

Abstract

In this paper, we compare the diurnal variations in middle atmospheric water vapor as measured by two ground-based microwave radiometers in the Alpine region near Bern, Switzerland. The observational data set is also compared to data from the chemistry-climate model WACCM. Due to the small diurnal variations of usually less than 1 %, averages over extended time periods are required. Therefore, two time periods of five months each, December to April and June to October, were taken for the comparison.

The diurnal variations from the observational data agree well with each other in amplitude and phase. The linear correlation coefficients range from 0.8 in the upper stratosphere to 0.5 in the upper mesosphere. The observed diurnal variability is significant at all pressure levels within the sensitivity of the instruments. Comparing our observations with WACCM, we find that the agreement of the phase of the diurnal cycle between observations and model is better from December to April than from June to October. The amplitudes of the diurnal variations for both time periods increase with altitude in WACCM, but remain approximately constant at 0.05 parts per million in the observations.

The WACCM data is used to separate the processes that lead to diurnal variations in middle atmospheric water vapor above Bern. The dominating processes were found to be meridional advection below 0.1 hPa, vertical advection between 0.1 and 0.02 hPa and (photo-)chemistry above 0.02 hPa. The contribution of zonal advection is small. The highest diurnal variations in water vapor are found in the mesopause region during the time period from June to October with diurnal amplitudes of 0.2 ppm (approximately 5 % in relative units).

1 Introduction

The dynamical regime of the middle atmosphere is dominated by global scale waves with large amplitudes and most of the observed spatiotemporal variability in winds,

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temperature and constituent concentrations is due to these wave motions (Pancheva and Mukhtarov, 2011). One type of wave motions are atmospheric tides, originating from the periodic solar heating of the stratospheric ozone layer and from latent heat release in the troposphere. These tidal waves propagate in the whole atmosphere and their amplitudes increase with altitude due to the decreasing density of air. Atmospheric tides are usually divided into migrating and non-migrating tides. Sun-synchronous waves are called migrating tides and propagate westward with the apparent motion of the sun, and all tides which are not sun-synchronous are called non-migrating tides. The sun-synchronous waves with zonal wavenumbers 1 and 2 are the most studied atmospheric tides (Chapman and Lindzen, 1970; Forbes and Garret, 1979 as cited by Pancheva and Mukhtarov, 2011) and are denoted as diurnal and semidiurnal migrating tides, respectively.

Various previous studies on atmospheric tides focus on the mesosphere and lower-thermosphere (MLT) region, since the tidal amplitudes maximize in this region. Observational studies on tides in temperature and wind in the MLT region were done with satellite instruments (e.g. Forbes and Wu, 2006; Zhang et al., 2006) and from ground-based wind and temperature measurements (meteor radars and lidars) (e.g. Vincent et al., 1988; Smith et al., 2007; Lu et al., 2011; Lübken et al., 2011). The main advantages of satellite instruments are their global coverage and the ability to separate migrating and non-migrating tides. On the other hand, the orbital parameters of satellite instruments often constrain the observations to a fixed local solar time. Ground-based instruments provide a continuous data set at a fixed location, allowing a detailed study of the diurnal variability at the measurement location. However global data sets are needed to draw conclusions about the characteristics of the observed tides. Numerical models have also been used to study the tidal behavior of the atmosphere (e.g. Hagan et al., 1995; McLandress, 1997; Smith et al., 2003; Morel et al., 2004; Chang et al., 2008). In order to validate and improve such models, observations are required. Since atmospheric tides in trace species are a combination of dynamical and (photo-)

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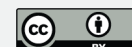
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chemical processes, their investigation and validation with observations provide helpful information to improve numerical models.

