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# Global observations of middle atmospheric water vapour by the Odin satellite: An overview

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Water vapour plays an important role for the chemistry and dynamics of the atmosphere. It is a strong greenhouse gas in the troposphere and contributes to cooling in the stratosphere. As the main source of chemically active HO<sub>x</sub> radicals, it is linked to many photo-chemical cycles controlling the composition of the middle atmosphere.

In order to improve our knowledge of the amount and variability of water in the middle atmosphere, the Sub-Millimetre Radiometer (SMR) on board the Odin satellite, launched in February 2001, observes several thermal emission lines of water vapour in the 486–581 GHz spectral range from the Earth's limb. Bands centred at 488.9 and 490.4 GHz are used to study water vapour and its isotopes, on the basis of four observation days per month. Vertical profiles of H<sub>2</sub><sup>16</sup>O, H<sub>2</sub><sup>18</sup>O, and HDO are retrieved between roughly 20 and 70 km in the stratosphere and mesosphere. A strong water vapour line at 556.9 GHz is simultaneously measured in a second band, providing information in the mesosphere and lower thermosphere between about 40 and 100 km. Measurements of H<sub>2</sub><sup>17</sup>O at 552.0 GHz in monthly intervals complete the picture of middle atmospheric water vapour provided by Odin/SMR.

The measurements of the isotope HDO in the 20–70 km altitude range allow to study the isotopic ratio of deuterium in stratospheric water vapour (*D/H*), potentially supplying information on the origin of stratospheric water vapour: transport of tropospheric air through the tropical tropopause layer (TTL) versus in situ chemical production such as from methane oxidation. The unique measurements of the molecules H<sub>2</sub><sup>18</sup>O and H<sub>2</sub><sup>17</sup>O containing heavy isotopes of oxygen may provide a crucial test for our understanding of the complex chemical reaction mechanisms controlling the exchange of oxygen between water vapour and ozone.

*Keywords:* Odin; Sub-Millimetre Radiometer; Microwave limb sounding; Middle atmosphere; Water vapour; Water vapour isotopes

## 1. Introduction

Water vapour is a key constituent in the Earth's middle atmosphere. It is a strong greenhouse gas in the troposphere

and its long-wave emissions in the mid- and far-infrared spectral region contribute to cooling in the stratosphere. Humidity in the upper troposphere and lower stratosphere region (UT/LS) is known to have a substantial effect on the outgoing long-wave radiation which regulates the global radiation budget. As the most abundant source of chemically active HO<sub>x</sub> radicals (H, OH, HO<sub>2</sub>), water vapour has a direct impact on the photo-chemical cycles and the composition of the entire middle atmosphere (e.g. Brasseur et al., 1999). If temperatures are low enough, water vapour

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may condense even at low pressures leading to formation of Polar Stratospheric Clouds (PSCs) and initialisation of associated ozone-destroying heterogeneous chemical cycles in the winter polar lower stratosphere (e.g. WMO, 1998) as well as to Noctilucent Cloud (NLC) formation in the cold polar summer mesosphere around 80 km (e.g. von Zahn et al., 2004; Petelina et al., 2005).

Abundant in the troposphere, water vapour enters the stratosphere primarily through the cold tropical tropopause layer (TTL). Cold temperatures cause the air to be freeze-dried and only very little water vapour actually reaches the stratosphere. Typical entry values are of the order of 3.5–4 ppmv (e.g. Kley, 2001). Variations of the temperature of the tropical tropopause, coldest during northern hemisphere winter, lead to a significant seasonal variation of water vapour propagating upward in the tropical lower stratosphere (“tape-recorder effect”) (Mote et al., 1996). As a relatively long-lived gas in the stratosphere, water vapour is redistributed according to the seasonal Brewer–Dobson circulation pattern with ascending motion in the tropics and strongest poleward–downward transport in the winter hemisphere.

In the stratosphere and lower mesosphere, water vapour is chemically formed by the irreversible oxidation of methane which leads to an increasing water vapour profile up to about 40–70 km with maximum mixing ratios of about 7 ppmv. Additionally, the hydrogen reservoirs, water vapour and molecular hydrogen ( $H_2$ ), may slowly convert into one another. The equilibrium depends on the air density and is shifted towards water vapour below about 65–70 km (Sonnemann et al., 2005). Other local sources of mesospheric water vapour such as extraterrestrial sources (release from small comets) and heterogeneous reactions on the surface of meteoric dust have been discussed to explain observations of a second water vapour maximum around 65–70 km at low latitudes (Siskind and Summers, 1998; Summers and Siskind, 1999). The seasonal variation of the global wind system with strong large-scale advection at the summer pole, meridional inter-hemispherical transport and subsidence at the winter pole is certainly the major cause of the observed large variability of mesospheric water vapour, characterised by an annual variation at the poles which gradually changes towards a semi-annual cycle in the tropics (e.g. Seele and Hartogh, 1999; Körner and Sonnemann, 2001).

