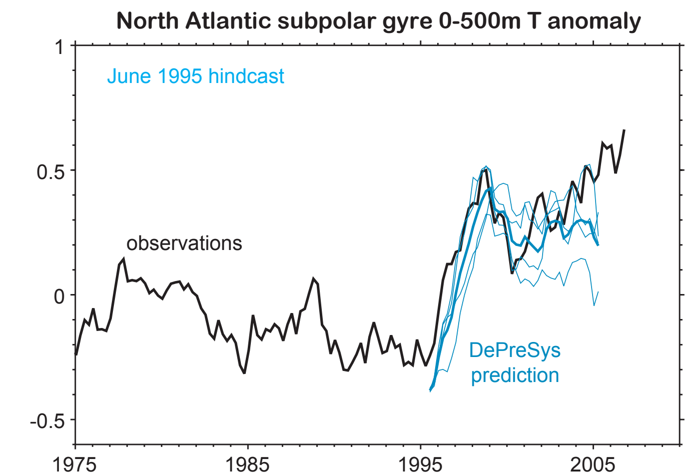

Figure 10: Evidence for decadal predictability of North Atlantic upper ocean heat content based on the successful prediction of the North Atlantic subpolar gyre warming in 1995/1996 with the DePreSys ensemble prediction system. Upper ocean (0-500 m) temperature anomalies averaged over the North Atlantic subpolar gyre for a DePreSys hindcast started from June 1995 initial conditions is shown in blue, which successfully captures the warming in the observations (black, taken from the Met Office ocean analysis (Smith and Murphy, 2007)). All temperature anomalies are relative to a 1941-1996 climatology. From PhD thesis of Jon Robson, University of Reading, 2010.

to improve the ocean/ice assimilation and forecasting systems. Two different methods were presented; one using the Ensemble Kalman Filter approach (**F. Counillon**), and a second using a four-dimensional variational approach (**F. Kauker**). Using data assimilation, it is possible to identify key parameters or areas that are particularly sensitive to perturbations, and thus guide process studies or measurement campaigns. In recent years there has been a large increase in studies related to decadal climate forecasts. Three talks were given on this subject, all demonstrating that hindcast experiments do show promising skill both in real and idealised experiments. **J. Jungclaus** focused on the sources and impacts of variations in the Atlantic meridional overturning circulation. Time scales and mechanisms differ between models, and more work is needed to identify those that work in the real world. **D. Smith** showed that the North Atlantic also plays an active role through Subpolar Gyre dynamics, with links to tropical convection and hurricane frequency. Of particular interest is the near collapse of the Subpolar Gyre around 1995, seen from altimetry and downstream hydrography, which was discussed by **E. Hawkins**. The fact that climate models reproduce this event in forecast mode (**Figure 10**) indicates that the anomalous atmospheric forcing that year (record low NAO after many positive years) played a smaller role than previously believed. **J. Walsh** gave the final talk in the session. He showed that model ensembles are generally more skillful in reproducing Arctic climate variations than single models, but only to a certain extent. The skill of the ensembles is reduced if the models with the largest biases are included. In general the models with the best performance also tend to show a stronger sensitivity to GHG forcing. Some predictability is expected from low-frequency variability in the Arctic climate.

Synthesis

We understand many of the physical sources of predictability in the polar climate system. For sea ice, memory resides in sea-ice thickness, rather than sea-ice extent, and spring-time ice-thickness anomalies can re-emerge in the fall with summer-time memory provided by the ocean. The initial sea-ice thickness distribution is the main control on modelled Arctic sea-ice loss for the first half of the 21st century. For snow, memory resides in snow depth (or snow water equivalent). There is longer-term memory in permafrost, whose disappearance can lead to an albedo feedback through rapid growth of shrubs. For the ocean, SST anomalies have a seasonal memory while longer-term memory resides in the heat and salinity of subsurface water masses, which provide a mechanism for lagged teleconnections. In the Antarctic there is also substantial memory provided by the baroclinic component of the ACC, which exerts a control on the Atlantic Meridional Overturning Circulation. For the atmosphere, there is seasonal memory in the stratosphere, which modulates tropospheric variability, because of the long radiative time scales in the lower stratosphere and the strong seasonal cycle of stratospheric polar variability. There is also longer-term memory in tropical stratospheric winds, manifested in part by the QBO. The Antarctic ozone hole has been the principal driver of summer-time trends in SH high-latitude surface climate over the last few decades, which may cease or even reverse as the ozone hole recovers over the coming decades.

Although the field is still in its infancy, early results concerning the extent of polar predictability show promise. Operational seasonal prediction systems for the Arctic show the impact of summer-time sea ice and fall Eurasian snow-cover anomalies, and September Arctic sea-ice extent appears to be predictable given knowledge of the spring-time ice thickness or early to mid-summer sea-ice extent. Stratospheric Sudden Warmings provide further predictability during winter and spring once they occur, although the extent to which they are themselves predictable is still unclear. On longer time scales, studies of potential predictability within a "perfect model" framework suggest multi-year predictability of the internal variability over the high-latitude oceans in both hemispheres, and the first attempts at decadal prediction have identified the Atlantic subpolar gyre as a key source of predictability, with a teleconnection to tropical Atlantic SSTs.

What we lack is a good understanding of many of the feedbacks between the different components of the climate system. The precise dynamical mechanisms of stratosphere-troposphere coupling remain to be elucidated, although they appear to be well represented in models that have sufficiently good climatological mean states. The robust surface responses to stratospheric variability and trends are in surface winds and mean-sea-level pressure gradients, which are dynamically controlled; the surface temperature responses, which are more thermodynamically controlled, are less clear except where they result from advection. The response of Arctic sea ice to surface winds appears to be well understood, but the origin of the overly pole-centric Beaufort Gyre in climate models, which induces significant biases in sea-ice export through the Fram Strait, is not well understood.

Although the basic mechanisms of Arctic amplification of GHG-induced warming, which involve feedbacks from sea ice and ocean, are well understood, there are large uncertainties in the magnitude of the surface temperature response arising from uncertainties in the response of Arctic clouds and systematic model biases in boundary-layer stability. While global ocean models generally have a good representation of intermediate-water transport, they have a very poor representation of the transport of surface and bottom water, and incorrectly form deep water by open-ocean convection. This could compromise the realism of the response of the ocean circulation to surface buoyancy forcing. In the SH, the response of the ACC and of poleward ocean heat transport to surface wind trends seems to be very different in eddy-permitting and non-eddy-permitting ocean models, suggesting that the latter may have non-conservative eddy parameterizations that do not correctly "buffer" the ocean response to wind stress forcing.

As a result of all these weaknesses in our knowledge, we do not well understand the physical causality of the large-scale modes of polar variability that are evident in the observed record. This compromises our ability to design appropriate observation, assimilation, and modelling systems for polar prediction, and to explain the observed record.

Unfortunately, we lack many of the key observations needed to constrain the presumed sources of polar predictability; examples include snow depth and snow water equivalent (estimates from passive microwave instruments are widely regarded as useless), sea-ice thickness (estimates from laser altimetry may be acceptable, but they are not currently available in real time), polar ocean state estimates including Antarctic warm deep water, and stratospheric tropical winds. An exception is the salinity and heat anomalies entering and exiting the Nordic (GIN) Seas, which appear to be well constrained by hydrographic data in the limited number of communicating channels. However, there has been an explosion of new subsurface ocean observations in the last decade from Argo floats and from the recent "seal" network, which are revolutionising the polar ocean observing system. These observations provide new opportunities for model validation — probably best performed in observation rather than model space, to avoid introducing errors from interpolation, and with a focus on "process-oriented" diagnostics that are not overly sensitive to the time period considered — and offer the potential for vastly improved estimates of the ocean state, a prerequisite for polar predictability. Nevertheless, since the "repeat cycle" for seasonal and especially decadal predictions is rather long, prediction systems will continue to be tested in hindcast mode, for which our poor historical knowledge of the ocean and sea-ice initial states will surely represent a major limitation.

Next steps

In considering what can be done to make progress in polar predictability, it needs to be kept in mind that it is not the job of WCRP to coordinate climate science. Nor is there much point in making unsolicited research recommendations. Rather, the WCRP aims to identity those aspects of climate science that benefit from international coordination. That means identifying particular gaps, typically where efforts by individual scientists or groups have run into a wall because of the lack of a wider effort. Since the WCRP has no staff of researchers, high-impact initiatives addressing those gaps need to be developed that can rally the community behind them and attract the support of funding agencies. In order to maintain momentum, these initiatives need to define achievable, tangible deliverables within a broader strategic research plan that is both scientifically exciting and societally relevant. Those deliverables need to leverage existing activities to the extent possible.

There was a clear consensus at the workshop that there exists a notable gap between scientific communities, as most people knew only a small minority of the other participants. As discussed above, it seems apparent that progress in polar predictability will require crossing disciplinary boundaries to understand the feedbacks between the troposphere and the stratosphere, ocean, land, and sea ice. In the discussions, it became evident that the nature of these feedbacks appears to be somewhat different in the two hemispheres, because of the different geometries, leading to rather different scientific questions.

In the Arctic, the ocean is contained within a basin with a couple of entry/exit points, and sea ice covers the polar region, allowing a strong ice-albedo feedback. While there are certainly important dynamical processes — *e.g.*, the export of sea ice through the Fram Strait depends on the position and strength of the Beaufort Gyre — climate scientists tend to treat the Arctic primarily from a thermodynamic perspective, focusing on budgets of heat and (in the ocean) salinity. Probably the most burning societal question is the rate of warming in the Arctic, as this has numerous local consequences, including those that relate to an ice-free summer-time Arctic. Whilst it is plausible that the most extreme model predictions of summer-time sea-ice loss are in fact our best predictions, and that the observed rate of decrease in summer-time sea-ice extent is well understood, the confidence we have in those statements needs to be greatly strengthened.

In the Antarctic, the ocean is annular, sea ice is largely seasonal, and the centre of the polar region is covered by land ice and ice shelves. While there are certainly features of interest arising from the longitudinal asymmetry of the Antarctic continent, the dominant climate structures are the circumpolar jets in the atmosphere and the ocean, and climate scientists tend to treat the Antarctic primarily from a dynamical perspective, focusing on eddy momentum fluxes and jet shifts. Furthermore, the largest observed changes in the Antarctic (which occur in summer) are thought to be associated with the stratospheric ozone hole, reinforcing this dynamical perspective. On the other hand, the basic mechanisms for polar amplification (sea ice-albedo feedback, enhanced atmospheric latent heat flux) also exist in the Antarctic but are being delayed by deep ocean heat uptake, although it is unclear how well climate models represent this delay. Probably the most burning societal question is what is the true response of the ocean circulation to the strengthening and poleward shift of the tropospheric jet, and how will this change in the future as the ozone hole recovers while GHG concentrations continue to increase, as this has implications for Southern Ocean upwelling and carbon uptake, and possibly for the long-term stability of the West Antarctic ice shelf. In contrast to the situation in the Arctic, there is as yet no plausible explanation for the observed increase in Antarctic sea-ice extent, which remains a major scientific puzzle.

These are, of course, just the current questions, but we can be sure that they will remain "grand challenges" for some years yet, and furthermore that answering them (and contrasting the different behaviour of the two hemispheres) will advance our understanding of the fundamental processes and feedbacks underlying polar predictability. At the same time, a number of general issues and opportunities were identified which apply to both poles:

(i) A better understanding of seasonal predictability, not only for its societal benefits but also for understanding the seasonality of longer-term variability and changes. The WCRP's Working Group on Seasonal to Interannual Prediction (WGSIP) has the infrastructure to perform prediction studies but needs the expertise of polar scientists to interpret the results of those studies in polar regions and design new experiments.

(ii) A better understanding of decadal variability and its partitioning between internally generated and externally forced components. The WCRP's Working Group on Coupled Modelling (WGCM) has defined a set of coordinated experiments focusing on the near term (*i.e.*, several decade) time horizon within its CMIP5 activity, which will provide a large archive of model simulations that can be analysed from this perspective.

(iii) Improved initial state estimates. Potential improvements in existing observations (or their availability) need to be identified for action by the relevant agencies; coupled assimilation systems including snow and sea ice need to be developed, in collaboration with weather prediction centres who are wrestling with this issue as part of their efforts to improve polar weather prediction; and there needs to be a better understanding of the sensitivity of polar predictability on decadal time scales to initial-state error in the ocean, to guide ocean observational network design.

(iv) A better understanding of potential predictability. The value of a "perfect model" methodology hinges entirely on how realistic the model is. In cases where models have some basic credibility, this approach can be exploited to determine where the predictability lies. In other cases, key model processes that are holding back progress need to be identified for a targeted effort at improvement.

The conclusion of the workshop was that a cross-cutting WCRP initiative was needed in the area of polar predictability, whose first action would be to hold a focused meeting in about six months' time, to develop a detailed implementation plan concerning the above issues. In developing such a plan it will of course be necessary to engage and partner with other relevant research bodies. It was felt that although there were important differences between the Arctic and Antarctic that could lead to differences in priorities, there were also considerable scientific and logistical benefits to be obtained by considering the two poles in parallel. Therefore it was suggested that there should be a single initiative, but with distinct Arctic and Antarctic foci.

Acknowledgements

The workshop received substantial financial support from the Norwegian Research Council and the WCRP, SPARC and CliC, and was also sponsored by the Bjerknes Centre, University of Bergen and the City of Bergen. We are extremely grateful to Beatriz Balino of the Bjerknes Centre for coordinating the excellent local arrangements, which made for a very productive meeting.