This study focuses on diurnal variations in water vapor from the upper stratosphere to the upper mesosphere as observed by two independent ground-based microwave radiometers located in the Alpine region. Ground-based microwave radiometry is a well-established and approved remote-sensing technique and commonly used to derive trends in atmospheric trace species (e.g. Nedoluha et al., 2003; Hartogh et al., 2011), to study anomalies during extreme events such as sudden stratospheric warmings (e.g. Flury et al., 2009; Scheiben et al., 2012) or intraseasonal oscillations of trace species (e.g. Studer et al., 2012). So far, there have been two observational studies on diurnal variations in middle atmospheric water vapor. The first study was done by Haefele et al. (2008) with observations from the same microwave radiometer as used in this study. However, this radiometer has been technically upgraded, resulting in a better temporal resolution and increased altitude range. A second study was done by Hallgren and Hartogh (2012) with data from a ground-based microwave radiometer in the polar region. The present study compares diurnal variations in middle atmospheric water vapor from two independent radiometers at the same site with each other to enhance confidence in the derived observational diurnal variations. In addition, the observations are compared with diurnal variations in water vapor from the Whole Atmosphere Community Climate Model (WACCM).

The paper is structured in the following way: Sect. 2 describes the instruments, WACCM and the used methods to derive the diurnal variations from these data sets. In Sect. 3, the results from the different data sets are presented for two time periods and the discussion follows in Sect. 4. In Sect. 5, a summary is given.

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2 Data and methods

2.1 Observational data

The observational water vapor data are obtained by two ground-based microwave radiometers. One of the two radiometers, MIAWARA (Middle Atmospheric WATER vapor RAdiometer), is a stationary instrument and has been operating continuously in Zimmerwald, Bern, Switzerland (46.88° N/7.47° E) since 2007 in the frame of the Network for the Detection of Atmospheric Composition Change (NDACC). The other instrument, MIAWARA-C, was built in 2008, has a very compact design and is used for measurement campaigns. Both radiometers measure the brightness temperature around the pressure broadened rotational transition line of water vapor at 22.235 GHz. The measured spectrum is inverted to a vertical water vapor profile by the Optimal Estimation Method (OEM) (Rodgers, 2000) using the radiative transfer model ARTS/QPack (Eriksson et al., 2011). A detailed description of the two instruments is given in Deuber et al. (2004) and Straub et al. (2010) for MIAWARA and MIAWARA-C, respectively. The vertical range of the instruments is between 35 and 75 km altitude and the vertical resolution (full width at half maximum of the averaging kernels) ranges from 13 km at 40 km altitude to 17 km at 70 km altitude. The systematic error is approximately 10 % at all altitudes and the random error increases from 5 % at 45 km to approximately 25 % at 75 km.

MIAWARA was upgraded in September 2010 by replacing the stepper motor for the rotating mirror and improving the calibration cycle. The aim of the upgrade was to increase the effective measurement time, resulting in an increase of the temporal resolution of the retrievals. The other instrument, the campaign instrument, was measuring in Zimmerwald next to MIAWARA from July 2010 until May 2011. During the stay in Zimmerwald, MIAWARA-C was also upgraded in December 2010. Before the upgrade, it was not possible to retrieve more than 5 profiles per day, but after the upgrade, more than 10 profiles per day are obtained during 80 % of the measurement days (Tschanz et al., 2013).

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The retrieval setup is the same for both instruments. The spectral bandwidth used in the retrieval is 100 MHz (± 50 MHz around 22.235 GHz). For every retrieval, the measured spectra are integrated until they reach a noise level of 0.01 K. Depending on tropospheric opacity, the required measurement time for such an integrated spectrum ranges from 1 h to more than 12 h. Retrievals with a constant measurement noise are preferred in our application, because the random errors and the vertical observation range remain almost constant. This is an important issue when averaging individual retrievals. The calibration technique of the instruments can introduce a baseline on the measured spectrum. Such a baseline varies over time, depending mainly on tropospheric opacity. To reduce these baseline artifacts, a polynomial fit of order 3 and a sine-fit with 6 periods are applied to the measurement. This leads to a loss of measurement sensitivity on lower altitudes and is the main reason why the instruments are not sensitive below 35 km altitude. The temperature profile is taken from the operational analysis of the European Center for Medium-range Weather Forecasts (ECMWF), considering also the diurnal variations in temperature. The a priori water vapor profile required by OEM is a monthly climatology of water vapor profiles from the Microwave Limb Sounder (MLS) onboard NASA's Aura satellite.