In the stratosphere, a chemical sink of water vapour is the reaction with excited oxygen  $O(^1D)$  atoms to form hydrogen radicals. With increasing altitude, photolysis by radiation in the Schumann–Runge bands becomes more important and above  $\sim 70$  km water vapour is primarily destroyed by solar Lyman- $\alpha$  radiation. The photo-chemical lifetime of water vapour decreases rapidly with altitude from several months around the stratopause down to several days around the mesopause (e.g. Brasseur et al., 1999). Through the formation of hydrogen radicals, water vapour exerts a major control on the spatio-temporal distribution of all other chemically active species in the mesosphere and lower

thermosphere region, reflected by diurnal and seasonal cycles (e.g. Sonnemann and Grygalashvily, 2003; Schneider et al., 2005), as well as by longer term variations such as those governed by the 11-year cycle of solar activity (e.g. Sonnemann and Grygalashvily, 2005).

It should also be mentioned that a long-term positive trend in stratospheric water vapour over the last  $\sim 50$  years with a substantial average increase of about 1% per year ( $\sim 2$  ppmv over 50 years) was recently reported (Rosenlof et al., 2001; Oltmans et al., 2000), and analyses of shorter-term satellite and ground-based data sets indicate a significant variability of the water vapour trend in the stratosphere below  $\sim 60$  km, where solar cycle effects are unimportant, with a larger increase in the first half of the nineties and a zero trend from 1996 to 2002 (Nedoluha et al., 2003).

In order to improve our knowledge of the amount and variability of water in the middle atmosphere, the Sub-Millimetre Radiometer (SMR) on board the Odin satellite was designed to observe several thermal emission lines of water vapour in the sub-millimetre wavelength range from the Earth’s limb. This paper aims to give an overview of the Odin water vapour measurements. In Section 2 the Odin/SMR experiment is described. Detailed information on the spectral observations of water vapour emission lines and characteristics of the retrieved vertical profiles are provided in Section 3. The data quality is further discussed in Section 4, whilst examples for the global water vapour distribution measured by Odin are given in Section 5.

## 2. Odin Sub-Millimetre Radiometer

The Odin satellite was launched on 20 February 2001 into a quasi-polar sun-synchronous orbit at  $\sim 600$  km altitude. It carries the SMR, which passively measures thermal emissions using a 1.1 m telescope, four radiometers operating within the 486–581 GHz range, as well as one acousto-optical and two auto-correlator spectrometers. Measurement times are equally shared between astronomical targets and observations of the Earth’s atmosphere (Murtagh et al., 2002; Frisk et al., 2003).

In aeronomy mode, different measurement modes are used alternately in regular intervals for height resolved measurements of spectral lines at the atmospheric limb. Stratospheric mode measurements are performed approximately every third day and focus on the observation of ozone ( $O_3$ ), chlorine monoxide (ClO), nitrous oxide ( $N_2O$ ), and nitric acid ( $HNO_3$ ) in the altitude range between roughly 15 and 70 km (Urban et al., 2004b, 2005a; Ricaud et al., 2005; Berthet et al., 2005). Water isotope mode observations, based on vertical scans between about 7 and 110 km, are performed in weekly intervals and are dedicated to the investigation of chemistry and dynamics in the middle atmosphere. Besides the study of water vapour and its isotopes, frequency bands of this mode are also used to gather information on strato-mesospheric

carbon monoxide (Dupuy et al., 2004; Jin et al., 2005), nitric oxide (NO), as well as stratospheric ozone isotopes.

Optimised non-linear retrieval schemes based on the *Optimal Estimation Method* (OEM) (Rodgers, 1976) have been developed in parallel in Sweden and France for retrieving vertical mixing ratio profiles (level-2 data) from the calibrated spectral measurements of the limb scans (level-1b data) (Baron et al., 2001, 2002; Lautié et al., 2001; Lautié, 2003; Merino et al., 2002; Olberg et al., 2003; Urban et al., 2004a, 2005b; Eriksson et al., 2002, 2005). Operational level-2 production is performed at the *Chalmers University of Technology*, Göteborg (Sweden). The French level-2 data processor CTSO (for *Chaîne de Traitement Scientifique Odin*), installed within the French atmospheric chemistry data base *Ether*, is used with the main goal of validating the operational product. In this work we use level-2 data of the *Chalmers-v2.0* and *CTSO-v223* retrieval schemes.

### 3. Water vapour emission lines

Global observations of  $\text{H}_2^{16}\text{O}$  and  $\text{H}_2^{18}\text{O}$  are performed on roughly one day per week using a 700 MHz wide band centred at 488.9 GHz. Examples for individual profile measurements are shown in Fig. 1. To allow for measurements of HDO, the local oscillator is switched approximately every second orbit to a band centred at 490.4 GHz (see Fig. 2). These measurements provide information in the stratosphere and lower mesosphere between about 20 and 70 km. A strong water vapour line at 556.9 GHz is simultaneously measured by a second radiometer, allowing profile information to be retrieved from the upper stratosphere to the lower thermosphere between about 40 and 100 km (Fig. 3). Measurements in monthly intervals of a  $\text{H}_2^{17}\text{O}$  line at 552.0 GHz, performed since October 2003, complete the picture of middle atmospheric water vapour provided by Odin (Fig. 4).

