FROM THE TROPOSPHERE TO THE THERMOSPHERE: COMBINING ATMOSPHERIC PROFILES FROM SATELLITES, ECMWF, AND GROUND-BASED MICROWAVE RADIOMETRY

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ABSTRACT

Profiling of the whole atmosphere from the troposphere to the thermosphere is required for further improvement of numerical weather prediction and understanding of atmospheric coupling processes. Combination of data sets from ECMWF reanalyses, TIMED/SABER, Aqua/AIRS and the ground-based microwave radiometers GROMOS, SOMORA and MIAWARA in Switzerland, leads to a description of the thermal structure and atmospheric composition from the surface to the lower thermosphere. The ozone, water vapor and temperature profiles of the various observation methods agree well. Time series of the atmospheric state over central Europe are analyzed for the winter 2003/2004. Perturbations of the temperature are propagating downwards from the mesosphere into the stratosphere.

Key words: whole atmosphere; atmospheric profiling; ozone; water vapor; temperature; ground-based microwave radiometry; ECMWF; TIMED/SABER; Aqua/AIRS; inter-comparison.

1. INTRODUCTION

The aim of the present study is going beyond cross-validations. We like to explore the potential of combining data from ground-based microwave radiometry, satellite experiments, and ECMW reanalyses. Time series of atmospheric profiles from the troposphere to the lower thermosphere are constructed, e.g., the satellite experiment TIMED/SABER describes the upper atmosphere beyond the stratopause, and ECMWF reanalyses are taken for the troposphere and stratosphere. Firstly, the coupling of dynamical, radiative, thermal and chemical processes of the lower, middle and upper atmosphere are illustrated by this method. Secondly, it informs about the agreement of the data sets at their intersection lines.

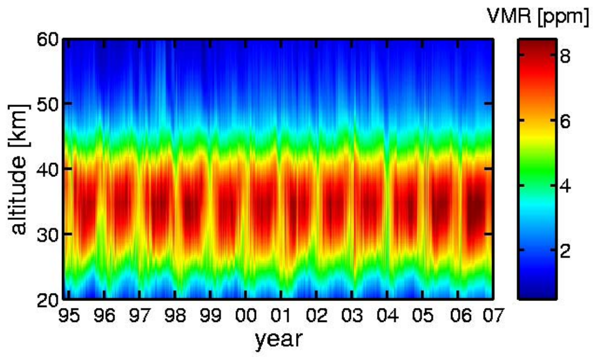

Figure 1. Time series of ozone volume mixing ratio as observed by the microwave radiometers GROMOS at Bern (1994-2000) and SOMORA at Payerne (2000-2007).

2. OZONE AND WATER VAPOR MEASUREMENTS BY GROUND-BASED MICROWAVE RADIOMETRY

Within the Network for the Detection of Atmospheric Composition Change (NDACC) and the Global Atmosphere Watch (GAW) programme, three microwave radiometers are continuously operated at Bern, Zimmerwald, and Payerne in Switzerland, measuring ozone and water vapor of the middle atmosphere. These data sets are used for cross-validations of satellite experiments [1, 2], detection of long-term trends [3], and monitoring of atmospheric variability, e.g., due to planetary waves, tides, gravity waves, changes of solar radiation [4, 5].

The ozone measurements by ground-based microwave radiometry are shown in Fig. 1. The ozone time series is composed of data from the GROMOS (ground-based ozone monitoring sensor) radiometer at Bern for the time interval November 1994 to December 1999, and from the SOMORA (stratospheric ozone monitoring radiometer) at Payerne for the time since January 2000. Both radiometers measure the thermal emission of ozone at 142 GHz. The SOMORA radiometer started the measurements in 2000. Since SOMORA has a better spectral resolution than GROMOS, the ozone profiles derived from

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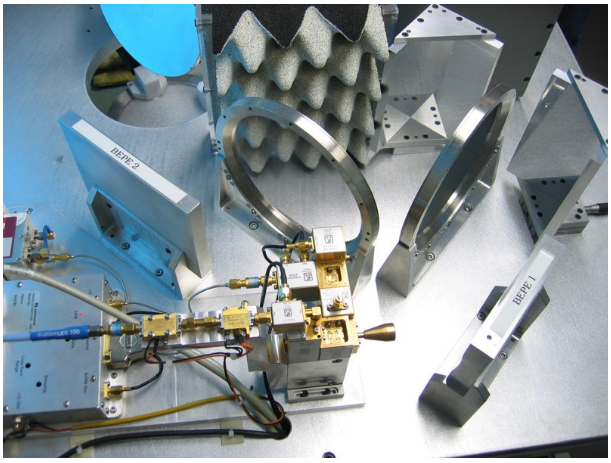

Figure 2. A detailed view of the microwave radiometer SOMORA measuring the thermal emission of ozone at 142 GHz. SOMORA has been designed by University of Bern and is continuously operated by MeteoSwiss at Payerne.