To derive diurnal variations of water vapor with magnitudes of approximately 1 %, averages over a time period of several months are required to obtain statistically significant results. The errors of the derived diurnal variations are calculated by dividing the observational error of the individual measurements by the square root of the number of measurements. The present results are obtained by post-upgrade measurements of both radiometers at the same site. That is from December 2010 until April 2011 in Zimmerwald. For the stationary instrument MIAWARA, the measurements from the consecutive year, i.e. from December 2011 until April 2012, are also considered. Results for MIAWARA are also shown for a time period shifted by 6 months, i.e. from June to October for the years 2011 and 2012. The observational results are compared to model data. It will be shown by the model data that the phase and amplitude of the

diurnal variations of water vapor do not change considerably over the different months within one time period.

2.2 Model data

The model data for water vapor used in this study is from the version 4 of the WACCM. WACCM has an excellent fast chemistry and a high accuracy of photolysis rates (SPARC CCMVal, 2010). As a numerical framework, WACCM uses the NCAR (National Center for Atmospheric Research) Community Earth System Model (CESM), which is a fully-coupled, global climate model. For this study, the WACCM composition set F2000 was used, where the atmospheric and land parts of WACCM are free-running and the ocean is prescribed by data from the year 2000. The model has 66 vertical levels on hybrid coordinates with the upper model limit at approximately 140 km altitude. The horizontal resolution is 5° in longitude and 4° in latitude. The model time step for the simulation run was 15 min and the simulation was performed for one model year, i.e. from 1 January 2000, until 31 December 2000. Since the atmospheric model is free-running and the focus of this study is on diurnal deviations from mean values, this model run is taken as representative for the diurnal variations in the middle atmosphere for all years, not only for the year 2000. To compare the model data with the observations, the model data was interpolated to the location of the two radiometers. Since the model has a higher vertical resolution compared to the observational data, the model data was convolved with the averaging kernels of the microwave radiometers for a proper comparison of the individual data sets.

2.3 Deriving the diurnal variations

In a first step in deriving the diurnal variations of water vapor, a 1-day moving-average is subtracted from the water vapor time series to remove any trends or periodicities with periods longer than one day. In a second step, the 24 h of a day are divided into 12 2-h-bins and every detrended water vapor profile is attributed to the corresponding

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2-h-bin. Then, the profiles within each 2-h-bin are averaged and subtracted by the average profile of all 2-h-bins. For the model data on an equally spaced time grid, this procedure is straight forward, but the observational water vapor data from the ground-based radiometers MIAWARA and MIAWARA-C are neither obtained in regular time steps nor do the retrievals cover constant time periods. Therefore, each retrieved water vapor profile is attributed to one or more 2-h-bins, depending on the actual measurement duration. In addition, a weighting factor of $1/(\# \text{ of covered 2-h-bins})$ is applied such that a retrieval is equally distributed among the 2-h-bins. By doing so, a retrieval which covers only one 2-h-bin is more strongly weighted for that bin than a retrieval covering more than one 2-h-bin.

2.4 Chemical and dynamical contribution

With the WACCM model, the chemical and the dynamical contribution to the diurnal variations in middle atmospheric water vapor can be separated. The material derivative for an atmospheric trace species is

$$\frac{d\psi}{dt} = \frac{\partial\psi}{\partial t} + u \frac{\partial\psi}{\partial x} + v \frac{\partial\psi}{\partial y} + w \frac{\partial\psi}{\partial z} \quad (1)$$

where ψ in our case is the water vapor volume mixing ratio (VMR), t is time and u , v , w are the zonal, meridional and vertical winds. The total derivative is the temporal change of water vapor from a Lagrangian perspective and is the sum of the chemical net production and phase changes of water vapor. In the altitude region of interest, phase changes of water vapor can be neglected. The first term on the right hand side, the local derivative, is the temporal change in water vapor at a fixed position. This is what a ground-based instrument observes. The remaining terms on the right hand side are the temporal changes in water vapor due to zonal, meridional and vertical advection. The terms on the right hand side of Eq. (1) can be calculated directly from the model output. To derive the relative contribution of each term with respect to the diurnal variation of water vapor at a fixed location, each term of Eq. (1) is integrated

in time, which yields individual time series of water vapor due to chemistry and zonal, meridional and vertical advection. The diurnal variations of these individual time series (calculated according to Sect. 2.3) are fitted by a sine wave with a period of 1 day. The amplitudes of the sine fit denote the diurnal amplitudes in water vapor due to each individual process and they are compared to each other.