Report on the SPARC DynVar Workshop 2 on Modelling the Dynamics and Variability of the Stratosphere-Troposphere System

3-5 November 2010, Boulder, USA

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The 2nd Workshop of the Stratospheric Process and their Role in Climate (SPARC) DynVar Activity took place in Boulder, Colorado, USA, 3-5 November 2010. The workshop was hosted by the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory's (ESRL) Physical Sciences Division in collaboration with the Cooperative Institute for Research in Environmental Sciences (CIRES) at University of Colorado, and was held at NOAA ESRL David Skaggs Research Center. CIRES, NOAA, including NOAA's Modeling, Analysis, Prediction and Projection (MAPP) Program, the European Commission COMBINE Integrating Project, and the SPARC project of the World Climate Research Programme (WCRP) kindly provided support for the workshop. A special thanks to the many people at NOAA and CIRES involved in the organization of the excellent local arrangements for the Workshop at NOAA ESRL.

The SPARC DynVar Workshop 2 attracted 68 participants from 11 countries: USA (35), Canada (8), United Kingdom (7), Japan (6), Germany (4), France (3), Denmark (1), Israel (1), Italy (1), Norway (1), Spain (1). The workshop consisted of 11 invited and 41 contributed presentations (11 orals and 30 posters) and was opened by a keynote presentation by Susan Solomon. Forty-five abstracts were submitted to the workshop, although submission of abstracts was not compulsory. The relatively large number of submitted abstracts indicates a growing interest in the role of stratospheric dynamics and variability on the climate system. Poster sessions were all well attended. Lunch and coffee breaks held on site were intensively used for informal discussions. A total of 5 hours was dedicated to discussing the core goals of the DynVar Activity, including difficulties and opportunities for those in the SPARC community, with most of the discussion focused on the role of stratospheric dynamical processes in the Earth system.

The goals of the DynVar Activity are to determine the dependence of the mean climate, climate variability, and climate change on stratospheric dynamics as represented in climate and Earth system models. Since the first DynVar Workshop (held in Toronto, Canada, 27-28 March 2008), a number of new studies contributing to our knowledge on how stratospheric representation affects climate simulated by models have appeared in the literature. In part, because of these advancements, a number of climate modelling groups are now planning to undertake the Coupled Model Intercomparison Project Phase 5 (CMIP5) experiments with models that include a well-resolved stratosphere. The interest in models with a well-resolved stratosphere has also led to the Stratosphere resolving Historical Forecast Project (SHFP), part of the WCRP's Working group on Seasonal to Interannual Prediction (WGSIP) cross cutting activity with the Climate Variability and Predictability project (CLIVAR), aimed at quantifying improvements in actual predictability by initializing and resolving the stratosphere in seasonal forecast systems.

The 2.5 day workshop provided a forum for:

- Presenting new works on key areas central to the Activity such as the influence of the stratosphere on the tropospheric circulation, the ocean circulation *via* air-sea interactions, and on snow and sea-ice fields; the role of the stratosphere in the tropospheric circulation response to climate change; and the mechanisms for two-way stratosphere-troposphere coupling;
- Assessing the status of the SHFP and CMIP5 runs with models with a well-resolved stratosphere.
- Discussing how to best analyse, make full use, and exchange knowledge from the data generated by the SHFP and CMIP5 runs, with the role of the stratosphere as the focus.

The workshop agenda was organised based based on time scales: Presentations on interannual and shorter time scales, including discussion on the SHFP, occupied the first day, while the second and third days were dedicated to decadal and centennial time scales, and CMIP5 models and experiments.

The first day of the workshop started with a welcome by **J. Perlwitz** and an introduction of the DynVar activity and workshop goals by **E. Manzini**. In her opening keynote presentation, **S. Solomon** reviewed a number of challenges that the climate community is facing, such as understanding the reasons for decadal variations in stratospheric water vapour, modelling the chain of processes in the tropical atmosphere that may bring meteorological signals originating in the lower atmosphere to the stratosphere, the importance of the location of the lid of a model, and the accurate representation of stratospheric processes in models. She acknowledged the role of variability, reviewed the role of the stratosphere in connecting changes occurring in the Antarctic region to global climate change, and presented new results on temperature trends in the UTLS. J. Perlwitz reported on the WRCP Workshop on Seasonal to Multi-decadal Predictability of Polar Climate held in Bergen, the week prior (25-29 October 2010). Topics of relevance to DynVar were the sources of potential predictability reviewed during the workshop, especially those associated with stratospheric processes, and the establishment of both an Arctic and an Antarctic Initiative. She also presented the SHFP-WGSIP activity on behalf of A. Sciafe, and called for leadership from the DynVar group in the analysis of the SHFP runs. The SHFP runs are seasonal hindcast experiments, generally carried out with coupled atmosphere-ocean-sea-ice models, which are also high-top models. **J. Scinocca** presented the CCCma contribution to SHFP, although in this case, the high-top seasonal hindcasts were performed with imposed sea surface temperatures (SSTs) and sea-ice concentrations (SICs).

M. Baldwin reviewed methodologies to diagnose stratosphere-troposphere coupling in both observations and simulations. A key issue is how to define a climatology in a changing climate. By defining a slowly varying climatology with specific statistical properties, the resulting Annular Mode (AM) indices have no trend by definition – meaning that the climatology will change but the annular mode of variability will not. Baldwin suggested using daily zonal-mean geopotential to define the AM from climate model outputs, after removing its daily global-mean, a slowly varying trend and the seasonal cycle to define the anomalies. **D. Waugh** reported that CCMVal-1 and CCMVal-2 have demonstrated the advantage of the multi-model evaluation strategy, combined with model grading, over a range of diagnostics for the identification of deficiencies and systematic biases in chemistry-climate models. These activities have also led to quantifiable improvements in some particular models in the subjects of transport, Cl_y abundance and tropical tropopause temperatures. However, the methodology of model grading has its own limitations, such as the robustness of the metrics and the determination of the uncertainties in the observations used for comparison. Of particular relevance to DynVar are the results of Chapter 10 of the SPARC CCMVal-2 report (Baldwin *et al*., 2010), which demonstrates that the CCMVal-2 models, which generally have a better-resolved stratosphere, perform better than AMIP CMIP-3 models in the stratosphere and perform equally well, if not better, in the troposphere. The reported CCMVal diagnostic tool appeared to be of interest to many analysts and model developers.

The contributed talks of the first day included oral and poster presentations on a variety of topics, including the role of the stratospheric ozone on the medium-range weather forecast (**M. Deushi**), the role of linear interference in the annular mode response to tropical forcing (**P. Kushner**), wave forcing of the QBO (**J. Anstey**), the evaluation of the stratosphere in seasonal forecast models (**A. Butler** and **A. Maycock**) and on the factors controlling decorrelation time scales in the lower stratosphere (**P. Hitchcock**).

N. Butchart opened the second day with a talk on climate change and stratosphere-troposphere interactions, and pointed out that the effect of stratospheric changes on surface may not be limited to the impact of Antarctic ozone depletion and recovery. According to the multi-model study reported, the inter-comparison of the atmospheric response to 4xCO_2 in low- and high-top models showed that stratospheric climate changes may contribute substantially to changes in storm tracks, sea level pressure and precipitation in the Northern Hemisphere during winter. The fact that the impact of a well-resolved stratosphere stands out in the reported multi-model comparison suggests that results are robust, despite widely differing parameter settings and schemes in the high- and low-top models. However, a limitation of the reported work is the specification of the SSTs and SICs, disabling any air-sea interactions in the high top models, such that the climate is slaved to the imposed SSTs and SICs. It is therefore paramount to call for a similar analysis, with high- and low-top atmosphere-ocean general circulation models (AOGCMs).

Discussion of the status of the development of AOGCMs with a well-resolved stratosphere followed. In most cases, these models are high-top versions of low-top models. **C. Cagnazzo** reported results from the CMCC, IPSL-CM5, and MPI models. These three modelling systems, together with EC-Earth presented by **S. Yang,** and the METO&UK Universities presented by **S. Hardiman**, participate in the COMBINE European Integrating Project that aims to develop the next generation of Earth System Models by including components such as a dynamical stratosphere. The model descriptions and status of the CMIP5 simulations were given for the GFDL CM3 model (**J. Austin**), MIROC-ESM (**S. Watanabe**), WACCM (**D. Marsh**), GEOS-5 (**S. Pawson**), and MRI (**K. Shibata**). There were therefore 10 high-top model systems present at the DynVar workshop, with at least three models (EC-Earth, METO&UK Universities and WACCM) that have low-top counterparts. At the time of the workshop, pre-industrial control simulations were completed (or close to completion) for all the models. Some centres (*e.g.*, GFDL) were finishing the majority of the core CMIP5 long-term experiments (pre-industrial control run, 1850-2005 historical run, RCP4.5 and RCP8.5 runs). GEOS-5 and the MPI model were the only high top AOGCMs planning to run the CMIP5 decadal prediction experiments. At least three model systems (GFDL CM3, MPI and MIROC-ESM) will also run with CO_2 emissions, requiring modules for the land and ocean carbon cycle. Interactive atmospheric chemistry was included in at least three model systems (GFDL CM3, MIROC–ESM and WACCM). Different modelling groups were using similar types of diagnostics to analyse some of the most current topics of research in the troposphere-stratosphere region. These topics include ENSO signals in the tropics, ENSO teleconnections in the Northern Hemisphere, the Atlantic meridional overturning circulation (AMOC), simulation of the QBO and its forcing, and changes in tropical upwelling due to climate change, and decadal variability in water vapour. This potential for collaborative studies is precisely what initiatives such as DynVar are meant to address.

The last 2 sessions of contributed oral and posters presentations featured, the relative role of ozone and dynamical trends (and their model biases) in the southern polar stratospheric temperature trends (**N. Calvo**), the relationship between stratospheric ozone and Antarctic sea-ice trends (**M. Sigmond**), changes in the reflective downward coupling associated with ozone depletion (**N. Harnik**), evidence of coupling between the North Annular Mode and low frequency AMOC variability, suggesting a connection between stratospheric variability and variation in deep ocean temperature variations (**J. Kim**), and the dynamical enhancement of the equator to pole contrast in tropopause height, by more than a factor 2 compared to the radiative equilibrium solution (**T. Birner**). Posters also covered a wide range of topics that were both directly relevant to DynVar, or indicate fruitful interactions between DynVar and other SPARC activities. For example, the connection with gravity waves was highlighted as a prerequisite to calculate accurate momentum budgets in the stratosphere, which is a focus of the SPARC Gravity Wave Activity and is also relevant to some of the DynVar topics. Different studies on changes in atmospheric composition, in particular water vapour and ozone also indicated that DynVar could exploit interactions with CCMVal. Similarly, the role of dynamics in mediating the solar cycle signal from the stratosphere to the surface indicates an interaction with SOLARIS. Other posters were more specific to the DynVar objectives, covering for example the role of resolved planetary waves generated in association with tropical warm pools of SSTs.

Presentation sessions were complemented by discussion sessions dedicated to addressing how the SPARC community could make use of the opportunities generated by international activities such SHFP and CMIP5. The final session on Friday was dedicated to consolidating future efforts and plans. A number of activities were proposed and are summarised here:

1. Evaluate the feasibility of writing "news and views" papers on the role of stratospheric dynamics on tropospheric climate (Edwin Gerber, Natalia Calvo and Tiffany Shaw)
2. Evaluate the feasibility of writing a review paper on the changes occurring in the Antarctica region, focusing on the effects of ozone depletion on the climate system, including the ocean carbon fluxes (Judith Perlwitz)
3. Coordinate two synthesis papers on the CMIP5 runs: (i) Multi-model high-top model comparison of stratospheric climate, variability and change (Andrew Charlton-Perez) and (ii) Multi-model high-top / low-top comparison focused on surface climate, variability and change (Elisa Manzini)
4. Establish research groups to foster analysis of the SHFP and CMIP5 archives, towards a workshop in mid-2012, to be proposed to SPARC at the next Scientific Steering Group (SSG) meeting.

While each modelling centre has planned its own papers on the validation and/or novel applications of the new high-top AOGCMs, it is envisaged that a number of studies may explore the simulations that will become available through the SHFP and CMIP5 archives. DynVar is seen in this respect as a facilitator, fostering collaborative analysis on the role of stratospheric dynamics in the climate system, and on the implications of stratosphere-troposphere dynamical coupling for the prediction of variability and change of the climate system at all time scales. This stage of DynVar is foreseen to last at least for the next two years. To this end, DynVar "Research Groups" are being established on a number of topics raised at the workshop. Proposed research groups proposed include: Antarctica: From Ozone to Carbon; Surface climate, variability and change; Sudden Stratospheric Warming; ENSO and QBO; AMOC and PDO; Water vapour; Annular Modes / Stratospheric memory; QBO and tropical waves; Tropopause and External forcing (volcanic). Concerning the solar external forcing and gravity waves topics, we note that the SPARC SOLARIS and Gravity Wave activities already exist to study these areas. Collaboration with CCMVal on a variety of issues is also envisioned. To foster the collaboration with CLIVAR, Amy Butler and Adam Scaife have volunteered to be the DynVar contacts on the SHPF project. Research Groups and their contacts will be posted on the DynVar web site (**http://www.sparcdynvar.org/**).

To recognize the engagement of a number of new people at the core of the SPARC DynVar Activity, the DynVar Committee has been restructured: Amy Butler, Natalia Calvo, Andrew Charlton-Perez, Edwin Gerber, Tiffany Shaw and Shingo Watanabe are welcomed as new members; while Judith Perlwitz, Lorenzo Polvani and Fabrizio Sassi will remain involved as ex-officio members.