In the water measurement modes, Odin scans the atmosphere between about 7 and 110 km with a vertical scan velocity of 0.75 km/s. The altitude resolution is mainly limited by the read-out interval of the spectrometers, which corresponds to about 3 km in terms of tangent-altitude. The integration time per tangent-view is  $\sim 1.85$  s, since half of the available time is used for cold-space calibration. The full width at half maximum of the antenna main beam corresponds to  $\sim 1.9$  km at 490 GHz ( $\sim 1.6$  km at 557 GHz and 30 km). The horizontal resolution of the limb measurements is of the order of 400 km, determined by the limb path in the tangent-layer. The satellite motion of 6–7 km/s leads together with the time needed for completing a scan to an uncertainty of the profile position, the mean position of the tangent-point during a scan, of similar magnitude. The precision of the profile measurements is determined by the signal-to-noise ratio resulting from the receiver noise of typically 3000–3500 K (single sideband), the strengths and widths of the target lines, as well as the water vapour mixing ratio. Whilst the upper altitude limit

is primarily given by the signal-to-noise ratio of the narrow lines, the lower altitude limit is determined by the spectrometer bandwidth as well as by increasing water vapour absorption with decreasing altitude. It may be 2–4 km lower at polar latitudes compared to the tropics.

The figures show typical spectral measurements and retrieved profiles for the different Odin/SMR water vapour target bands. Diagnostics information on the retrieval results is calculated during the processing and extracted from the retrieval error covariance and averaging kernel matrices. The typically achieved measurement capabilities of the SMR instrument with respect to the primary target gases  $\text{H}_2^{16}\text{O}$ , HDO,  $\text{H}_2^{18}\text{O}$ , and  $\text{H}_2^{17}\text{O}$  are summarised in Table 1.

### 4. Data quality

In order to assess the quality of the Odin/SMR water vapour retrievals and to identify possible systematic biases, the different level-2 data versions have been compared to correlative satellite measurements and also to observations of a ground-based microwave radiometer. A systematic validation study is being conducted at the time of writing of this manuscript and the detailed results will be published elsewhere. Here we just summarise preliminary results obtained for the level-2 data versions used in Section 5 of this paper.

*CTSO-v223* zonal mean water vapour profiles retrieved from the 488.5 GHz line were found to be in relatively good agreement (within  $\sim 10$ – $20\%$ ) with profiles of two ground-based water vapour radiometer installed at *Lauder* (New-Zealand) and *Mauna Loa* (Hawaii) (e.g. Nedoluha et al., 1995), providing data between about 40 and 80 km with moderate vertical resolution. Differences vary with season, but indicate that the profiles of the ground-based instruments are slightly higher than the *CTSO-v223* retrievals with maximum differences usually found in the 50–60 km altitude range. Compared to measurements of the space borne POAM-III sensor (*Polar Ozone and Aerosol Measurement*) (e.g. Nedoluha et al., 1997), *CTSO-v223* data were found to be in reasonable agreement in the upper and middle stratosphere, but tend to lower mixing ratios at altitudes below 25–30 km. In particular values at  $\sim 20$  km were found to be too low by roughly 50% (G. Nedoluha, personal communication). Odin/SMR 488.9 GHz data at 50 hPa ( $\sim 20$  km) were also found to be unrealistically low by comparison to data from the *Michelson Interferometer for Passive Atmospheric Sounding* (MIPAS) on the *Envisat* satellite (ESA, 2000). The agreement was within 10–20% at 10–20 hPa with SMR being slightly higher. At lower pressures in the middle and upper stratosphere, *CTSO-v223* data showed slightly lower mixing ratios, possibly due to a high bias in the MIPAS  $\text{H}_2\text{O}$  retrievals (Payne et al., 2005). Compared to water vapour from the *Halogen Occultation Experiment* (HALOE) on board the *Upper Atmosphere Research Satellite* (UARS) (e.g. Harries et al., 1996), the retrieved mixing ratios agreed within 0.4 ppmv