3 Results

3.1 Comparison between observational and model data

Figure 1 shows the diurnal variations in water vapor VMR as described in Sect. 2.3 for the month December to April, observed by MIAWARA and MIAWARA-C and simulated by WACCM for the measurement location of the ground-based instruments. The lower-most panel in the Figure shows the correlation coefficients between the observational and the convolved WACCM data. In the following description, we are continuously going down in altitude from the upper mesosphere to the upper stratosphere. At the upper measurement limit of the observations, i.e. at 0.02 hPa, water vapor has a maximum during the morning and a minimum during the evening. Going down in altitude, there is an abrupt phase shift above 0.03 hPa in the observational data sets by approximately 180 degrees, such that the minimum in water vapor is now observed in the morning. WACCM reproduces this phase shift, but it occurs at 0.02 hPa, slightly higher than in the observations. In the convolved WACCM data, this phase shift is smoothed out. Throughout the mesosphere, i.e. down to approximately 1 hPa, the phase of the diurnal cycle remains constant in each data set. The diurnal amplitude in the observational data remains approximately constant between 0.05 and 0.1 ppm throughout the mesosphere, whereas the amplitude decreases with decreasing altitude in the WACCM data. At the stratopause, there is again a phase shift, such that the minimum in water vapor is now occurring in the evening. This phase shift is very abrupt in the unconvolved and the convolved WACCM data, but smooth in the observational data. Again, this phase

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shift occurs at higher altitudes in the model data than in the observational data. The amplitude continues to decrease in the WACCM data, but remains constant in the observational data. In the observational data, a semidiurnal tide is also evident in the upper stratosphere (from 2 to 10 hPa), which is not visible in the model data.

The two observational data sets are correlated over the whole vertical observation range, except at the upper measurement limit where the sensitivity of the instruments starts to decrease. The correlation coefficients range from 0.8 at the upper stratosphere to 0.5 at the 0.03 hPa pressure level. The correlation between MIAWARA and WACCM is very high in the mesosphere between 0.5 and 0.03 hPa with correlation coefficients higher than 0.8, but breaks down in the upper mesosphere. In the stratopause region, the correlation breaks down between MIAWARA and WACCM. Between MIAWARA-C and WACCM, the correlation is negative, which is due to the offset in altitude of the phase shift at the stratopause. In the stratosphere, the correlation between MIAWARA and WACCM is positive again, but not as strong as in the mesosphere, whereas MIAWARA-C and WACCM do not show a significant correlation. Overall, MIAWARA shows a slightly better agreement with the model data than MIAWARA-C.

For a better comparison of the diurnal amplitudes among the data sets, Fig. 2 shows the diurnal water vapor variations for the same time period but on four distinct pressure levels, namely on 0.05, 0.3, 1 and 3 hPa. The plots include error bars for the observational data. The diurnal variations in WACCM are split into the five different months. These months show that there is no major monthly change of the diurnal variation. The diurnal amplitudes in the mesosphere (0.05 and 0.3 hPa) are in the same range for all datasets and the error bars show that the observed diurnal variability is significant. In the stratopause region (1 hPa) and the upper stratosphere (3 hPa), the amplitudes in the observational data are much larger than in the model data, but still significant according to the error bars.

During the time period from June to October (Fig. 3, analogous to Fig. 1 but without MIAWARA-C), water vapor at the upper limit of the observations has a minimum in the afternoon, just like during time period from December to April. This is also found in the

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WACCM data, but the diurnal amplitude in WACCM at this altitude is higher than in the observations. Going down in altitude, there is a phase shift in WACCM such that the water vapor minimum is now found in the morning. This phase shift is seen in the observational data as well, but less pronounced. The sharp phase shift in the WACCM data from December to April at the stratopause region is also present during the time period from June to October, but occurring at a higher altitude, namely at 0.3 hPa. In the observations, this phase shift also occurs, but at a lower altitude (approximately 2 hPa). Similar to the other time period, the amplitude of the diurnal cycle is larger in the observational data than in the model data, except for the upper mesosphere.