We would like to note in closing that the larger than expected participation in the workshop clearly highlights the need for a forum of discussion on stratospheric dynamics in the interim period between the last SPARC General Assembly in 2008 and the next one in 2014, possibly reaching out to CLIVAR and CliC (The Climate and Cryosphere project). Given the above and the proposed 2-year time scale for the fostering the analysis of the SHFP and CMIP5 runs, we propose to hold a one week Workshop in spring/summer 2012 with SPARC DynVar and CLIVAR/SHFP, and possibly CliC.

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The SPARC Data Initiative

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The SPARC Data Initiative is the newest SPARC activity and was launched during the 2009 SPARC SSG meeting in Kyoto, Japan. Its aim is to compare data sets of vertically resolved chemical trace gas observations obtained from different satellite instruments, and to provide a "user's guide" for the use of such data in different applications, such as model-measurement comparisons or empirical studies of stratospheric climate and variability.

About 10 years ago, the GCM-Reality Inter-comparison Project for SPARC (GRIPS) found that there was considerable uncertainty in its model inter-comparison of dynamics and radiation arising from the fact that different observed data sets often delivered conflicting results. Accordingly, a middle atmosphere climatology study was initiated by SPARC, which compared the available meteorological data products in terms of various aspects including mean biases, seasonal cycle, variability, and long-term changes. No data set was problem-free, and all data sets were found to have both strengths and weaknesses. The findings were published in the SPARC Report No. 3 (2002), which provided something of a user's guide to the data.

The same sort of situation was faced in the SPARC CCMVal (Chemistry-Climate Model Validation) project (Eyring *et al*., 2005) for chemical trace gas measurements. While ozone and water vapour measurements are the subject of specific SPARC activities, there is no equivalent activity for other chemical trace gases. Yet these gases play an essential role in the ozone budget, and, together with age of air (a derived product), provide tracer information on atmospheric transport; a topic extensively analysed in the recent CCMVal Report. There are a variety of trace gas data sets available and a user cannot easily determine which is the most reliable for any particular application. While comparison of different measurements is often done as part of instrument validation studies, this information is not readily available to users. Moreover, the data sets are not always available in a standard data format, or with appropriate documentation. The result was that for the CCMVal inter-comparison, different observational data sets were used by different people, and scores based on model metrics were highly dependent on the data set employed. The SPARC CCMVal report therefore identified the need for an assessment of the available data sets of chemical trace gases analogous to what was done in SPARC Report No. 3 for the meteorological data sets. A specific recommendation states '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'.

Responding to this recommendation, the SPARC Data Initiative aims at assessing and consolidating our knowledge of current and past space-based observations of chemical trace gas species in the upper troposphere, the stratosphere, and the lower mesosphere. Both long-lived (O_3, H_2O, N_2O, CH_4, CFCs, SF_6, HF, NO_y, Br_y, HCl and CO) and short-lived trace gas species (NO, NO_2, NO_x, HNO_3, HNO_4, N_2O_5, $ClONO_2$, $BrONO_2$, ClO, HOCl, BrO, OH, HO_2, CH_2O), as well as aerosols will be assessed. The goal of the project is to assemble and compare climatologies derived from observations, to identify differences between the data sets, and to provide expert judgment on the source of those differences. The results will be documented in a new SPARC report, which will also provide essential knowledge of the measurement and retrieval techniques used. The report will compare quantities including zonal mean climatologies, seasonal evolution, and interannual variability of the chemical species.

Table 1: List of core members.

John Anderson	Hampton University, USA	HALOE, UARS
Samuel Brohede	Chalmers University, Sweden	OSIRIS, Odin
Lucien Froidevaux	Jet Propulsion Laboratory, USA	MLS, Aura-MLS, UARS
Bernd Funke	Instituto de Astrofísica de Andalucía, Spain	MIPAS, ENVISAT
Michaela Hegglin (co-lead)	University of Toronto, Canada	data-analysis
Ashley Jones	University of Toronto, Canada	ACE-FTS, SCISAT-1
Erkki Kyrölä	Finish Institute for Meteorology, Finland	GOMOS, ENVISAT
Jessica Neu	University of California Irvine, USA	TES, Aura
Alexei Rozanov	University of Bremen, Germany	SCIAMACHY, ENVISAT
Susann Tegtmeier (co-lead)	IMF-GEOMAR, Germany	data-analysis
Matthew Toohey	IMF-GEOMAR, Germany	data-analysis
Joachim Urban	Chalmers University, Sweden	SMR, Odin
Thomas von Clarmann	Karlsruhe Institute of Technology, Germany	MIPAS, ENVISAT
Kaley Walker	University of Toronto, Canada	ACE-FTS & MAESTRO, SCISAT-1

The timeliness of the SPARC Data Initiative is supported by the fact that the last few decades represent something of a golden age of stratospheric composition measurements, and it is unlikely that the stratosphere will be as well observed in the future. This initiative will help to capture and summarize existing knowledge on current and recent instruments, measurement and retrieval techniques, and validation activities. In particular, the initiative will help to identify priorities for reprocessing existing data or enhanced validation efforts with the active support of the measurement groups. In addition, the project will identify measurement gaps, which could motivate and provide community support for future missions.

At this point, a core team of instrument scientists and data analysts has been defined, and has started assembling trace climatologies from different satellite instruments and evaluating the available data products. The core team consists is listed in **Table 1**. The instruments represented by the core team members and by confirmed contributors to the SPARC Data Initiative currently include ACE-FTS, ACE-MAESTRO, Aura-MLS, GOMOS, HALOE, HIRDLS, LIMS, MIPAS, Odin OSIRIS, Odin SMR, SAGE, SCIAMACHY, SMILES, TES, and UARS-MLS. The core team met for a first successful workshop at the International Space Science Institute (ISSI) in Bern, Switzerland from 22-26 November 2010, thanks to generous support for local costs provided from ISSI through their international team programme (see our ISSI team website **http://www.issibern.ch/teams/atmosgas/index.html/Welcome.html**) and for travel from the WCRP. A workshop report will appear in the July issue of the SPARC newsletter. There will be a second and possibly even a third workshop, leading to the completion of a SPARC report.

Program of the Antarctic Syowa MST/IS Radar (PANSY)

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Introduction

The polar regions play an important role in the Earth's climate system. They are the exit regions of the material circulation in the stratosphere, and the entry (exit) regions during the summer-time (winter-time) in the mesosphere. This material circulation is essentially wave-driven and maintains a thermal structure of the middle atmosphere far from that expected by radiative balance. The resulting low temperatures in the summer upper mesosphere and winter lower stratosphere lead to conditions under which polar mesospheric clouds (PMC) and polar stratospheric clouds (PSC) can form, respectively. The PSCs serve as an environment for producing the conditions that can lead to catalytic destruction of ozone during Antarctic spring, forming the ozone hole. PMCs are a phenomenon that was first reported late in the 19th century and were considered to have appeared due to the changing climate, after the Industrial Revolution. The PMCs have also recently been observed even at mid-latitudes, such as those observed over Paris in the summer of 2009, which are still fresh in our memory. Thus, PMCs can be directly related to human activity and considered "the canaries in a coal mine" of the Earth climate system. Therefore, the monitoring and study of these phenomena is an important tool in detecting climate change, and in understanding the Earth system.

Another interesting polar phenomenon is the high albedo and high elevation of the Antarctic continent, which can cause strong downslope (katabatic) winds in the coastal region. These winds are an important source of gravity waves in the

Table 1: Basic parameters of the PANSY radar.

System	Pulse Doppler radar Active phased array system
Centre Frequency	47 MHz
Antenna	A quasi-circular array consisting of 1045 crossed Yagi antennas. Diameter about 160 m (18000 m^2)
Transmitter	1045 solid-state TR modules Peak Power: 520 kW
Receiver	(55+8) channel digital receiving systems Ability of imaging and interferometry observations
Peripheral	24 antennas for E-layer FAI observation

Antarctic. Moreover, the polar atmosphere is different from lower latitude regions because of possible strong energy inputs from geospace due to the orientation of the Earth's magnetic field lines, which are directly connected to the plasma sheet there.

Despite the importance of the southern polar atmosphere, observational studies have thus far been restricted due to the harsh physical conditions on the Antarctic continent. In order to address this deficiency, to explore the physics of these unique phenomena, and to study the quantitative effects of the polar atmosphere on the Earth's climate, a Mesosphere–Stratosphere-Troposphere/ Incoherent Scatter (MST/IS) radar (a VHF clear-air Doppler radar) will be installed at Syowa Station (69°S, 40°E) in early 2011; the first of its kind in the Antarctic (see Figure 1; colour plate III). We call this radar the PANSY radar after the name of the project. "PANSY" is a flower name coming from a French word "penser" which means "to think".

Radar system

The PANSY radar is a monostatic pulse Doppler radar operating at 47 MHz. Its antenna is a circular active phased array 160 m in diameter, consisting of 1045 three-element crossed Yagi antennas. The half-power beam width is 2.4 degrees, and the beam direction can be pointed to any specified direction within 30 degrees from the zenith. Each of the 1045 antennas is equipped with a solid-state transmit-receive module with 500 W peak output power, and the total output power is 520 kW. Fundamental parameters of the radar are given in **Table 1**.

The basic concept of the PANSY radar is to have a sensitivity comparable to that of the MU radar in Shigaraki, Shiga, Japan, which covers the height region of 1.5-600 km (Fukao *et al.,* 1985). One of the major technical limitations in designing the PANSY radar is its power consumption. While the MU radar with its class-AB power amplifier consumes 230 kW, the maximum available power for the PANSY radar at Syowa Station is less than 100 kW. Since the sensitivity of an atmospheric radar is determined by the product of the total output power and the antenna's effective area, we reduced the output power to half of that of the MU radar, and doubled the antenna area. In order to further reduce the power consumption, we developed a new class-E amplifier, with a total power efficiency exceeding 50%. As a consequence, we achieved a total power consumption of 75 kW, including the power needed for the digital signal processing system. This power-efficient design enabled us to avoid the use of a cooling fan, resulting in a robust transmit-receive module free from any moving components, ideal for the long-term operation in the severe weather conditions in Antarctica.

Another important design issue is the construction of the radar at Syowa Station in the Antarctic. The construction must be performed during a short summer period of about 2 months, and by untrained members of the Antarctic research expedition, most of whom are scientists (not technicians). Also, due to restrictions by the Antarctic Treaty, the rough ground cannot be altered, preventing the use of heavy construction vehicles. We have thus made our best effort to minimise the weight of the antenna and the transmit-receive module. In addition, the three-element crossed Yagi antenna has to withstand maximum continuous wind speeds of up to 65 m/s. After examining several test antennas at Syowa Station, we developed the current design, with a weight of 12 kg. The transmit-receive module is also designed to have minimum weight (18 kg) and cross-section. The supporting mast is inserted into a mounting hole of 130 mm diameter and 1 m depth, and the antenna is attached to its top together with the transmit-receive module. The height of each antenna is variable, in a range of about 2 m, depending on the ground surface condition, and the phase of the radiated signal is electronically adjusted to compensate for the height difference.

The antennas are arranged to form a grid of equilateral triangles with 4.5 m intervals, which corresponds to a wavelength of 0.7 m. Nineteen antennas constitute one group in a hexagonal shape, and a divider/combiner module is located at near the centre of each group. The entire antenna array consists of 55 hexagonal groups. The cables for the RF signal, the control signal, and the DC power supply spread from the operating building located next to the array field.

The transmitted pulse length is variable with minimum length of 0.5 microseconds, corresponding to a height resolution of 75 m. In order to increase sensitivity, Spano codes, which are an extension of complementary codes, are employed. Because of the non-linear nature of the class-E amplifier, each bit of the pulse code has to be separated in time. We thus use a train of pulses with an interval equal to the pulse length. The antenna beam direction can be switched by electronically controlling the phase of each antenna module for each transmitted pulse. The basic observation scheme for the troposphere and stratosphere will be 5 beam directions (vertical, north, east, south, and west) with a one-minute time resolution. The received signal is processed by an array of 55 digital receivers. Each group of the antenna is connected separately to a digital receiver, so that imaging observations of atmospheric turbulence, as well as the ionospheric irregularities can be performed.

One special nature of the Antarctic VHF radar is the existence of a strong coherent echo due to ionospheric field-aligned irregularities (FAI) of auroral origin. These echoes are observed in a direction perpendicular to the Earth's magnetic field, which has a declination angle of about 70 degrees near Syowa Station. As the main antenna array cannot be pointed to an elevation angle of 20 degrees, a one-dimensional array of 24 Yagi's is arranged around the outer edge of the main circular array. The output of the array can be connected to each of 8 digital receivers devoted to the FAI observations. The same peripheral array will be used to suppress possible interferences of FAI echoes with weak incoherent scatter echoes observed by the main array. A special adaptive antenna algorithm will be developed to cope with this problem.

The first stage of the radar construction will take place at Syowa Station in December 2010, and is scheduled for completion in March 2011. Tropospheric observation will be started with a small system of 57 antennas at this stage. The full system will start operation in March 2012. For the purposes of training the radar operators and developing the observation software, including the adaptive clutter rejection algorithm, a small system consisting of 22 antennas was constructed in the MU Observatory, as shown in **Figure 2**.

Figure 2: The training system of the PANSY radar located at the MU Observatory, Shigaraki, Shiga, Japan.