Figure 3. The microwave radiometer MIAWARA measures water vapor from 20 to 80 km altitude.

Figure 4. The new observatory for H_2O located at Zimmerwald close to Bern.

SOMORA's ozone line spectra are favored. The time series of ozone show annual and inter-annual variations. Ozone fluctuations due to traveling planetary waves appear during the winter months.

For atmospheric water vapor, the microwave radiometer MIAWARA (middle atmospheric water vapor radiometer) monitors the thermal emission spectra of water vapor at 22 GHz. MIAWARA has been operated since January 2003 at the University of Bern [6, 7]. In September 2006, MIAWARA moved to the new observatory for atmospheric water vapor at Zimmerwald (907 m altitude) which is close to Bern. The MIAWARA radiometer and the H_2O observatory Zimmerwald are shown in Figures 3 and 4. MIAWARA has a broadband acousto-optical and a narrowband chirp transform spectrometer permitting the retrieval of the H_2O volume mixing ratio at altitudes from 20 to 80 km.

3. THE EXPERIMENT SABER ON THE TIMED SATELLITE

The NASA satellite TIMED (Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics) was launched into a near-polar orbit (74° inclination) at 625 km altitude on December 7, 2001. The multichannel infrared radiometer SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) scans the atmosphere at the Earth's limb. Atmospheric profiles of temperature, density, pressure, and the concentration of several trace gases such as CO_2 and O_3 are retrievable from the recorded emission line spectra [8].

4. INTER-COMPARISON AND COMBINATION OF TEMPERATURE MEASUREMENTS OF TIMED/SABER AND ECMWF

The temperature measurements of TIMED/SABER are compared with ECMWF reanalyses data as recalculated and provided by the meteorological archival and retrieval system MARS at the end of each day.

The inter-comparison is restricted to the time interval September 1, 2003 to April 1, 2004 (severe solar storms happened around October 28, 2003). The ECMWF temperature profiles belong to the ECMWF grid point close to Bern, and we select SABER profiles over central Europe (circle of about 800 km around Bern). In addition we only select nighttime profiles (since we show later the interesting behaviour of nighttime mesospheric ozone which depends to some extent on the temperature). A composite of both temperature data sets is shown in Fig. 5. Here, we limit the temperature profiles of ECMWF to the range from 800 hPa ($h \approx 2$ km) to 3 hPa ($h \approx 40$ km). Beyond 40 km altitude, the SABER measurements are depicted in Fig. 5.

Using ground-based lidar measurement, Xu et al. (2006)

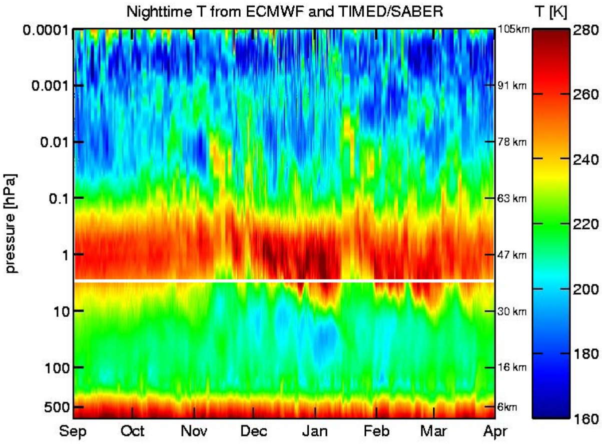

Figure 5. Temperature at altitudes from 2 to 105 km over Bern during the time interval from September 1, 2003 to April 1, 2004. Beyond 40 km (or 3 hPa), nighttime temperature data of TIMED/SABER are used, while ECMWF reanalyses data are shown below the white, horizontal intersection line.

