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

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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-

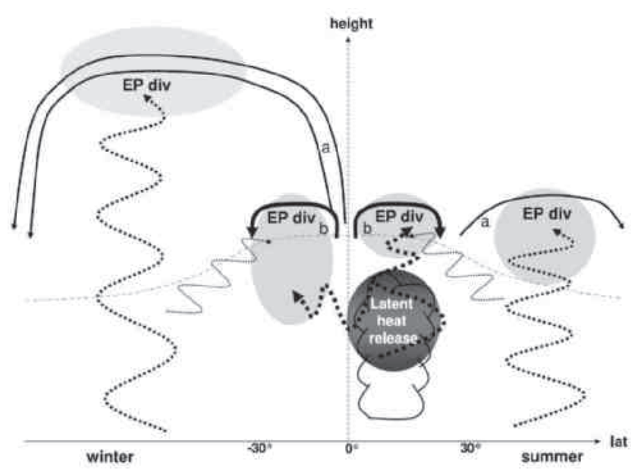

Figure 1: Schematic of the two branches of the meridional circulation in the stratosphere, and its wave driving. Wave flux convergence is indicated in light grey patches (negative EP divergence). The global classical BDC (a) is driven by extra-tropical waves, and a deep hemisphere-wide cell exists in 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.

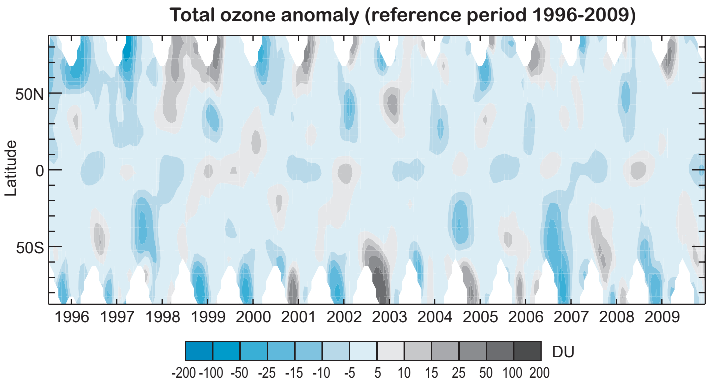

Figure 2: Total ozone anomaly from the merged GOME1/SCIAMACHY/GOME2 (GSG) data set. The anomalies are calculated with respect to the seasonal mean from 1995-2006 (adapted from Weber and Steinbrecht, 2010).

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.

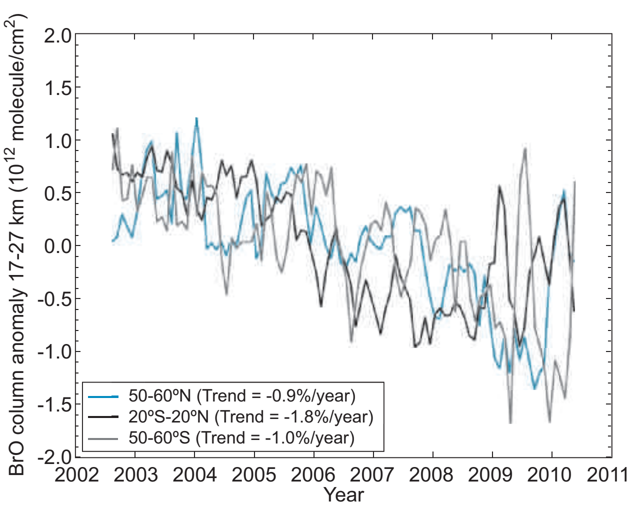

Figure 3: The change/trend of BrO at 50°-60°N, 20°N-20°S and 50°-60°S from SCIAMACHY (A. Rozanov and J. P. Burrows IUP University of Bremen).

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.

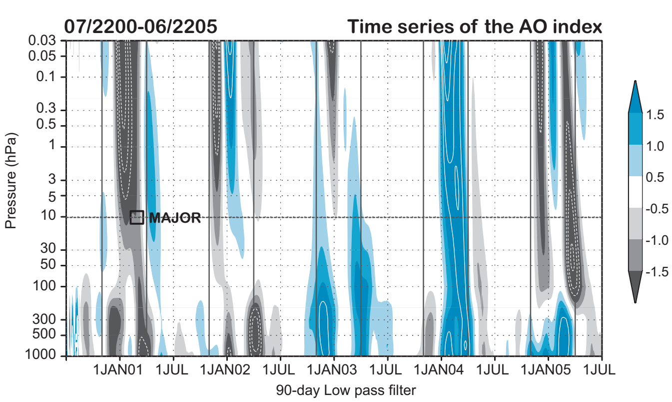

Figure 7: 90-day low-pass filtered time series of the NAM signature for five model years of a 300-year present day simulation with the EGMAM AOGCM. Positive values represent negative polar geopotential height anomalies and strong stratospheric vortices; negative values represent positive polar geopotential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

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.