Backscattering of the atmospheric radar is caused by fluctuations in the refractive index of the air. More precisely, the backscattering is the Bragg scattering from the wave number component of the fluctuations that are half the radar wavelength (3.2 m for the PANSY radar). The main contribution to fluctuations in the index of refraction in the lower and middle atmosphere is disturbances in the background gradient of air density with height caused by atmospheric turbulence. Fluctuations in water vapour also play an important role in the lower troposphere. In addition to the background wind, the intensity of the atmospheric turbulence can be measured in this height region. As the air density decays exponentially with height, the fluctuations, and thus the echo power, also decay. The mean lapse rate of the echo power in the mid-latitude lower stratosphere is about 2-3 dB/km. The maximum observation height of the PANSY radar in the stratosphere is expected to be about 25 km.

Ionization becomes the major contribution to the refractive index above about 50 km. The advantage of using the lower VHF band is that the turbulent eddies still have substantial magnitude at the size of half the radar wavelength at mesospheric heights. Coherent scattering echoes due to turbulence and enhanced by the ionization are observed in the daytime mesosphere (60-80 km). During the summer season, enhanced coherent echoes, called Polar Mesosphere Summer Echo (PMSE), are also observed.

Above about 100 km up to about 500 km, incoherent scattering by ionospheric electrons can be observed by the PANSY radar. Electron and ion density, their temperatures, and the ion drift velocity are derived by analysing the echo power spectra. At around 80-105 km, spontaneous echoes from meteor trails can also be used to measure the background wind.

Scientific targets

The basic observation mode of the PANSY radar for the neutral atmosphere provides vertical profiles of three-dimensional wind vectors over a wide height range in the troposphere, stratosphere and mesosphere. Vertical resolution is at best 75 m, but is usually 150 m for the troposphere and stratosphere and 300 m for the mesosphere. Horizontal resolutions corresponding to the half-power beam width 2.4 degree are 840 m at the height of 20 km and 3.14 km at 75 km. Various atmospheric phenomena and dynamical processes are examined by continuous observation with the fine vertical and horizontal resolutions (*e.g.*, polar lows causing severe snow storms, tropospheric circulation associated with katabatic winds, fine structure of the tropopause, stratopause and mesopause, sudden stratospheric warming, polar vortex break-up, medium-scale Rossby waves trapped at the edge of the polar vortex, dynamics of PSC and PMC, atmospheric turbulence, and atmospheric gravity waves). The response of the neutral atmosphere to the injection of high energy particles from the magnetosphere is also an important topic of the PANSY project. Among these numerous themes, here we focus on possible research regarding gravity wave dynamics and PMC physics, which we consider the most important topics.

The spectra of atmospheric gravity waves are distributed over a wide range of frequency, and horizontal and vertical wavenumbers. Consequently, it is usually impossible to observe the whole gravity wave continuum by a single instrument because of the observational filter problem (Alexander *et al*., 2010). Continuous observation with fine temporal resolution at one location by the MST radar allows us to extract gravity wave components by their high frequency nature using a time filter. The horizontal and vertical resolution of the MST radar is sufficiently high to detect gravity waves with even small horizontal and vertical scales. Thus, it can observe gravity waves in almost all horizontal and vertical wavenumber ranges if they have high ground-based frequencies, which covers a part of the spectral range that is invisible to conventional radiosondes and recent high-resolution satellite observations. Moreover, the ground-based frequency is conserved during wave propagation if the background field is steady. The conservation of frequency is a reasonable assumption compared with that of the vertical wavenumber since the mean wind usually has vertical shear. Thus, the wave force can be estimated by using the vertical profile of the momentum fluxes associated with gravity waves observed by the MST radar. Moreover, direct and accurate estimates of the momentum flux vector associated with atmospheric gravity waves are possible using the dual beam method (Vincent and Reid, 1983).

According to the gravity wave study by Yoshiki and Sato (2000) using operational radiosonde data, the characteristics of the atmospheric gravity waves at Syowa Station are similar to those at the other Antarctic Stations. Thus, it is expected that the nature of the waves observed by the PANSY radar will be representative of those over the Antarctic, despite the fact that observations are only at a single location. Recent work using high-resolution satellite observations (Ern *et al*., 2004; Alexander *et al.*, 2008) and a gravity-wave resolving general circulation model (Watanabe *et al.*, 2008; Sato *et al.*, 2009) show that gravity waves have large energy in the high latitude regions of the Southern Hemisphere in austral winter. Generation and propagation of such gravity waves, as well as their momentum deposition to higher latitudes, will be elucidated by the PANSY radar in combination with satellite and model data. Collaboration with the radars at the other stations such as the ST radar at Davis station (Australia) is also important to examine the locality of wave characteristics.

Another interesting topic is clouds in the polar middle atmosphere, in particular, PMCs. It is well known that a strong coherent echo (PMSE) is observed from the polar summer mesosphere. This echo is considered to be related to the PMCs (Cho and Roettger, 1997; Rapp and Luebken, 2004). The PMSE is observed by various kinds of radars with frequencies ranging from a few MHz to several hundred MHz. In addition to the PMSE, the PANSY radar can detect echoes from turbulence in the mesosphere. Thus, three-dimensional winds can be estimated regardless of the presence of PMCs. A Rayleigh lidar to be co-located at Syowa Station in early 2011, together with the PANSY radar, will be useful in clarifying the structure and evolution of PMCs/PMSE over the Antarctic. By imaging observations, the three-dimensional fine structure of PMSE and turbulence will be elucidated. A similar observational project is planned by MAARSY (Middle Atmosphere Alomar Radar System), installed at Andøya, Norway (Latteck *et al.*, 2010). The comparison of PMC characteristics in the Antarctic and Arctic atmosphere should be interesting. First, it is known that the PMSE is much weaker in the Antarctic than in the Arctic. In addition, recent studies (Becker and Fritts, 2006; Karlsson *et al.*, 2009) have shown a possible link between the two hemispheres.

Global models for weather prediction and climate projection with relatively low resolution still have a cold bias in the winter polar stratosphere, probably in part because of unrealistic gravity wave parameterizations. This bias significantly degrades the predictions of the Antarctic ozone hole and its recovery because stratospheric temperature affects PSC volume. Quantitative understanding of polar atmospheric dynamics by adding the PANSY radar to the current observational network in combination with higher-resolution GCMs will reduce such model biases and contribute to the improvement of climate prediction. See the PANSY programme website for details: **http://pansy.eps.s.u-tokyo.ac.jp**

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Announcement

2011 NDACC Symposium

An International Symposium Celebrating 20 Years of Global Atmospheric Research Enhanced by NDACC/NDSC Observations

7-10 November 2011, Reunion Island, France

The 2011 NDACC Symposium, celebrating 20 years of atmospheric research fostered by Network observations, expands on the Symposium held in Arcachon in 2001 that marked 10 years of measurements. It will coincide with the opening of the NDACC high-altitude station at Maïdo in the Southern Tropics. The aim of the Symposium is to provide a forum to exchange information on the latest scientific achievements using NDACC and related observations, and is structured along five themes:

- Long-term evolution and trends in ozone, atmospheric composition, temperature, aerosols, and surface UV in the polar regions and at mid-latitudes
- Tropical and sub-tropical observations and analyses
- Interactions between atmospheric composition and climate, in collaboration with NDACC Cooperating Networks
- Satellite calibration / validation
- New observational capabilities

The Observatoire de Physique de l'Atmosphère de la Réunion (OPAR, http://opar.univ-reunion.fr) is organising the Symposium, which will be held 7-10 November 2011 in Saint Paul, Reunion Island (http://www.reunion.fr). Attendees will be given the opportunity to visit the Maïdo Observatory, currently under construction, which is scheduled to begin operations in early 2012. A Symposium web site will be available in March 2011 for registration, abstract submission, and booking.

Concordiasi: A Project Dedicated to the Polar Atmosphere

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Concordiasi is an international effort lead by Météo-France, and involving several research centres and polar institutes (Rabier *et al*., 2010). The project is organised around several observation campaigns in Antarctica, and its main scientific objectives are:

- to improve the assimilation in numerical weather prediction (NWP) models of infrared radiances provided by IASI-like hyper-spectral space-borne sounders over icy surfaces;
- to enhance the representation of polar processes in numerical models, and in particular to improve the simulation of precipitation and clouds, so as to better describe the mass budget of ice sheets, as well as to provide observational constraints on gravity-wave drag parameterizations used in global circulation models;
- to advance our knowledge of microphysical and dynamical processes involved in stratospheric ozone loss, and to better understand the interactions between them.

To this end, a campaign of intensive radio-soundings and surface measurements took place in 2008 and 2009 at Concordia, the French-Italian station on the Antarctic plateau. Radio-soundings were performed at Concordia, and coordinated with the passage of the MetOp satellite (carrying IASI) over the station. In addition, specific ground-based instrumentation was deployed at the station, for example snowfall and snow accumulation instruments on the ground, and a 45-m tower equipped with meteorological sensors (wind, moisture, temperature) at several levels to monitor the structure of the polar boundary layer.

The second part of the project is a long-duration balloon campaign that is currently taking place above Antarctica, and will last till early 2011. Nineteen 12-m diameter superpressure balloons were released in September and October in the stratospheric polar vortex from McMurdo station by the French space agency (CNES). The balloons fly at approximately 17 km altitude and carry up to 60 kg of instrumentation and flight devices. Similar balloons have already been successfully used during the Vorcore campaign in 2005, and can typically perform flights that last for several months (Hertzog *et al*., 2007). Most of the balloons will be flying simultaneously for a few months in the austral spring and early summer, and will provide continuous observations of the polar atmosphere during that period.

All balloons carry a small *in situ* meteorological package that measures temperature and pressure every 30 seconds. The horizontal wind at the flight level is obtained from successive GPS positions of the balloons. These observations are sent in near real time to the Global Telecommunication System, so as to be assimilated in the NWP

Balloon launch. Photo courtesy of CNES (Philippe Cocquerez).

systems operated by the various meteorological services around the world, and thus contribute to the improvement of meteorological forecasts.

Furthermore, thirteen balloons carry the driftsonde gondola developed at NCAR. Each driftsonde gondola contains about 50 miniaturized dropsondes, which can be released individually on demand during the stratospheric balloon flight to provide high-resolution profiles of thermodynamic variables below the balloon. During the campaign, the dropsoundes are usually coordinated with the passage of the MetOp over the balloon location, in order to provide an *in situ* truth that can be compared with the temperature profile retrieved from IASI observations. Some dropsondes are also deployed in the "sensitive regions" of numerical forecasts, where small improvements in the description of the atmospheric flow can lead to large improvements in the simulation.

The remaining 6 balloons carry scientific payloads devoted to tackling scientific issues linked to stratospheric dynamics and chemistry. This equipment provides *in situ* observation of ozone (with two instruments developed at LMD, France and at the University of Colorado), as well as condensation nuclei with a particle counter developed by the University of Wyoming. These *in situ* observations, performed by instruments onboard quasi-Lagrangian tracers, enable us to follow the depletion of ozone during the spring season, and to assess the potential effect of mesoscale waves in triggering the formation of polar stratospheric clouds. In particular, the role of waves generated above the Antarctic Peninsula, which seems to be important for the formation of PSCs leeward of the mountains, will be monitored during the campaign. Furthermore, two of the balloons carry a GPS radio-occultation system developed by the University of Purdue to retrieve the temperature profile below the balloon several times per day. These observations, together with the *in situ* meteorological measurements, will be used to diagnose the stratospheric wave activity over Antarctica. A full report on the preliminary results of the field campaign will be provided in a few months.

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The High-Energy-Particle Precipitation in the Atmosphere (HEPPA) Model vs. Data Inter-comparison: Lessons Learned and Future Prospects

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Energetic particle precipitation (EPP) has important implications for atmospheric chemistry. The principal mechanism of EPP affecting the atmospheric composition is the formation of odd nitrogen and hydrogen radicals, which are both involved in catalytic ozone destruction, *via* a cascade of dissociation, ionization, and recombination processes. Solar eruptions and associated coronal mass ejections sporadically generate intense particle fluxes of very high energy with the potential to penetrate deep into the Earth's atmosphere in the polar cap regions. During such solar proton events (SPEs), which are more frequent near solar maximum, stratospheric and mesospheric chemistry can be dramatically altered.

During the last solar cycle, there were several large SPEs that were intensively observed by several instruments on different satellite platforms, including NOAA 16 SBUV/2 and HALOE data (Jackman *et al*., 2001; Jackman *et al*., 2005a,b; Randall *et*

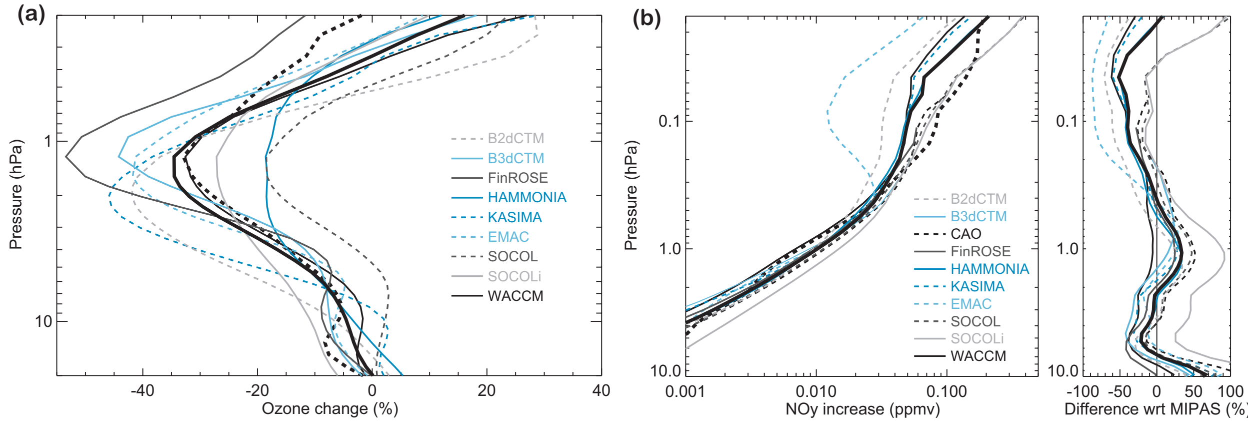

Figure 1a: Area-conserving averages (70–90°N) of observed and modelled relative O_3 changes with respect to 26 October during 16– 26 November. Thick solid and dashed lines represent multi-model mean average and MIPAS observations, respectively. Figure 1b: Area-conserving averages (40–90°N) of observed and modelled NO_y enhancements during 30 October – 1 November with respect to 26 October (left), and relative deviations of modelled averages from the MIPAS observations (right). Thick solid and dashed lines represent multi-model mean average and MIPAS observations, respectively.

al., 2005); GOMOS, MIPAS, and SCIAMACHY on Envisat (Seppälä *et al*., 2004; López-Puertas *et al*., 2005a,b; von Clarmann *et al*., 2005; Funke *et al*., 2008; Orsolini *et al*., 2005; Rohen *et al*., 2005); and MLS on AURA (Verronen *et al*., 2006). In particular, during late October and early November 2003, three active solar regions produced solar flares and energetic particles of extremely large intensity; the fourth largest event observed in the past forty years. During and after this SPE, often referred as the "Halloween" event, stratospheric and lower mesospheric composition changes were observed in both hemispheres. This includes enormous enhancements in NO_x, large depletions in O_3, as well as significant changes in other NO_y species and N_2O. In addition, perturbations of HO_x and chlorine species (ClO and HOCl) abundances were observed.