successfully validated the temperature measurements of SABER in the altitude range h=85-100 km. The inter-comparison of SABER and ECMWF at the intersection line at around 40 km altitude indicates a very good agreement of both data sets in the upper stratosphere. The colors and structures of the temperature series of ECMWF and SABER are almost equal at 40 km altitude. The transition from ECMWF to SABER is actually invisible in Fig. 5. This result is also important for validation of ECMWF at upper altitudes. An extension of ECMWF's altitude range from the stratosphere into the mesosphere is already in progress since numerical weather prediction is expected to be significantly improved by inclusion of the upper atmosphere. Indeed, Fig. 5 shows during November 2003 a temperature disturbance in the mesosphere which is laterly propagating downward into the stratosphere (within a week or so). On a longer time scale, from November 2003 to begin of January 2004, the temperature maximum of the stratopause slowly descends from around 47 to 30 km altitude. This possibly illustrates the evolution of a "sudden" stratospheric warming. In mid of January 2004, a similar disturbance occurs again in the mesosphere and propagates downward into the stratosphere (until March 2004). A quite variable and high mesopause is visible at around 100 km which is typical for the winter season at mid-latitudes [9]. Occasionally, a second mesopause occurs at around 80 km altitude in Fig. 5.

5. INTER-COMPARISON AND COMBINATION OF O_3 MEASUREMENTS OF TIMED/SABER AND SOMORA

The ozone microwave radiometer SOMORA is located in Payerne which is around 50 km away from Bern. Because of the small distance between Bern and Payerne, the time-height plot of temperature over Bern (Fig. 5) can be used for interpretation of the ozone distribution over Payerne measured by SOMORA. The composite of the ozone data of TIMED/SABER and SOMORA is shown in Fig. 6, for the same time interval from September 1, 2003 to April 1, 2004. Again, we can see that both data sets are fitting well. The colors and the temporal fluctuations are quite similar at the white, horizontal intersection line which is at h=55 km in the lower mesosphere. While mesospheric ozone is dissociated by the short-wave radiation of the Sun during daytime, O_2 and O can recombine during nighttime. This roughly explains the red ozone layer at h=90-100 km in Fig. 6. Smith and Marsh (2005) modeled the variable ozone layer of the cold mesopause region which depends not only on diurnal photochemistry but also on tidal transport of ozone, and concentration of other trace gases such as NO, H_2O, and OH. The stratospheric ozone layer is disturbed and depleted during the winter months. Coincidently, the mesospheric ozone at h=55-80 km is disturbed, and strong enhancements of nighttime ozone are visible during the winter months. The SABER observations of the ozone enhancements at h=55-80 km are often confirmed by the SOMORA measurements at h=50-55 km.

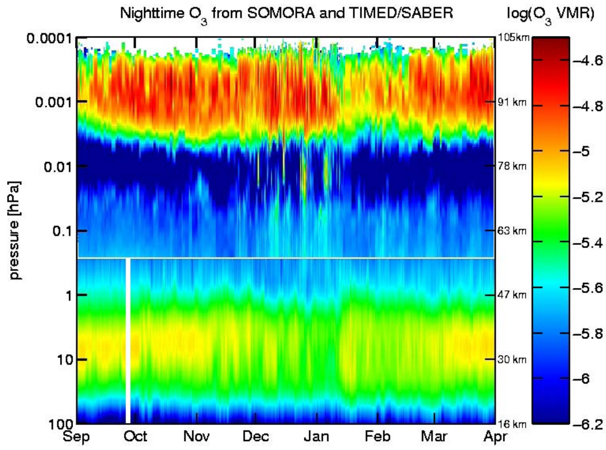

Figure 6. Nighttime ozone volume mixing ratio at altitudes from 16 to 105 km over Payerne during the time interval from September 1, 2003 to April 1, 2004. Beyond 40 km (or 3 hPa), ozone data of TIMED/SABER are used, while SOMORA radiometer data are shown below the white, horizontal intersection line.

We suggest that these enhancements might be explained by meridional transport of polar mesospheric ozone during nighttime. Observations and modeling by Marsh et al. (2001) gave evidence for the existence of a tertiary ozone maximum at around h=72 km at high latitudes during the dark, polar winter months. For some events of ozone enhancement (e.g., at 0.02 hPa and begin of November 2003), we can find a decreased temperature in Fig. 5 suggesting a transport of cold, ozone-rich air masses. The enhanced atmospheric transport in begin of November 2003 could be a consequence of the severe solar storms around October 28, 2003.

6. THE SATELLITE EXPERIMENT AQUA/AIRS

The NASA satellite Aqua was launched into a near-polar orbit (98° inclination) at 705 km altitude on May 4, 2002. The spectrometer AIRS (Atmospheric InfraRed Sounder) scans the atmosphere in a large area around the nadir providing high-resolution (ca. 20 km x 20 km) maps of water vapor columns, cloud cover, and other parameters [12]. Additionally, atmospheric profiles of temperature and water vapor mixing ratio are retrieved on 28 pressure levels from the surface up to 0.1 hPa [13]. We will use the atmospheric profiles of the standard retrieval product AIRX2RET (`http://disc.sci.gsfc.nasa.gov/AIRS/data_products.shtml`).