Looking at the individual months in the WACCM data in Fig. 4, one can see that the 5-month-average indeed represents each individual month, except that the phase shift in the diurnal variations of water vapor at the stratopause is occurring at different altitudes for each month. The altitude of this phase shift moves upward during the considered time period from June to October.

3.2 Contribution to the diurnal variations in water vapor according to WACCM

Based on the WACCM data, the different sources of the diurnal variations in water vapor can be individually calculated (as described in Sect. 2.4). Hereafter, we divide the sources into meridional, zonal and vertical advection and chemistry. Figure 5 shows the diurnal amplitudes of each individual source obtained by fitting a sine wave for the month December to April (left panel) and for the month June to October (right panel). In addition, the total diurnal amplitude as modeled by WACCM and the diurnal amplitudes as measured by MIAWARA and MIAWARA-C are shown.

From December to April, the diurnal variations in water vapor below 0.03 hPa mainly originate from advection, where meridional advection dominates below 0.1 hPa and vertical advection dominates above 0.1 hPa. The influence of (photo-)chemistry increases from 0.1 hPa upwards and dominates over dynamics above 0.02 hPa. On 0.01 hPa, the diurnal amplitude due to chemistry alone is twice as large as for the vertical advection. The overall diurnal amplitude in water vapor on 0.01 hPa is smaller

than the diurnal amplitude due to chemistry alone, meaning that the advection (mainly the vertical advection) damps the diurnal amplitude from the (photo-)chemistry.

From June to October, the diurnal variations in water vapor are dominated by meridional advection below 0.1 hPa, similar to the other time period, but with larger amplitudes. Above 0.1 hPa, vertical advection dominates over meridional advection up to 0.01 hPa, from where meridional advection is dominating again. However, the influence of (photo-)chemistry increases strongly with altitude, much stronger than from December to April, and exceeds the dynamical influence above 0.03 hPa. At 0.01 hPa and above, the diurnal cycle in water vapor is mainly originating from (photo-)chemistry and reaches amplitudes of 0.2 ppm. Compared to the time period from December to April, this is higher by a factor of 4. However, in relative units, the amplitudes from (photo-)chemistry are approximately the same (not shown).

4 Discussion

In the mesosphere, the observations and the model data agree well with each other. However, going down in altitude towards the stratosphere, there are large differences in the amplitude of the diurnal variations between the observations and the model. The differences between the model data and the observations could originate from various sources. One question that arises is about instrumental artifacts leading to a systematic diurnal cycle in the observations. A good indicator for the reliability of a radiometer is a constant receiver temperature. We did not find any diurnal anomalies in the receiver temperatures of our instruments. Instrumental calibration parameters with a diurnal cycle could induce systematic diurnal variations in the retrieved water vapor profiles. Such parameters are the calibration target temperatures, the ambient temperature and the tropospheric opacity. Both radiometers perform a balancing calibration and therefore, a tropospheric correction needs to be applied to the measured spectrum. This correction factor depends on the above mentioned diurnally varying parameters. Since the tropospheric correction factor is scalar, a faulty diurnal variation of this factor would

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induce a diurnal variation in the retrievals which would be independent on altitude. However, the observational diurnal variations in water vapor are altitude dependent. Another source of an artificial diurnal cycle in the retrieved water vapor profiles might be the temperature profile used in the retrieval process. The temperature profiles used for this study were taken from ECMWF and averaged over the actual duration of each measurement. There are diurnal variations in the temperature profiles in the order of approximately 5 K in the mesosphere. We made a distinct retrieval data set without diurnal variations in the temperature profiles and found that the influence of the temperature variation on the retrieved water vapor profiles is very small and that the diurnal variations in water vapor are almost equal for both data sets. A potential diurnal component in the radiometric measurements could arise from the spectral baseline, which mainly affects the retrieval on pressure levels below 1 hPa. The instrumental baseline originates mainly from the reference absorber used for the balancing calibration. The diurnally varying solar insolation on the reference absorber could therefore result in a diurnally varying baseline which in turn could lead to artificial diurnal water vapor variations on pressure levels below 1 hPa. There are indeed the largest discrepancies between model and observations on pressure levels below 1 hPa. Hence, the observations on those altitudes have to be interpreted with care.