Additionally, magnetospheric electrons precipitate into the atmosphere during geomagnetic perturbations and generate large amounts of nitric oxide in the polar upper mesosphere and lower thermosphere. This perturbation occurs throughout the solar cycle, with a maximum intensity approximately 2 years after solar maximum, when the solar wind accelerates. In the absence of sunlight during polar winter, large amounts of EPP-generated odd nitrogen can be transported down to the stratosphere by the meridional circulation without being photochemically destroyed. This mechanism is often called the EPP indirect effect. Observational evidence for the EPP-related NO_x deposition into the stratosphere has been given by a number of authors (*e.g.*, Siskind *et al*., 2000; Randall *et al*., 1998). Funke *et al*. (2005) deduced from MIPAS data that a total amount of 2.4 Gmole of NO_x was released into the stratosphere during the Antarctic winter 2003, making up 9% of the stratospheric production due to N_2O oxidation in the SH.

EPP indirect effects are strongly linked to the dynamical conditions, showing more pronounced variability in NH polar winters than in the SH. Indeed, Randall *et al*. (2007) have shown that interannual variations of the NO_x enhancements in the SH polar winter stratosphere are closely linked to variations of the geomagnetic A_p index (a measure of geomagnetic activity over the globe), suggesting that downward transport of NO_x is predominantly controlled by the upper atmospheric EPP source rather than dynamical transport. On the other hand, exceptional dynamical conditions during 3 out of 7 recent NH winters has led to surprisingly strong EPP indirect effects there (Randall *et al*., 2009). In the 2008/2009 winter, large amounts of NO_x entered the stratosphere despite low geomagnetic activity, which clearly demonstrates the importance of dynamical modulations of EPP indirect effects in the NH.

Therefore, EPP represents an important solar-terrestrial coupling mechanism that is directly linked to solar variability. The influence of EPP on climate through stratospheric chemical and dynamical processes is barely understood. This influence is likely to extend beyond the polar middle atmosphere. Evidence for EPP-induced variability in the polar troposphere and tropical stratosphere has recently been demonstrated (*i.e.,* Seppälä *et al*., 2009, Semeniuk *et al*., 2010). A joint effort of both the atmospheric modelling and the satellite observation communities is required to advance towards a comprehensive understanding of climate implications, and – in a second step – towards an accurate representation of these effects in climate modelling.

The High Energy Particle Precipitation in the Atmosphere (HEPPA) model *vs*. data inter-comparison initiative was established during the first HEPPA workshop held in Helsinki in May 2008. It brings together scientists involved in atmospheric modelling using state-of-the art CCMs and CTMs on one hand, and scientists involved in the analysis and generation of satellite data on the other hand. The objective of this community effort is (i) to assess the ability of state-of-the-art atmospheric models to reproduce EPP-induced composition changes, (ii) to identify and, if possible, remedy model deficiencies related to chemistry, dynamics, and ionization schemes, and (iii) to serve as a platform for discussion between modellers and data providers. This is achieved by a quantitative comparison of observed and modelled species abundances during selected periods of pronounced particle forcing, as well as by comparing the simulations performed by different models. In this sense, there is a strong link between the HEPPA model *vs*. data inter-comparison initiative and the SOLAR Influence for SPARC (SOLARIS) working group (see article on SOLARIS activities in this issue). Both initiatives focus on modelling and understanding the solar influence on climate through chemical and dynamical processes in the middle atmosphere, and complement each other by investigating different aspects of solar variability (particles vs. radiation). See **Table 1** for a list of involved scientists.

Past activities

During the last 2 years, the HEPPA initiative has focused on the inter-comparison of MIPAS/Envisat data obtained in the aftermath of the “Halloween” SPE (26 October – 30 November 2003) with model results. We have compared observations obtained at 25–0.01 hPa in the NH (40-90°N) with simulations performed with the following CCMs and CTMs: the Bremen 2D and 3D Chemical Transport Models (Sinnhuber *et al*., 2003), FinROSE (Damski *et al*., 2007), HAMMONIA (Schmidt *et al*., 2006), KASIMA (Kouker *et al*., 1999), EMAC (Jöckel *et al*., 2006), SOCOL and SOCOLi (Egorova *et al*., 2010), the CAO model (Krivolutsky *et al*., 2006), and WACCM4 (Garcia *et al*., 2007). The large number of models participating in the inter-comparison exercise allowed for an evaluation of the overall ability of atmospheric models to reproduce observed atmospheric perturbations generated by SPEs, particularly with respect to NO_y and ozone changes. This model validation represents a necessary first step towards an accurate implementation of particle precipitation effects in long-term climate simulations. Further, the quasi-instantaneous perturbation of the atmosphere due to an SPE acts as a natural laboratory for studying stratospheric and mesospheric chemistry. This has allowed us to test and to identify deficiencies in the chemical schemes, particularly with respect to nitrogen and chlorine chemistry, both of which are relevant to stratospheric ozone chemistry.

Among the species affected by SPEs, we focused on NO, NO_2, N_2O, N_2O_5, HNO_3, HNO_4, H_2O_2, O_3, ClO, HOCl, and $ClONO_2$. We have further assessed the meteorological conditions in both the models and the real atmosphere, as observed by MIPAS, by comparing temperature and tracer fields (CH_4 and CO). In general, atmospheric models are able to reproduce most of the observed composition changes. In particular, simulated SPE-induced ozone losses agree on average within 5% with the observations. This excellent agreement is found on a short-term scale (HO_x-driven) in the mesosphere, as well as on a mid-term scale (NO_x-driven) in the stratosphere (see **Figure 1a**). Simulated NO_y enhancements around 1 hPa, however, are on average 30% higher than indicated by the observations (see **Figure 1b**). This systematic behaviour suggests that these differences are related to the simulated ionization rate profile shape.

The analysis of the observed and modelled NO_y partitioning in the aftermath of the “Halloween” SPE has clearly demonstrated the need to implement additional ion chemistry (*e.g.,* ion-ion recombination between NO_3- and H+ cluster ions, and HNO_3 formation *via* water cluster ions) into the chemical schemes. An overestimation of observed H_2O_2 enhancements by all models hints at an under-estimation of the OH/HO_2 ratio in the upper polar stratosphere during the SPE. The analysis of perturbations of the chlorine species ClO, HOCl and $ClONO_2$ has shown that the encountered differences between models and observations, particularly the under-estimation of observed $ClONO_2$ enhancements, are related to a smaller availability of ClO in the polar region before the SPE.

In general, the inter-comparison has demonstrated that differences in the meteorology and/or initial state of the atmosphere in the simulations causes a significant variability of the model results, even on the short time scale of only a few days. Furthermore, this sensitivity of the simulated atmospheric responses to the background conditions, indicated by the spread in the model results, also implies that the response to proton events in the real atmosphere depends strongly on the actual conditions.

Future activities

At the second HEPPA workshop held in Boulder, CO in October 2009, it was decided to focus future activities on EPP indirect effects (*i.e.*, polar winter NO_x descent). This decision was motivated by the higher potential of EPP indirect effects to influence middle atmospheric composition on longer time scales compared to direct effects (*i.e.*, SPEs), and by the large variability in EPP indirect effects related to dynamical modulations, making its representation in current atmospheric models challenging.

In particular, the 2008/2009 NH polar winter turned out to be a very interesting period because of the peculiar dynamic conditions which were characterized by an unusually strong and persistent stratospheric sudden warming (SSW) that occurred in January, followed by the reformation of a strong upper stratospheric vortex, with very efficient descent of the vortex during the following weeks. MIPAS observations of NO_x and the tracer CO in the 70-90°N region (see **Figure 2** - colour plate III) illustrate the dynamical modulations of the EPP indirect effects during this particular NH winter: After the SSW in late January, which provoked a depletion of CO and NO_x in the upper stratosphere and mesosphere, large amounts of these species descended very quickly into the upper

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stratosphere. Similar situations were also found in the NH during January 2004 and 2006, however, the period November 2008 – May 2009 was better covered by satellite data than the previous winters.

The planned inter-comparison exercise will focus on the assessment of the EPP source (and its spatial distribution) by analysing observed and modelled NO_x distributions from the mesosphere up to the thermosphere (60-150 km) during the period of interest; the analysis of vertical coupling mechanisms by inter-comparison of observed and modelled tracer and temperature fields with particular emphasis on the MLT region; and the assessment of stratospheric mid-term composition changes induced by EPP indirect effects during 2009 with particular emphasis on ozone and NO_y repartitioning.

Spatially resolved observational data during November 2008 – May 2009 is available from a large number of instruments (*e.g.*, ACE-FTS; GOMOS, MIPAS, and SCIAMACHY on Envisat; MLS/Aura; SMR/Odin; SABER/TIMED), including NO and temperature up to the middle thermosphere, O_3 and CO up to 100 km, as well as stratospheric and mesospheric distributions of NO_2, HNO_3, N_2O_5, N_2O, and CH_4.

Interested scientists working on satellite data or atmospheric modelling are encouraged to participate in this activity. Atmospheric models to be included in the inter-comparison should have the capacity to be nudged to meteorological analyses during the period of interest, and preferably cover the MLT region. It has been shown, however, that models with lower lids can successfully be employed for simulations of EPP indirect effects by means of adequately chosen upper boundary conditions (Vogel *et al*., 2008, Reddmann *et al*., 2010). The expected outcome of this new inter-comparison exercise is (i) the validation of EPP implementations in atmospheric models, (ii) a better understanding of the EPP source distribution and vertical coupling mechanisms, and (iii) the quantification (and model validation) of EPP indirect effects on stratospheric chemistry. A dedicated workshop will be held during the upcoming third HEPPA meeting in Granada/Spain (9-11 May 2011, **http://heppa2011.iaa.es/**), focusing on the coordination of these activities and providing an opportunity to present first results.

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Stratospheric Change and its Role for Climate Prediction (SHARP): A contribution to SPARC

U. Langematz, Freie Universität Berlin, Germany (ulrike.langematz@met.fu-berlin.de) and the SHARP consortium

Since June 2009, scientists and students from eight German institutions have been working together on SPARC-related science issues in the research unit Stratospheric Change and its Role for Climate Prediction (SHARP) funded by the Deutsche Forschungsgemeinschaft (DFG; German Science Foundation). The proposal for SHARP was strongly motivated by the New SPARC Initiatives and this article aims to introduce the goals and current research activities of SHARP to the international SPARC community. International partners (*e.g.*, Bodeker Scientific, University Cambridge, UK Met Office, University of Utrecht, and Columbia University in New York) are associated members of SHARP.

The primary objective of SHARP is to improve our understanding of global climate change and the accuracy of climate change predictions, with emphasis on the relevance of the stratosphere. SHARP is coordinating research activities in Germany with two leading themes:

- The interactions between climate change, stratospheric dynamics and atmospheric composition.
- The interaction between stratospheric change and tropospheric climate and weather.

To foster optimal collaboration between modelling and measurement groups and across the locally distributed institutions, four collaborative scientific projects have been defined in SHARP that address the following current key research aspects:

1. The detection, investigation and explanation of recent and potential future changes in the **Brewer-Dobson circulation** and their implications for stratospheric dynamics, physics and chemistry in a changing climate. This combines optimised retrievals of atmospheric data products and simulations of improved Chemistry Climate Models (CCMs) and General Circulation Models (GCMs).
2. The detection and attribution of changes in **stratospheric ozone (O3)** during the anticipated turnaround of chlorine loading, and the prediction of O_3 change in response to and as a result of feedback with global climate change.
3. The explanation of recent **stratospheric water vapour (H2O)** concentration changes by extending the time series of ground based and satellite data products in conjunction with model studies, and a reliable assessment of future H_2O concentrations based on the improved understanding about the key processes gained from studying the past.
4. The attribution and prediction of changes in tropospheric weather and climate in response to **stratosphere-troposphere coupling**, and our understanding of the underlying mechanisms based on atmospheric observations and simulations of CCMs and GCMs.

SHARP staff at 2010 annual meeting in Bremen.