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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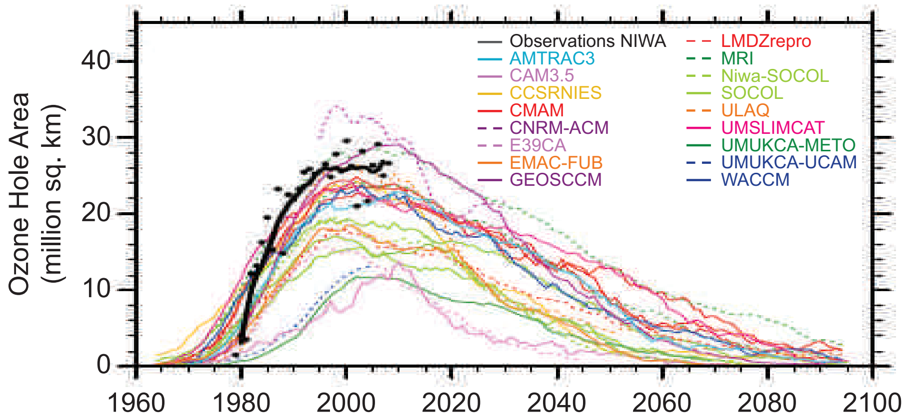

Figure 4: Simulated ozone hole areas based on the 1960-1965 minimum in the CCMVal projections, including EMAC-FUB and E39C-A. Figure taken from Austin et al. (2010).

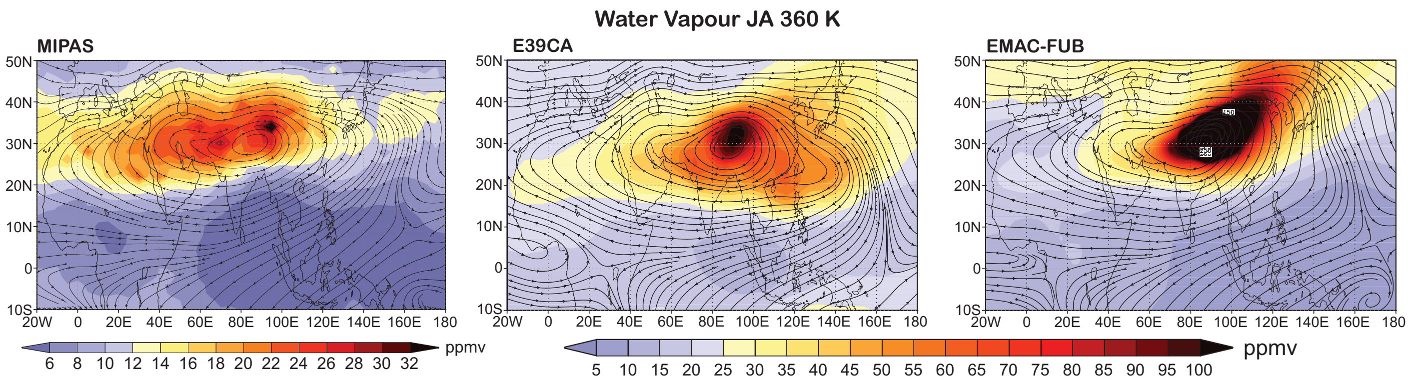

Figure 5: Water vapour (ppmv) for July-August at 360 K for the region 10°S–50°N, 20°W–180°E. Left: 4 years of MIPAS data; overlaid as streamlines are the horizontal wind components of ECMWF analyses. Other panels: Long-term monthly mean water vapour (ppmv) (41/44 yr) for the two CCMs as indicated. Note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

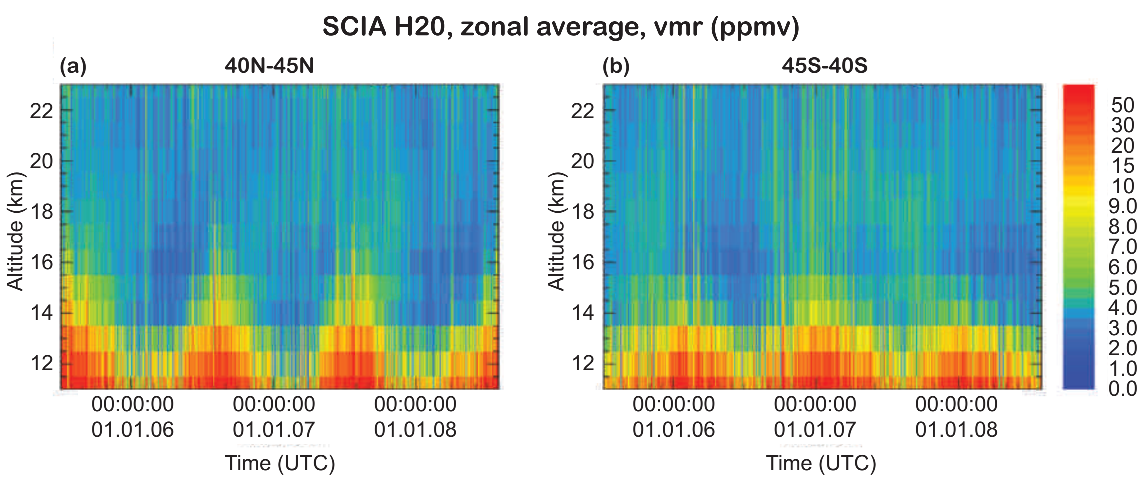

Figure 6: Zonal mean water vapour values retrieved from SCIAMACHY limb measurements and ECMWF temperature and pressure averaged between (a) 40°N - 45°N and (b) 40°S -45°S. Every seventh day of SCIAMACHY measurements between August 2006 and August 2008 is used.