An apparent difference between the model and the observational data is the altitude offset of the phase shift in the stratopause region, which is at higher altitudes in the model data. A possible reason for that could be that the water vapor maximum is located at higher levels in WACCM than in the observations. The averaging kernels of the OEM retrievals would not produce such an offset in altitude. It is also not clear why the phase shift in the stratopause region is very sharp in WACCM, even in the convolved WACCM data set, but smooth in the observational data. The averaging kernels are not responsible for the smoothing of this phase shift, because this would be visible in the convolved WACCM data set.

The previous study by Haefele et al. (2008) on diurnal variations in mesospheric water vapor as observed by MIAWARA showed diurnal variations for the months

September and October 2005 on 0.1 hPa. The phase of the diurnal cycle in their study is similar to the phase obtained in the current study for the months April to October on the same pressure level, showing a minimum in water vapor during daytime. However, the amplitude in the current study is approximately twice as large. This is due to the fact that the upper measurement limit in the previous study was at approximately 0.1 hPa, such that the observations at this pressure level were less sensitive than in the present study.

5 Summary

In this paper, the diurnal variations in middle atmospheric water vapor as obtained from two ground-based microwave radiometers in the Alpine region were compared with each other and with WACCM. Due to the small diurnal variations of usually less than 1 %, averages over long time periods are used to obtain robust results. Therefore, two time periods were used for the comparison, December to April and June to October.

The two microwave radiometers agree well with each other in amplitude and phase of the diurnal cycle. In the altitude range from 3 hPa to 0.05 hPa the amplitude derived from the observational data is approximately 0.05 ppm. The phase changes with altitude. The linear correlation coefficients range from 0.8 in the upper stratosphere to 0.5 in the upper mesosphere. Comparing our observations with WACCM, we find that the agreement of the phase of the diurnal cycle between observations and model is better from December to April than from June to October. The amplitudes of the diurnal cycle for both time periods increase with altitude in WACCM, but remain approximately constant in the observations. The discrepancy between modelled and observed diurnal cycle below 1 hPa could be attributed to instrumental effects.

The WACCM data allows to separate the processes leading to diurnal variations in water vapor. The processes that dominate the diurnal variations in water vapor were found to be meridional advection below 0.1 hPa, vertical advection between 0.1 and 0.02 hPa and (photo-)chemistry above 0.02 hPa. The contribution of zonal advection

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is small. The (photo-)chemical influence on the diurnal amplitude of water vapor from June to October is higher by a factor 4 in absolute units compared to the other analyzed time period. In relative units, the amplitudes are approximately equal.

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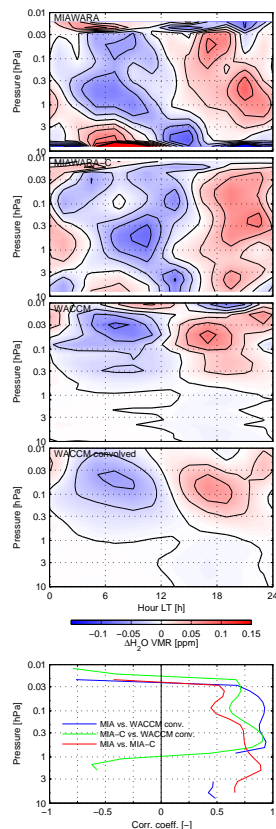


Fig. 1. Diurnal variations of water vapor [ppm] from observational (MIAWARA and MIAWARA-C) and model (WACCM and WACCM convolved) data averaged over the months December to April. The contour line interval is 0.025 ppm. The lowermost panel shows the linear correlation coefficients between the observational and the convolved WACCM data. Correlations are only shown where they exceed 95 % confidence ($p < 0.05$). Times are given in Local Time.