To achieve these goals, leading German modelling and measurement research groups have organised and coordinated their research in a synergistic and complmentary effort. SHARP makes use of:

- Measurements of stratospheric composition, in particular from the SCIAMACHY satellite instrument of University Bremen and the MIPAS instrument of Karlsruhe Institute for Technology, for the analysis of stratospheric change and the validation of the model simulations. For the derivation of long-term trends, the data analysis is supported by measurements from balloon platforms of the Universities Frankfurt and Heidelberg. In addition the SHARP team collaborates with the German Weather Service (DWD) long term measurement programme.
- The EMAC-FUB and E39C-A Chemistry-Climate Models (CCMs) run at Freie Universität Berlin (FUB) and DLR, which simulate the complex interactions between chemical processes, dynamics and radiative forcing for the attribution and prediction of climate change. The CCM studies are supported by sensitivity studies with the ECHAM5 General Circulation Models (GCMs) of MPI for Meteorology (MPIM) and the ECHAM5 and EGMAM Atmosphere-Ocean GCMs (AOGCM) of MPIM and FUB to investigate natural variability and separate the effects of specified climate forcings.

Table 1 gives a summary of the SHARP consortium and the contributions of the individual members to the research unit. Currently, one post-doc, 8 PhD students, 4 student assistants, and one administrative assistant are employed in SHARP projects. The photo shows the SHARP group at the first annual meeting in Bremen in May 2010. The research unit is coordinated at Freie Universität Berlin. More information can be found on the SHARP website **www.fu-berlin.de/sharp/**. The following sections present an overview of the objectives of the four individual science projects and selected new results.

Project SHARP-BDC

In the project SHARP-BDC, coordinated by Martin Dameris (DLR), the most important focus addressed is **"How is the Brewer-Dobson circulation affected by climate change, and which processes are relevant?"** In this project, dynamical, physical and chemical processes, as

Table 1: *Principle Investigators (PI) and Co-Investigators (Co-I) in the SHARP research unit.*

Participants	Institution/Institute	Contribution to SHARP	Scientific Area
Ulrike Langematz	Freie Universität Berlin (FUB), Institut für Meteorologie	Speaker of SHARP, **PI of SHARP-STC,** Co-I of SHARP-BDC, SHARP-OCF, SHARP-WV	Chemistry-Climate Modelling, EMAC-FUB CCM
Martin Dameris	Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Atmosphärenphysik	**PI of SHARP-BDC,** Co-I of SHARP-OCF, SHARP-WV, SHARP-STC	Chemistry-Climate Modelling, E39C-A CCM
John P. Burrows	Universität Bremen (UBR), Institut für Umweltphysik	PI of SHARP-OCF	Stratospheric trace gases, GOME, SCIAMACHY
Gabriele Stiller	Karlsruher Institut für Technologie (KIT), Institut für Meteorologie und Klimaforschung	**PI of SHARP-WV,** Co-I of SHARP-BDC, SHARP-OCF	Stratospheric trace gases, MIPAS
Christoph Brühl	Max-Planck-Institut für Chemie (MPIC)	Co-I of SHARP-OCF	Chemistry-Climate Modelling,EMAC CCM
Ulrich Cubasch	Freie Universität Berlin (FUB), Institut für Meteorologie	Co-I of SHARP-STC	Climate Modelling, AO-GCM EGMAM
Andreas Engel	Goethe Universität Frankfurt (JWGU), Institut für Atmosphäre und Umwelt	Co-I of SHARP-BDC, SHARP OCF	Stratospheric trace gases,Balloon-borne whole air sampler
Marco Giorgetta	Max-Planck-Institut für Meteorologie (MPIM)	Co-I of SHARP-BDC, SHARP WV, SHARP- STC	Climate modelling, ECHAM GCM and AO-GCM
Patrick Jöckel	Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Atmosphärenphysik	Co-I of SHARP-WV	Water isotopes, EMAC CCM
Klaus Pfeilsticker	Universität Heidelberg (UH), Institut für Umweltphysik	Co-I of SHARP-OCF	Stratospheric trace gases, LPMA/DOAS balloon measurements
Björn-Martin Sinnhuber	Karlsruher Institut für Technologie (KIT), Institut für Meteorologie und Klimaforschung	Co-I of SHARP-OCF	VSLS, CTM-Modelling
Mark Weber	Universität Bremen (UBR), Institut für Umweltphysik	Co-I of SHARP-OCF, SHARP-WV	Trace gases and dynamics, SCIAMACHY, GOME

well as feedback effects relevant for the stratospheric residual circulation (Brewer-Dobson circulation, BDC) are investigated. Moreover, the impact of changes in atmospheric composition and climate on these processes are studied in detail using numerical simulations with the Chemistry-Climate Models (CCMs) EMAC-FUB and E39C-A in connection with observations. The influences of atmospheric changes on the BDC will be identified and quantified, as well as their feedback on tracer distributions and surface climate (see also SHARP-STC).

First results of the climatology and trends in tropical upwelling in the lower stratosphere simulated with E39C-A have been presented in Stenke *et al*. (2009) and Garny *et al*. (2009). The aim was to quantify changes in tropical upwelling and examine potential contributing mechanisms. The drivers of upwelling in the tropical lower stratosphere were investigated using results of different multi-decadal simulations (transient and in time-slice mode) of E39C-A. The climatological annual cycle in upwelling and its wave forcing were validated against ERA-Interim analysis. It turned out that the strength in tropical upwelling and its annual cycle can be largely explained by local, resolved wave forcing. The climatological mean forcing is due to both stationary planetary-scale waves that originate in the tropics, and to extra-tropical transient synoptic scale waves that are refracted equatorward. In the CCM, further increases in atmospheric greenhouse gas concentrations to the year 2050 force a year around positive trend in tropical upwelling, maximising in the lowermost stratosphere. Tropical ascent is balanced by downwelling between 20° and 40°. Increases in tropical upwelling can be explained by stronger local forcing by resolved wave convergence, which is driven in turn by processes initiated by increases in tropical sea surface temperatures (SSTs). Higher tropical SSTs cause a strengthening of the subtropical jets and modification of deep convection affecting latent heat release. While the former can modify wave propa-

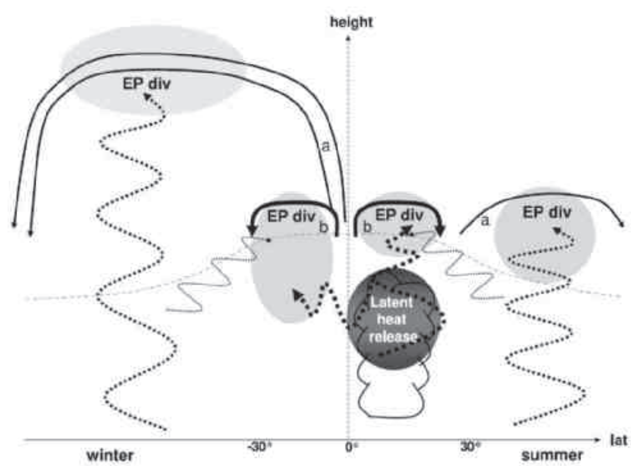

Figure 1: Schematic of the two branches of the meridional circulation in the stratosphere, and its wave driving. Wave flux convergence is indicated in light grey patches (negative EP divergence). The global classical BDC (a) is driven by extra-tropical waves, and a deep hemisphere-wide cell exists in the winter hemisphere. The secondary circulation (b) is confined to the (sub-) tropical lower stratosphere, and driven locally by wave dissipation. Both tropical waves (mostly generated by strong deep convection in the summer tropics) and extra-tropical waves (mostly refracted to low latitudes) contribute to the wave convergence in the upper troposphere/lower stratosphere. Figure taken from Garny et al., 2010.

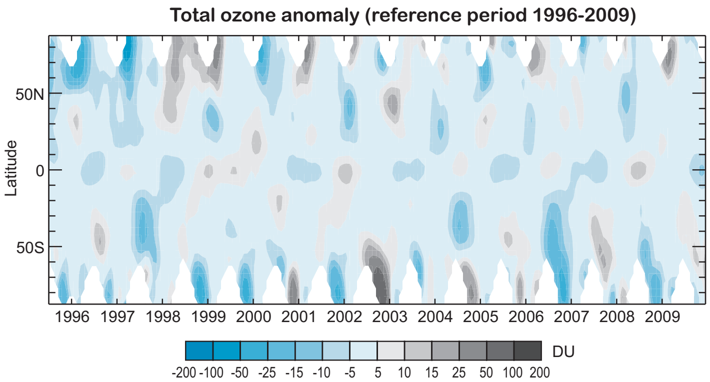

Figure 2: Total ozone anomaly from the merged GOME1/SCIAMACHY/GOME2 (GSG) data set. The anomalies are calculated with respect to the seasonal mean from 1995-2006 (adapted from Weber and Steinbrecht, 2010).

gation and dissipation, the latter affects tropical wave generation. The dominant mechanism leading to enhanced vertical wave propagation into the lower stratosphere is an upward shift of the easterly shear zone due to the strengthening and upward and equatorward shift of the subtropical jets. A summary of the mechanisms is given in **Figure 1**. More details about this study can be found in Garny *et al*. (2010).

Project SHARP-OCF

SHARP-OCF focuses on the question **"How is the evolution of stratospheric ozone affected by climate change, and how strong is the feedback?"** SHARP-OCF is coordinated by John P. Burrows, University Bremen. One major goal of this project is to analyse present observational trace gas data together with state-of-the art models in order to obtain a better understanding of the interaction between ozone and climate change and the underlying dynamical and chemical processes. Satellite, balloon and aircraft observations are used to assess the budgets and changes/trends of stratospheric ozone and the key halogenated substances, in particular, very short-lived substances (VSLS). Transient CCM simulations and supplementary sensitivity studies together with the observational data record are to be analysed to assess past and future evolution of stratospheric ozone and other key species.

Long-term total ozone data sets are now available from the "European" satellites GOME1, SCIAMACHY and GOME2 starting in 1995, and provide both total column and vertical profiles in an early morning orbit. Before these data sets can be used for long-term trend assessments, any biases and possible drifts between instruments must be removed. This has been done by matching the SCIAMACHY and GOME2 data record to GOME1. Using zonal-mean monthly mean data, the drifts and biases for SCIAMACHY and GOME2 have been corrected and a merged data set produced, which is called the GSG merged (GOME1/SCIAMACHY/GOME2) data set (**http://www.iup.uni-bremen.de/gome/wfdoas_merged.html**, Weber *et al*., 2007). **Figure 2** highlights the interannual variability of the GSG data set shown as anomalies with respect to the seasonal average from 1995-2009. The cold Arctic winters in the mid-1990s with severe polar ozone losses, the Antarctic ozone hole anomaly in 2002, as well as the record ozone hole in 2006 are clearly seen. In both the tropics and extra-tropics, the QBO signal is a prominent feature.

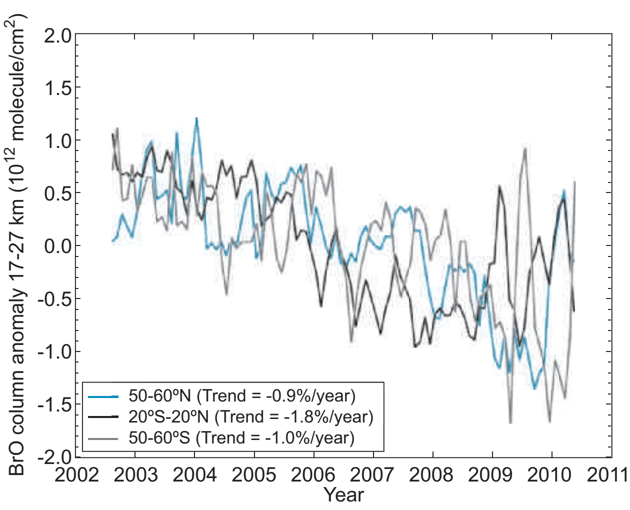

Figure 3: The change/trend of BrO at 50°-60°N, 20°N-20°S and 50°-60°S from SCIAMACHY (A. Rozanov and J. P. Burrows IUP University of Bremen).

Some of the recent work on stratospheric BrO retrieved from SCIAMACHY is shown in **Figure 3**. The integrated BrO between 2002 and 2010 is plotted for 50°-60°N, 20°N-20°S, and 50°-60°S. Both the seasonal variation at mid-latitudes and the longer term decrease of BrO are clearly observed. Detailed analysis will be undertaken within SHARP.

Transient CCM simulations with the E39C-A and EMAC-FUB models that have been performed within SHARP contributed to the CCMVal initiative (SPARC CCMVal, 2010) and were part of the projections of the future evolution of ozone for the upcoming WMO Assessment of Stratospheric Ozone: 2010. **Figure 4** (see colour plate IV) shows that most CCMs project that the ozone hole will vanish with respect to their 1960-1965 minimum area in the second half of the 21st century, however with a large uncertainty in the return date (Austin *et al*., 2010).

Project SHARP-WV

SHARP-WV focuses on stratospheric water vapour and the question: How is stratospheric water vapour affected by climate change, and which processes are responsible? SHARP-WV is coordinated by Gabriele Stiller (KIT Karlsruhe). SHARP-WV will analyse observational data sets from the satellite instruments MIPAS and SCIAMACHY, merged with the HALOE and SAGE data sets, and data from long-term simulations with CCMs in order to improve our understanding of past variations and trends in stratospheric H_2O, and to assess the future evolution of the stratospheric H_2O budget in a changing climate.