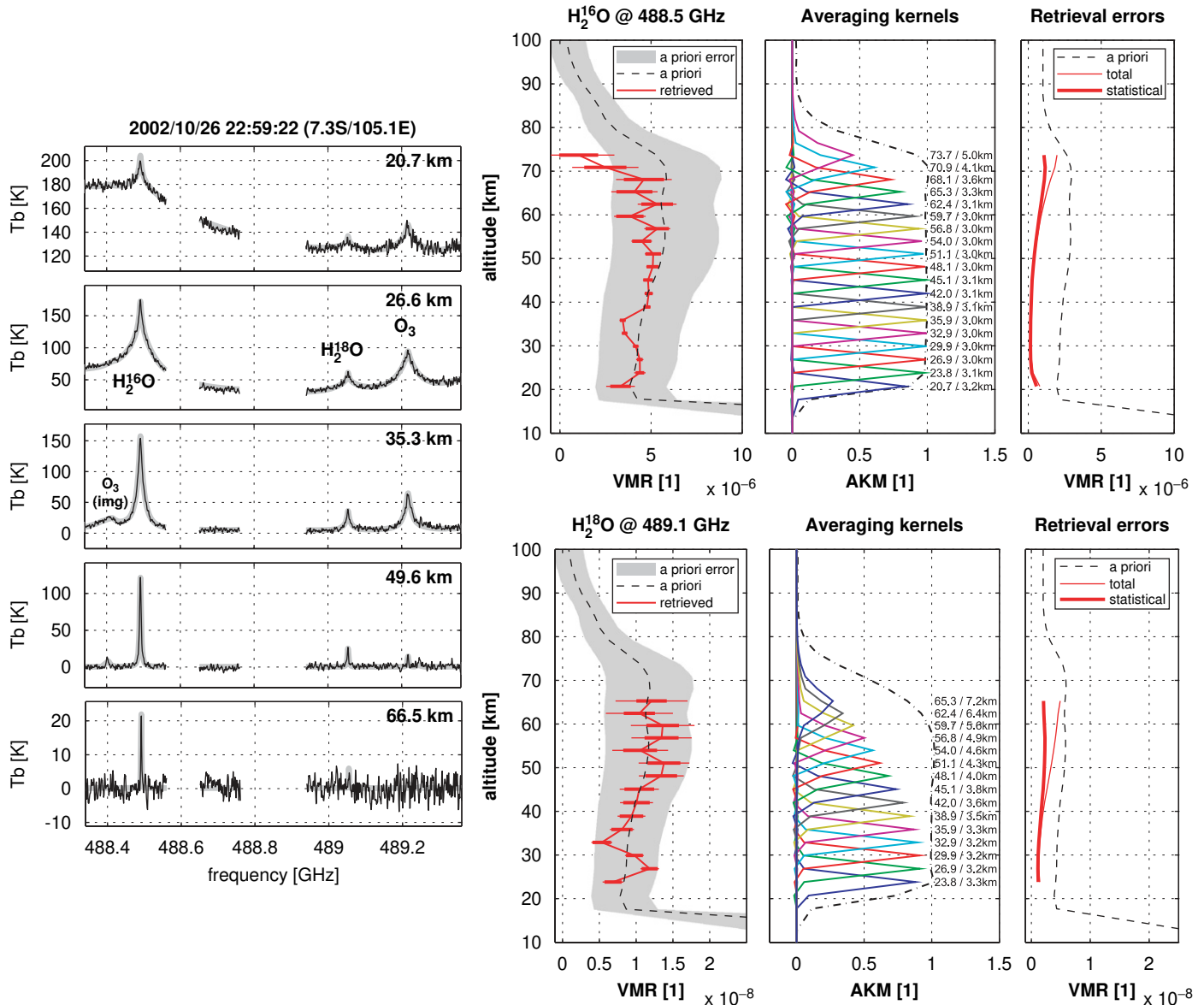


Fig. 1. Example of an Odin/SMR water isotope mode measurement in the 488.9 GHz band. Left: limb emission spectra for five different tangent-altitudes taken on 26 October 2002 at low latitudes. A water vapour emission line at 488.5 GHz and a line of the isotope  $\text{H}_2^{18}\text{O}$  at 489.1 GHz are observed simultaneously. Right: retrieval diagnostics for  $\text{H}_2^{16}\text{O}$  (top) and  $\text{H}_2^{18}\text{O}$  (bottom). The individual plots show retrieved and a priori profiles, averaging kernel functions indicating altitude resolution and vertical range, as well as absolute retrieval errors.

between 30 and 65 km, whilst *CTSO-v223* retrievals yield about 1 ppmv lower values at the lower and upper edges of the retrieval altitude range at 20 and 75 km, respectively.

Correlative data for the validation of the water isotope measurements are considerably more difficult to obtain. Payne et al. (2005) compared MIPAS HDO retrievals of the *University of Oxford* (UK) with Odin/SMR *CTSO-v223* HDO data and report an agreement within 20–30% and qualitatively similar zonal mean fields observed by both sensors. Similar results were obtained for  $\text{H}_2^{18}\text{O}$ . Comparisons of Odin/SMR water isotope fields to other measurements, for example from balloon-borne infrared limb sensors or from the more recently launched *Atmospheric*

*Chemistry Experiment/Fourier Transform Spectrometer* (ACE/FTS) (Bernath et al., 2005), are subject to further work.

Concerning the latest *Chalmers-v2.0* mesospheric water vapour product derived from measurements of the strong 556.9 GHz line, a first evaluation against data from HALOE indicates a reasonably good agreement within  $\sim 0.5$  ppmv between 60 and 85 km, but the SMR data were in average lower by  $\sim 1$  ppmv at 50 km. Note that at the time of writing of this manuscript, a new version of the Chalmers level-2 product, based on an improved calibration scheme as well as on more realistic parameterisations of the SMR instrument characteristics, is in preparation.

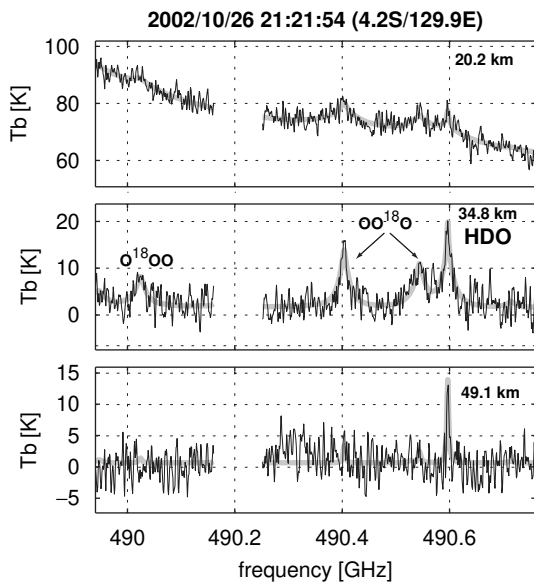


Fig. 2. Odin/SMR measurement of a HDO line at 490.6 GHz. See caption of Fig. 1 for an explanation.