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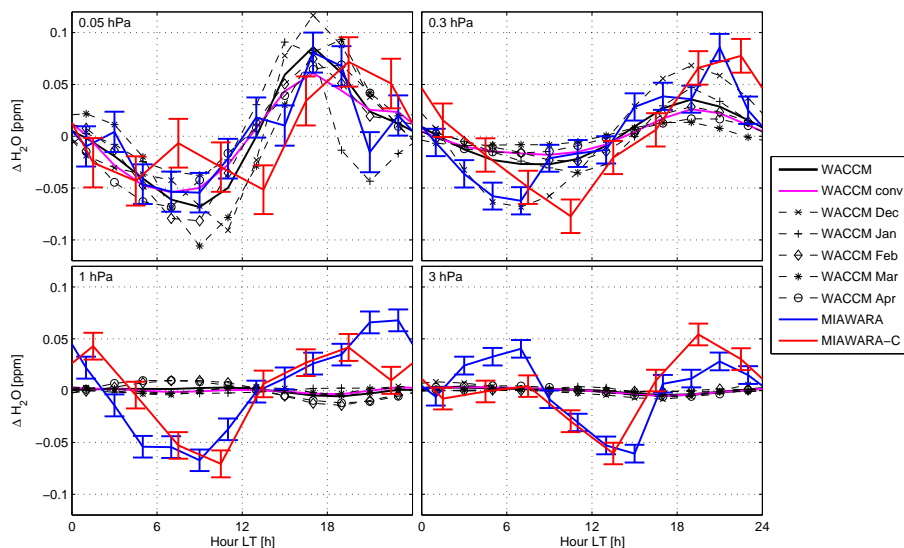


Fig. 2. Diurnal variations of water vapor as in Fig. 1 on four pressure levels (0.05, 0.3, 1 and 3 hPa), including error bars for the observational data. Also shown are the individual months (December to April) of the WACCM data.

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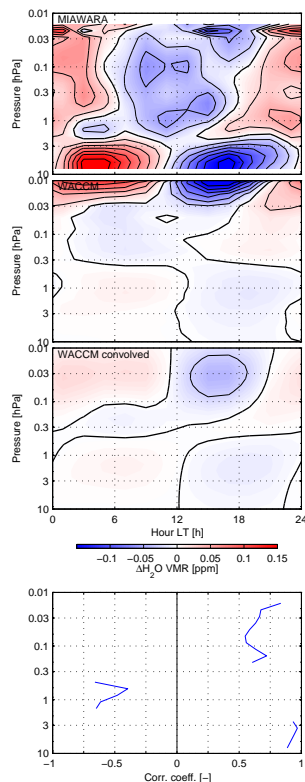


Fig. 3. Diurnal variations of water vapor [ppm] from observational (MIAWARA) and model (WACCM and WACCM convolved) data averaged over the months June to October. The contour line interval is 0.025 ppm. The lowermost panel shows the linear correlation coefficients between MIAWARA and the convolved WACCM data. Correlations are only shown where they exceed 95 % confidence ($p < 0.05$). Times are given in Local Time.

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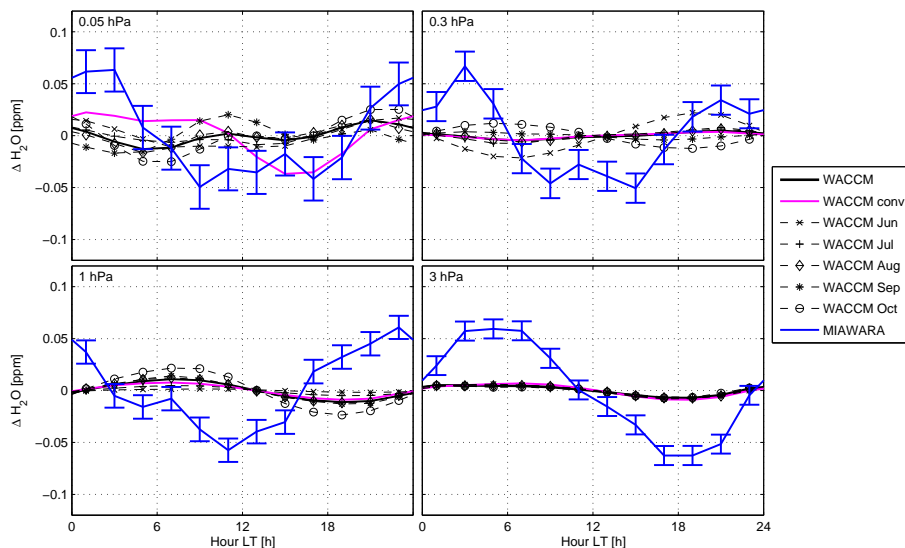