In particular, the satellite observations will be used to study the stratospheric water vapour distribution and its temporal (on various scales) and spatial anomalies, as well as changes on a decadal scale. The tropical and extra-tropical mechanisms for water vapour transport into the stratosphere (*e.g*., monsoon activity) and their relative importance will also be investigated, making additional use of the isotopic composition of stratospheric water vapour, which is provided by MIPAS observations. Series of multi-year simulations with several different set-ups of the CCMs ECHAM5/MESSy and E39C-A will be analysed in the same way as the observational data in order to validate the understanding of relevant processes of transport, and stratospheric sources and sinks under present and future conditions.

First results on the analysis of water vapour transport through the Indian monsoon anticyclone have been published by Kunze *et al*. (2010). **Figure 5** (see colour plate IV) shows the distribution of water vapour at 360 K in the region of the Asian Monsoon Anticyclone (AMA) as a four-year average of July-August MIPAS observations and a long-term monthly mean for the three CCMs involved in SHARP, respectively. Although the absolute water vapour mixing ratios between observation and models differ, the overall structure of enhanced water vapour, hinting towards upward transport in the AMA, is well reproduced. In detail, however, the models differ considerably regarding the position of the water vapour maximum relative to the centre of the AMA.

For the first time, vertical distributions of stratospheric water vapour were obtained from space borne limb observations of the scattered solar radiation using SCIAMACHY (Rozanov *et al*., 2010). Within SHARP-WV, it is planned to produce time series of zonal mean water vapour for the entire SCIAMACHY observation period beginning in August 2002. The water vapour retrieval is fairly time consuming because multiple scattering must be considered, in particular from the troposphere where water vapour is several orders of magnitude more abundant than in the stratosphere. **Figure 6** (see colour plate IV) shows the zonal mean water vapour volume mixing ratios derived from SCIAMACHY using ECMWF temperatures and pressures as input into the retrievals in the zonal bands 40°N - 45°N (a) and 40°S - 45°S (b) for altitudes between 10 and 25 km. The annual cycle in each hemisphere is clearly visible from these data.

Project SHARP-STC

SHARP-STC deals with stratosphere-troposphere coupling and the question: **"How is the coupling of the stratosphere and troposphere affected by climate change, and how strong is the feedback on climate?"** The project is coordinated by Ulrike Langematz (FUB). The focus of SHARP-STC is to determine the role of the interaction between the stratosphere and troposphere in a changing climate, in particular to assess the impact of a changing stratosphere on surface climate and weather.

Figure 7 illustrates the dynamical coupling between the stratosphere and troposphere in five Northern Hemisphere winters of a 300-year simulation with the Atmosphere-Ocean GCM (AO-GCM) EGMAM (Langematz *et al*., 2010). Negative anomalies in the signature of the Northern Annular Mode (NAM) that are associated with major warmings, as for example in February 2001, propagate downward into the troposphere, where they modify weather patterns with a delay of several weeks. Similarly, positive NAM anomalies associated with intense stratospheric polar vortices are followed by tropospheric positive anomalies.

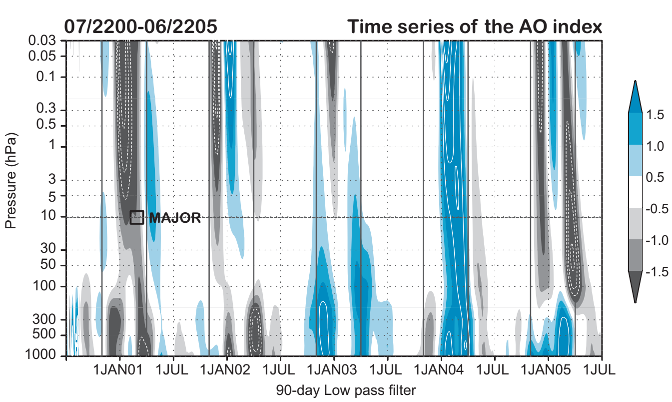

Figure 7: 90-day low-pass filtered time series of the NAM signature for five model years of a 300-year present day simulation with the EGMAM AOGCM. Positive values represent negative polar geopotential height anomalies and strong stratospheric vortices; negative values represent positive polar geopotential height anomalies and weak stratospheric vortices. From Langematz et al. (2010).

In SHARP-STC, the transient simulations of the past and future with the EMAC-FUB and E39C-A CCMs are analysed to study how well current models are able to reproduce the observed stratosphere-troposphere coupling, to understand the responsible mechanisms, and to assess its future evolution. Complementary sensitivity simulations will be performed with a spectrum of models of different complexity (GCMs with different horizontal and vertical resolution, with and without coupled ocean and chemistry) to isolate the effects of changes in greenhouse gases, stratospheric ozone, water vapour and sea surface temperatures on near-surface climate through downward coupling.

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Future SPARC and SPARC-related Meetings

2011

23-27 January — **91st Annual Meeting of AMS**, Seattle, WA, USA, http://www.ametsoc.org/MEET/meetinfo.html.
- 16th Confrence on Middle Atmosphere
- 23rd Conference on Climate Variability and Change

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/

5-9 June — **Canadian Meteorological and Oceanographic Society Congress (CMOS/SCMO)** Victoria, BC, Canada http://www.cmos.ca/congress2011/index.html
- Special SPARC session

13-17 June — **18th Conference on Atmospheric and Oceanic Fluid Dynamics**, Spokane, Washington, USA, http://www.ametsoc.org/MEET/meetinfo.html

27 June - 8 July — **International Union of Geodesy and Geophysics Assembly "on" Earth on the Edge: Science for a Sustainable Planet"**. Melbourne, Australia, http://www.iugg2011.com

24-28 October — **WCRP Open Science Conference,** Denver, CO, USA, www.wcrp-climate.org/conference2011

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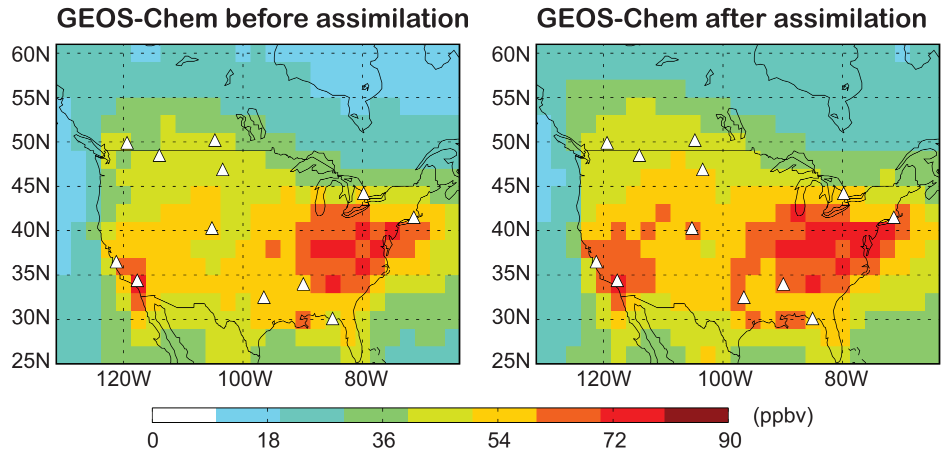


Figure 4: Monthly mean surface O_3 (averaged between 12 h – 18 h local time) over North America for August 2006 as simulated by GEOS-Chem (a) without assimilation and (b) with the assimilation of TES observations. Tropospheric O_3 profiles from TES were assimilated using a sequential suboptimal Kalman filter between 1 July and 31 August 2006. The assimilation increased surface O_3 abundances across western North America, reflecting the influence of transport of background O_3 (O_3 not produced from North American emissions) from the free troposphere into the North American boundary layer. (From Parrington et al., 2009.)

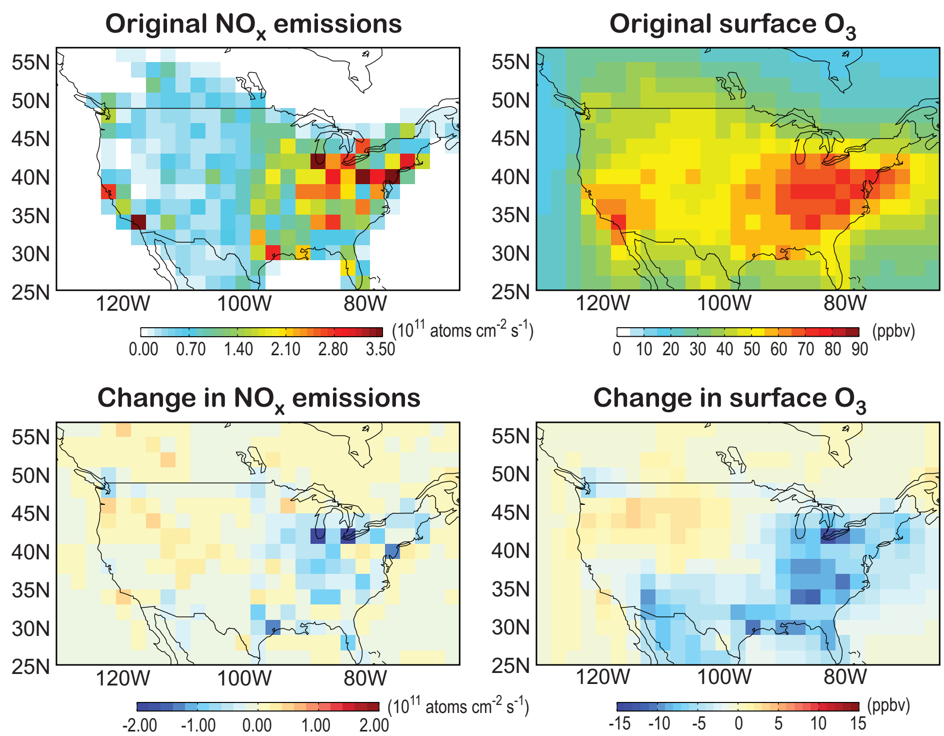


Figure 5: Impact of top-down NO_x emissions on surface O_3 abundances in GEOS-Chem. (a) The original NO_x emissions, in 1011 N cm^{-2} s^{-1}, for August 2006. (b) Simulated surface O_3 abundances based on the original NO_x emissions. (c) The difference in the top-down and original NO_x emissions. The top-down emissions were inferred from SCIAMACHY observations of NO_2 (Martin et al., 2006) and suggest lower NO_x emissions across the eastern USA. (d) The change in surface ozone abundances due to incorporating the top-down NO_x emissions in GEOS-Chem. The reduced NO_x emissions in the eastern USA produced a significant reduction in surface O_3 abundances. (Figure courtesy of Mark Parrington.)

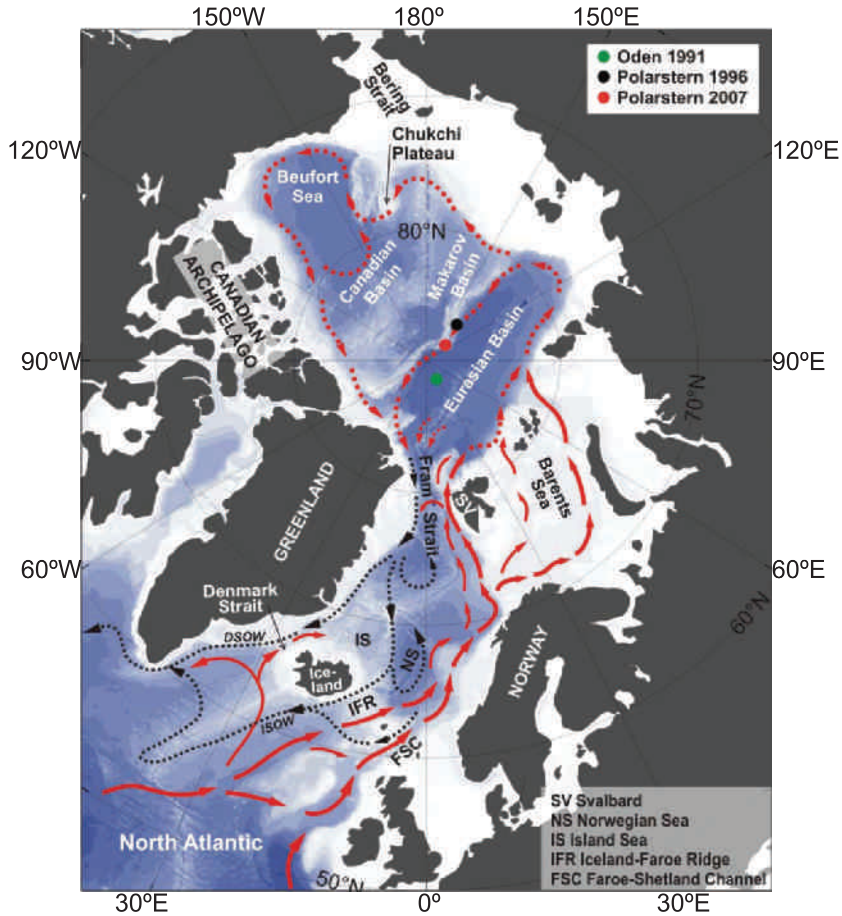


Figure 6: Physical mechanisms of decadal predictability associated with the production of Denmark Strait overflow water (DSOW), which is a major source of North Atlantic deep water. The North Atlantic inflows come through just two entry points, the Faroe-Shetland Channel (FSC) and the Iceland-Faroe Ridge (IFR), and then are modified by surface fluxes while they transit through the Nordic seas. The Arctic Ocean and Barents Sea act as 'switchyards', adding decadal time scale delays to the system. These delays are variable in time and differ for surface and mid-depth waters. The latter feed the overflows and offer a predictive potential in the form of transient anomalies of the density stratification. For the mid-depth, the figure shows a schematic circulation of Atlantic derived water (red solid) and dense, deep water (black dashed). From Karcher et al. (JGR, in revision).