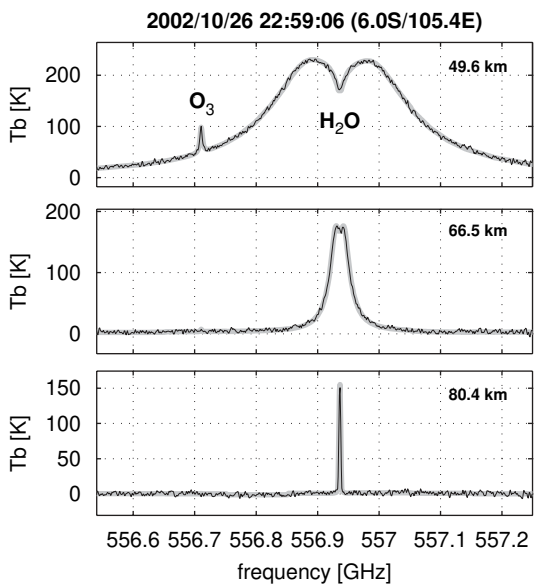
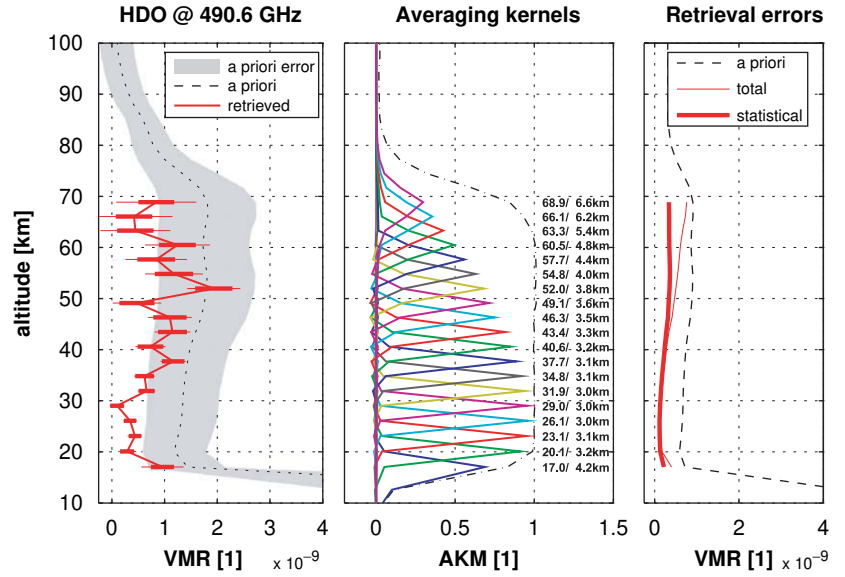
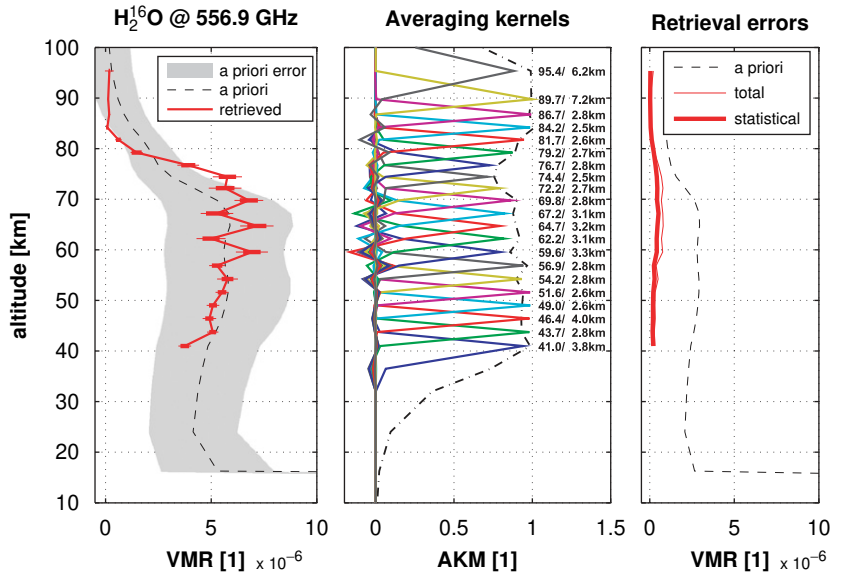


Fig. 3. Example of an Odin/SMR measurement of the 556.9 GHz rotational transition of water vapour. See caption of Fig. 1 for details.