7. INTER-COMPARISON AND COMBINATION OF H_2O MEASUREMENTS FROM MIAWARA, AQUA/AIRS, AND ECMWF

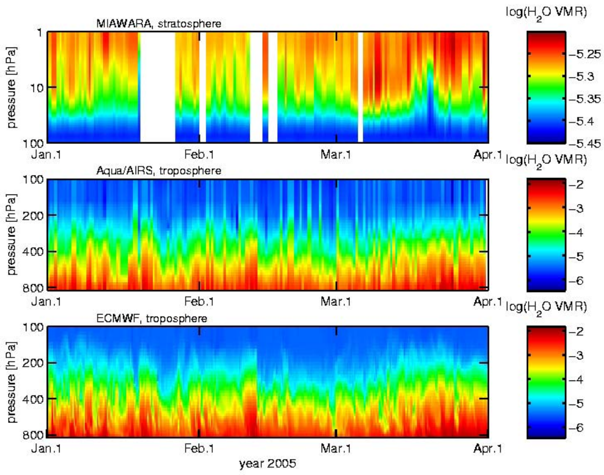

Figure 7. H_2O volume mixing ratio over Bern during the time from January 1, 2005 to April 1, 2005. The upper panel shows the observations of the ground-based microwave radiometer MIAWARA at pressure levels from 100 to 1 hPa. The middle panel shows the observations of Aqua/AIRS at pressure levels from 800 to 100 hPa. The lower panel shows the ECMWF reanalyses data at pressure levels from 800 to 100 hPa for the sake of comparison with Aqua/AIRS

The inter-comparison is restricted to the time interval from January 1, 2005 to April 1, 2005. A strong traveling planetary wave was present during this time, and the edge of the polar vortex passed several times over Switzerland. We select atmospheric profiles of water vapor volume mixing ratio from Aqua/Airs which are within a 100-km surrounding of Bern. For ECMWF, the water vapor profiles of the grid point close to Bern are taken. ECMWF and Aqua/AIRS mainly describe tropospheric water vapor since the radiosondes and the nadir sounder AIRS are not so sensitive to changes of stratospheric water vapor density which is around six magnitudes smaller than in the troposphere. Thus we use the observations of the ground-based 22-GHz microwave radiometer MIAWARA which monitors the stratospheric water vapor over Bern. Here we only use the spectra of MIAWARA's broadband spectrometer. The spectra of MIAWARA's narrowband chirp transform spectrometer permit the retrieval of mesospheric water vapor.

The water vapor data of MIAWARA, Aqua/Airs and ECMWF are shown in Fig. 7. MIAWARA shows quasi-periodic (20-30 day) variability at stratospheric pressure levels from 20 to 1 hPa, possibly due to a traveling planetary wave and movements of the polar vortex. To some extent, the stratospheric variability seems to be correlated with the tropospheric variability which is obvious in the water vapor observations of Aqua/AIRS and ECMWF at pressure levels from 800 to 200 hPa (tropopause is at around 200 hPa). We find a very good agreement of the colors, height-dependence, and temporal structures of the cross sections of H_2O volume mixing ratio as provided by Aqua/AIRS and ECMWF reanalyses. Divakarla et al. (2006) found that the water vapor measurements of Aqua/Airs and ECMWF agree within 10% in the troposphere.

8. CONCLUSIONS

A joint research ideal of the Earth's observation and modeling communities is the full access to the whole atmosphere from the surface to the thermosphere. Alpers et al. (2004) utilized different lidar measurement techniques to obtain the temperature profile from 1 to 105 km altitude. In the present study, we combine data sets from satellites, ground stations, and ECMWF reanalyses. Particularly, the time-height cross section of temperature over Bern during the winter 2003/2004 shows atmospheric disturbances propagating downward from the mesosphere into the stratosphere and back again. Figure 5 suggests that modeling of the lower atmosphere can benefit from the inclusion of the upper atmosphere. The time series of atmospheric profiles strongly motivate for studies about atmospheric variability from the troposphere to the lower thermosphere. Secondary results of our investigations are: 1) upper stratospheric temperatures of TIMED/SABER and ECMWF reanalyses are in an excellent agreement, 2) measurements of lower mesospheric ozone by TIMED/SABER and the ground-based microwave radiometer SOMORA agree well, 3) tropospheric water vapor of ECMWF reanalyses and Aqua/AIRS are in a good agreement. A more detailed assessment of the differences between the various data sets is planned as well as inclusion of observations of mesospheric water vapor.

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