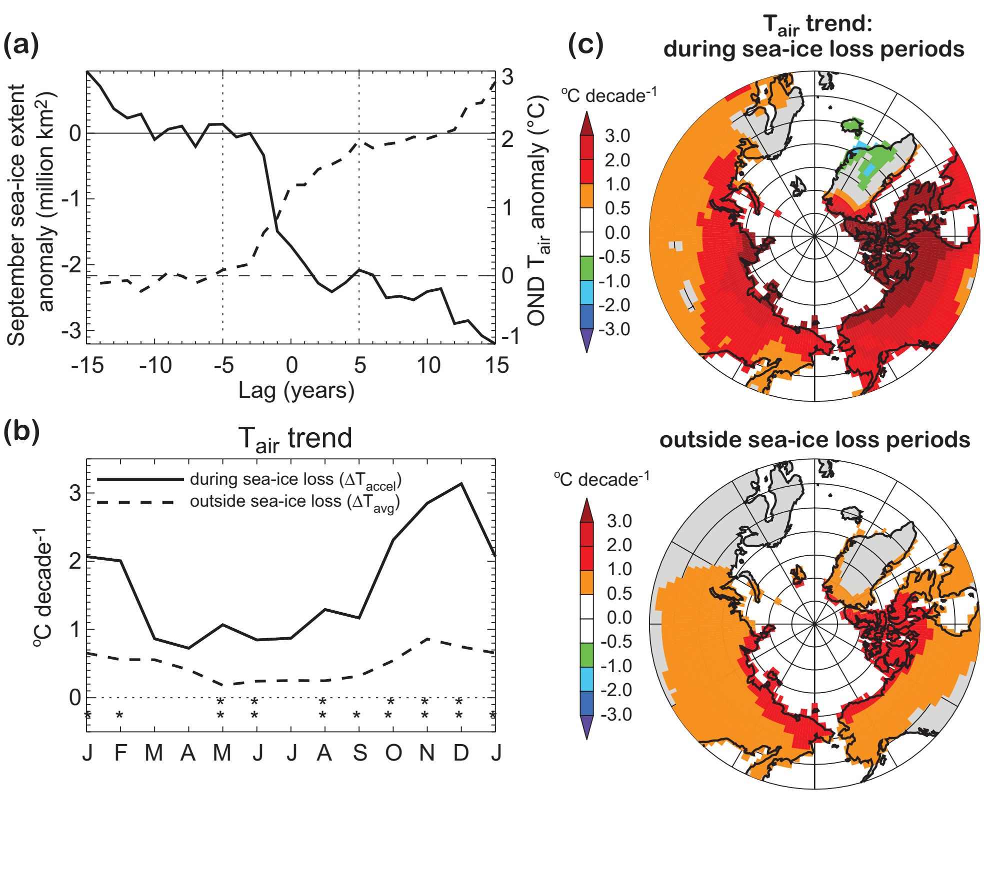


Figure 7: Evidence for decadal-scale impact of sea-ice loss on Arctic land warming rates. (a) Composite anomaly time series of September sea-ice extent (solid line) and October-November-December (OND) surface air temperature T_{air} (dashed line) over the Arctic land area (within 65–80°N, 60–300°E). Composites are formed by averaging nine 31-year anomaly time series that are centred about the mid-point (lag 0 years) of a rapid sea-ice loss event simulated in a CCSM3 21st century A1B simulation. The individual time series are anomalies from the lag -10 to -5 year mean. (b) Average monthly Arctic land T_{air} trends during periods of rapid sea-ice loss compared to periods of moderate sea-ice loss. The asterisks indicate the months for which the differences in the trends are statistically significant at the 90% (single asterisk) and 95% (double asterisk) levels. The largest impact is found in autumn and winter. (c),(d) Maps of T_{air} trends for OND during periods of rapid and moderate sea-ice loss. From Lawrence et al. (2008 GRL).

Program of the Antarctic Syowa MST/IS Radar (PANSY)

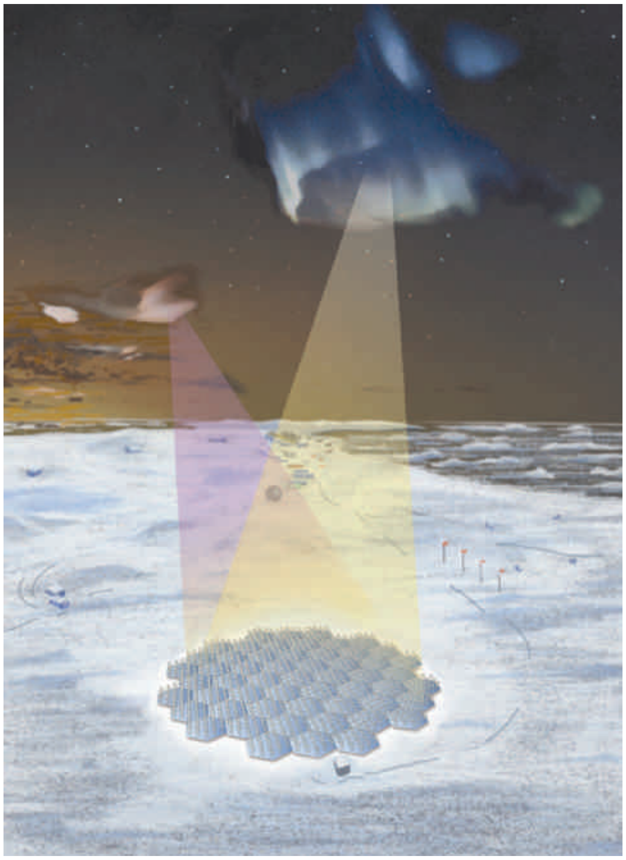
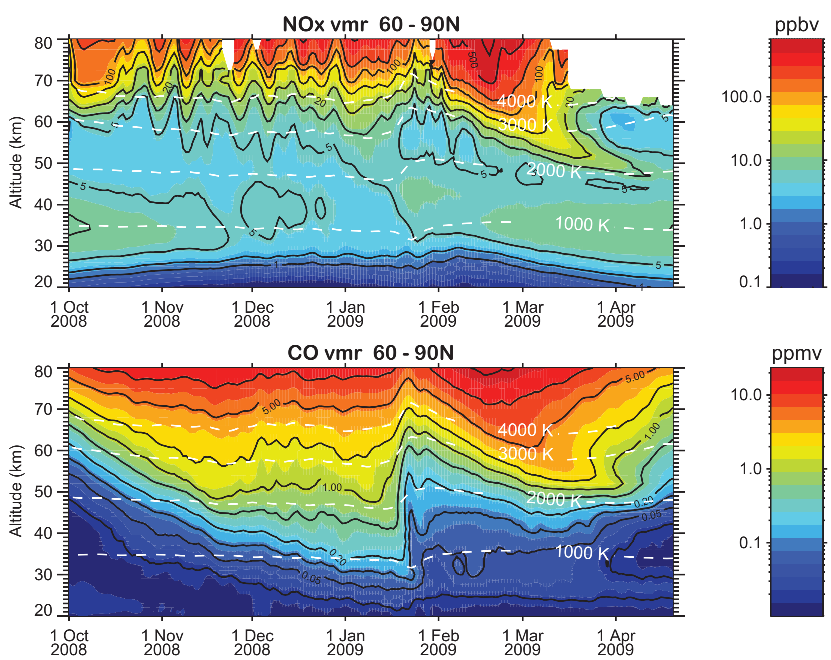


Figure 1: An image of the PANSY radar.

The High-Energy-Particle Precipitation in the Atmosphere (HEPPA) Model vs. Data Inter-comparison: Lessons Learned and Future Prospects

Figure 2: Temporal evolution of NO_x (top) and CO (bottom) as observed by MIPAS during the 2008/2009 NH winter at 70-90°N. The white dashed lines indicate selected potential temperature levels.



Stratospheric Change and its Role for Climate Prediction (SHARP): A contribution to SPARC

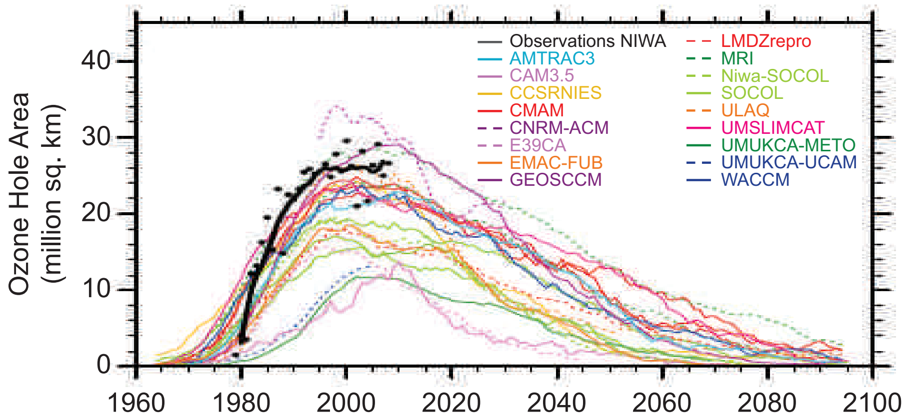


Figure 4: Simulated ozone hole areas based on the 1960-1965 minimum in the CCMVal projections, including EMAC-FUB and E39C-A. Figure taken from Austin et al. (2010).

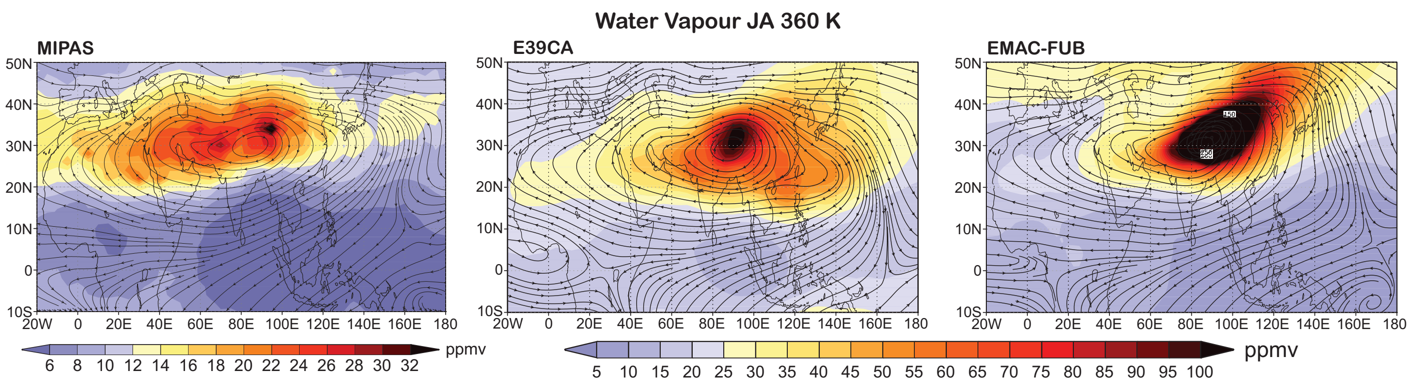


Figure 5: Water vapour (ppmv) for July-August at 360 K for the region 10°S–50°N, 20°W–180°E. Left: 4 years of MIPAS data; overlaid as streamlines are the horizontal wind components of ECMWF analyses. Other panels: Long-term monthly mean water vapour (ppmv) (41/44 yr) for the two CCMs as indicated. Note the differing absolute values and colour scales in the MIPAS observational distributions and the CCM results, respectively. Figure updated from Kunze et al., 2010.

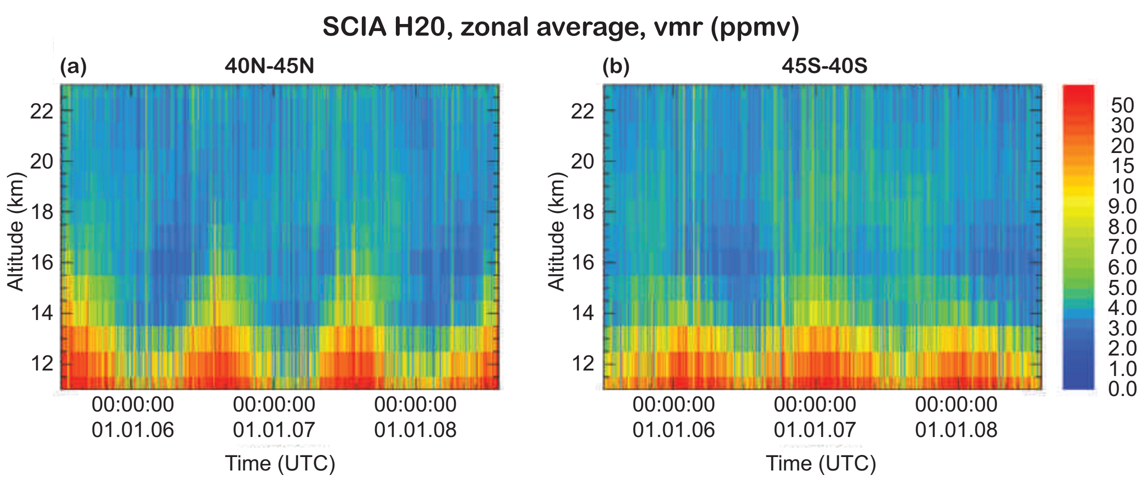


Figure 6: Zonal mean water vapour values retrieved from SCIAMACHY limb measurements and ECMWF temperature and pressure averaged between (a) 40°N - 45°N and (b) 40°S -45°S. Every seventh day of SCIAMACHY measurements between August 2006 and August 2008 is used.