## 5. Global water vapour distribution

Odin/SMR measurements cover the latitude range  $82.5^{\circ}\text{S}$ – $82.5^{\circ}\text{N}$ , determined by *Odin's* sun-synchronous near polar orbit and the nominal (along-track) pointing characteristics. The orbit period of 97 min leads to about 15 orbits per day. In the water isotope modes, the atmosphere is scanned between  $\sim 10$  and 110 km and about 40 scans are performed per orbit. An observation period for a selected mode starts usually at 12 UT and lasts 24 h, except for special campaigns when longer measurement periods are scheduled.

As an example for the morphology of the global data set of water vapour obtained from Odin/SMR measurements in the two bands around 489 GHz, Fig. 5 shows the zonally averaged distribution of  $\text{H}_2^{16}\text{O}$ ,  $\text{H}_2^{18}\text{O}$  and HDO for selected observation days during the year 2002. The tropical water vapour profile is characterised by an increase with altitude due to methane oxidation, a maximum in the upper stratosphere and lower mesosphere and a decrease above  $\sim 65$  km, depending on season. Due to the relatively long photo-chemical lifetime of water vapour, its global distribution depends strongly on the seasonal variation of the meridional circulation with large scale ascending and

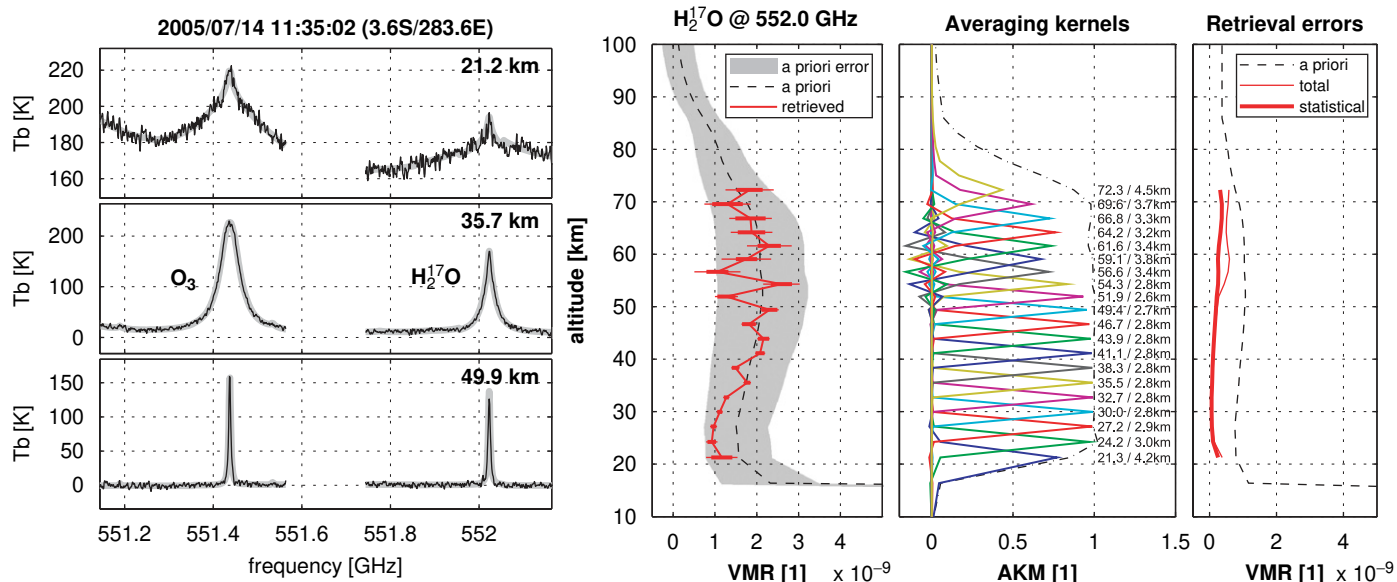


Fig. 4. Typical Odin/SMR measurement of  $\text{H}_2^{17}\text{O}$  at 552.0 GHz. The spectra were observed on 14 July 2005 at low latitudes. See caption of Fig. 1 for a detailed explanation.

Table 1  
Typically achieved single-scan retrieval capabilities of Odin/SMR for the observation of water vapour in the middle atmosphere. Indicated are target line centre frequencies, typical single-scan precision (error due to statistical measurement noise), altitude resolution (full widths at half maximum of the averaging kernel functions), altitude range, as well as the number of observation days per month

Species	Frequency (GHz)	Retrieval mode	Single-scan precision ( $1\sigma$ )	Altitude resolution (km)	Altitude range (km)	Days/month
$\text{H}_2^{16}\text{O}$	556.9	IM_AC1c	5–15%/0.5–1 ppmv	~3 km	~40–100 km	4
		HM_AC1c				
		HM_AC1e				
$\text{H}_2^{16}\text{O}$	488.5	IM_AC2ab	5–15%/0.5–1 ppmv	~3 km	~20–70 km	4
		HM_AC1d				
HDO	490.6	IM_AC2c	10–20 %/ $\leq 0.5$ ppbv	3–4 km	~20–70 km	4
$\text{H}_2^{18}\text{O}$	489.1	IM_AC2ab	10–20%/20–30 ppbv	3–4 km	~20–65 km	4
$\text{H}_2^{17}\text{O}$	552.0	IM_AC1de	5–20%/ $\leq 0.4$ ppbv	~3 km	~20–70 km	1

Based on Chalmers-v2.0 single-scan retrieval (latitude  $\sim 5^\circ\text{S}$ , 26/10/2002, orbit 23A0 + 23A1, 11b data v-6). Chalmers-v2.0 retrieval levels are given by the tangent-altitudes of the limb scan ( $\Delta z \sim 3$  km).

descending motions in the summer and winter hemisphere, respectively, and a reversal observable in autumn and spring.