Fig. 4. Diurnal variations of water vapor as in Fig. 3 on four pressure levels (0.05, 0.3, 1 and 3 hPa), including error bars for the observational data. Also shown are the individual months (June to October) of the WACCM data.

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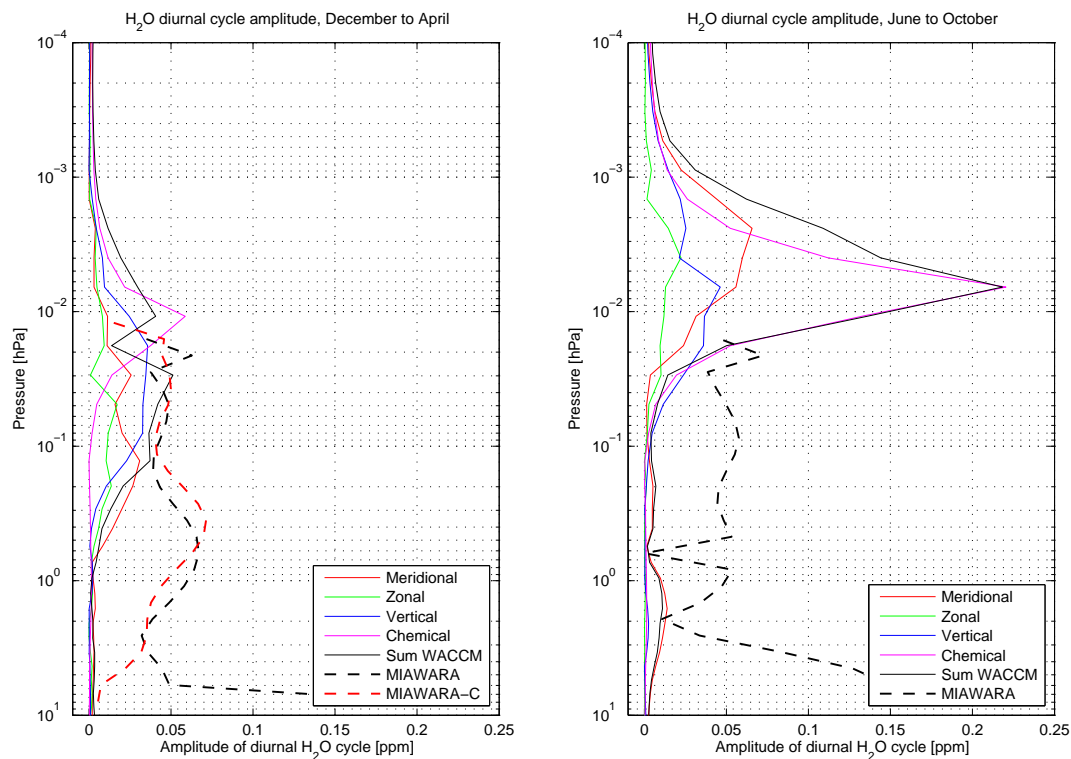


Fig. 5. Amplitudes of the diurnal cycle of water vapor from MIAWARA, MIAWARA-C and WACCM and due to meridional, zonal and vertical advection and (photo-)chemistry (based on the WACCM data). Left panel: December to April. Right panel: June to October. MIAWARA-C was not available from June to October.

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