The distributions of the isotopic species  $\text{H}_2^{18}\text{O}$  and HDO follow a similar seasonal pattern, albeit the level-2 data are slightly more noisy. Differences are mainly visible in the lower stratosphere of the tropics, in particular for HDO. Very low amounts of HDO are indeed expected in the lower stratosphere of the tropics, since due to its lower vapour pressure compared to the main isotope, more HDO should be trapped when entering the stratosphere through the TTL. A first analysis indicated a depletion  $\delta D$  in the range 55–65% at 25 km compared to the isotopic ratio  $D/H$  of *Standard Mean Ocean Water* (SMOW), depending on latitude and season (Lautié et al., 2004). In situ chemical production of HDO from methane, which is

only slightly depleted in deuterium when entering the stratosphere, leads in the tropical stratosphere to an increase of the  $D/H$ -ratio with altitude, consistent with model calculations (Ridal, 2002; Ridal and Siskind, 2002; Bechtel and Zahn, 2003). The Odin measurements of  $D/H$  will thus potentially supply information on the origin of stratospheric water vapour: transport of tropospheric air through the TTL versus in situ chemical production such as from methane oxidation. In addition, the global measurements of the isotope  $\text{H}_2^{18}\text{O}$  and the study of variations of its isotopic ratio  $^{18}\text{O}/^{16}\text{O}$  may provide a crucial test for our understanding of the complex chemical reaction mechanisms controlling the exchange of oxygen between water vapour and ozone. Note that isotopes of ozone ( $\text{O}_3$ ,  $\text{OO}^{18}\text{O}$ ,  $\text{O}^{18}\text{OO}$ ,  $\text{OO}^{17}\text{O}$ ) are measured in the same bands.

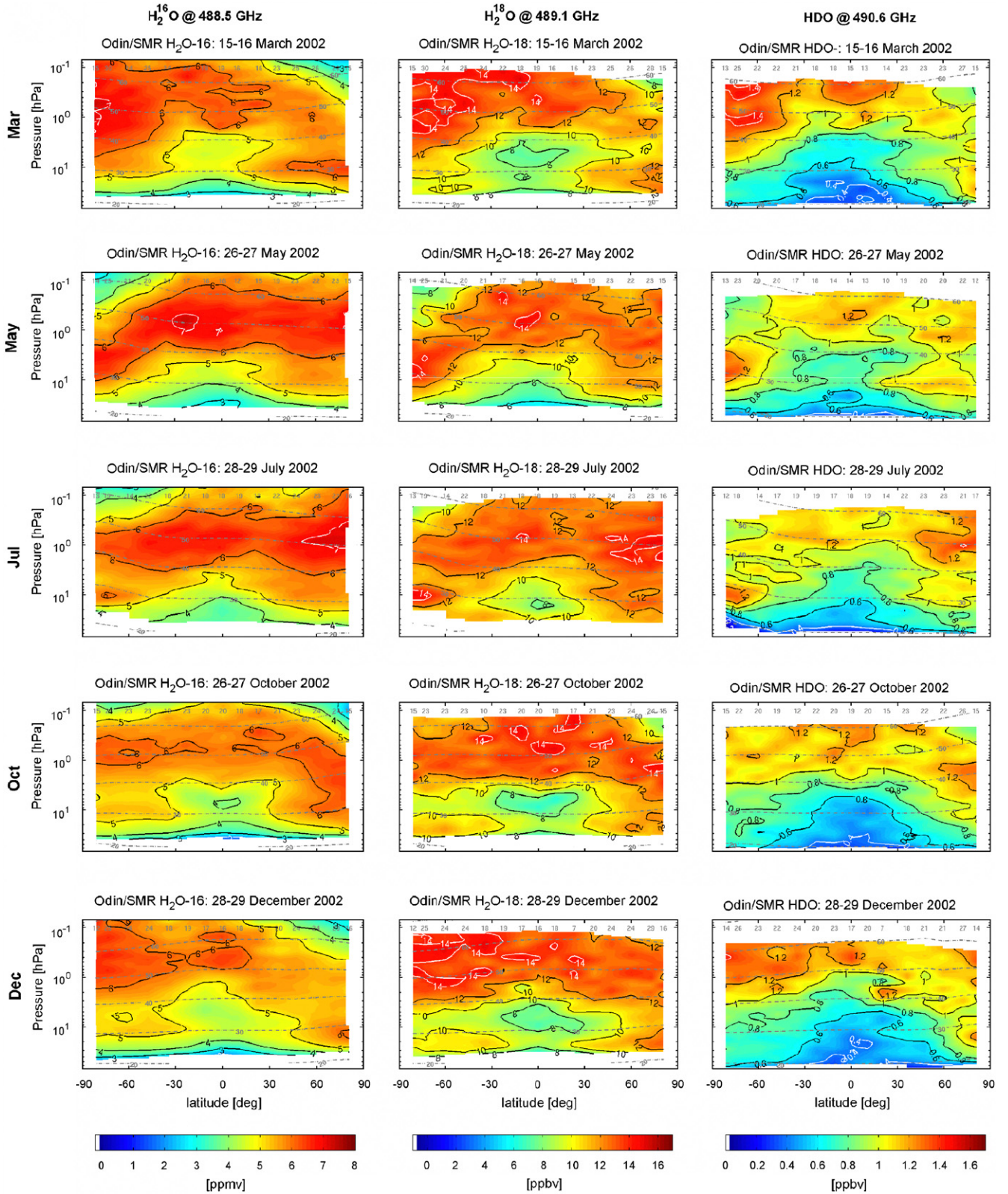


Fig. 5. Daily zonal mean fields of the water isotopes  $\text{H}_2^{16}\text{O}$ ,  $\text{H}_2^{18}\text{O}$ , and HDO measured by Odin/SMR in the 488.9 and 490.4 GHz bands. Shown are selected observation days in March, May, July, October, and December 2002. Altitude levels are drawn with thin grey (dash-dotted) lines and the number of profiles used for calculating the individual  $12^\circ$  wide latitude bins is indicated at the top of the plots. Based on Bordeaux/CTSO-v223 level-2 data.

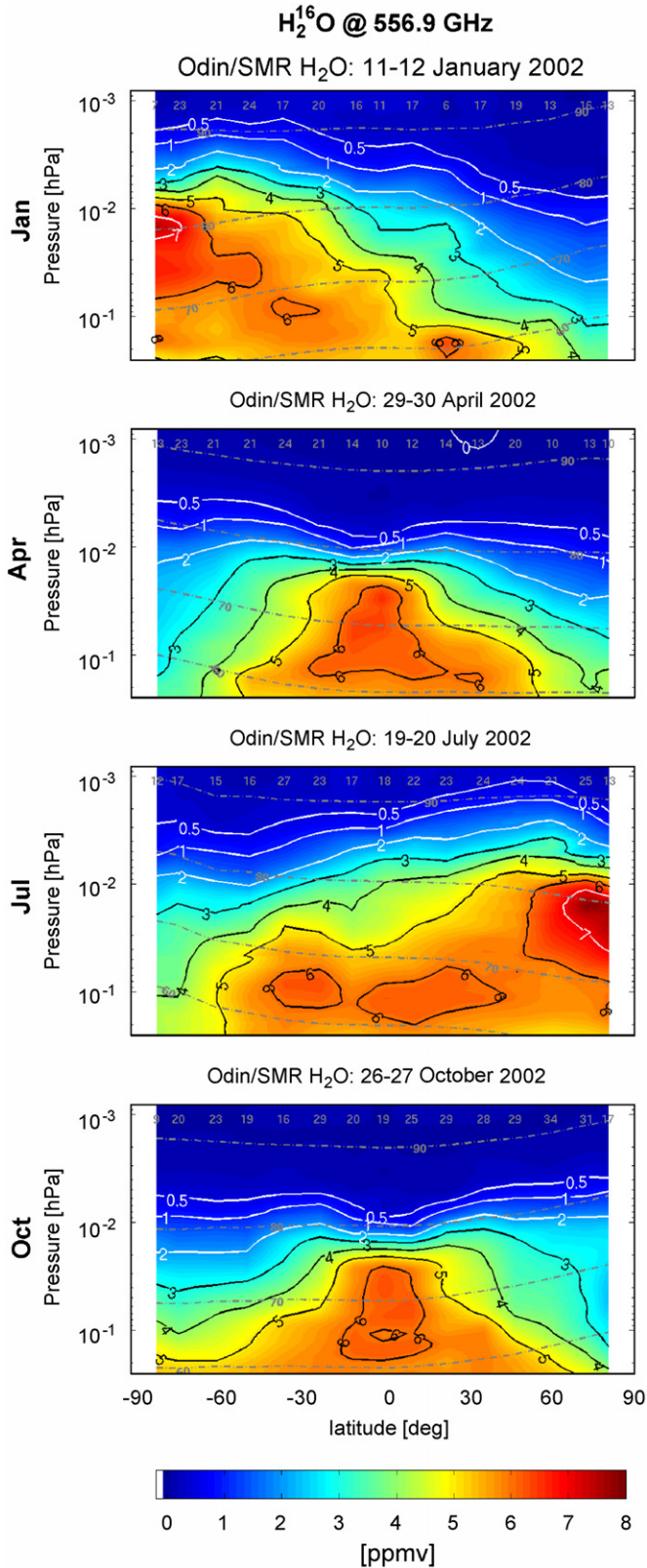


Fig. 6. Daily zonal mean fields of water vapour in the mesosphere as measured by Odin/SMR in the 556.9 GHz band on selected observation days in 2002. Based on Chalmers-v2.0 level-2 data.

Zonal mean fields of mesospheric water vapour, derived from the measurements at 556.9 GHz on selected observation days during the year 2002 and covering higher altitudes than the 488.9 GHz measurements, are presented in Fig. 6. The seasonal variation of the meridional circulation leads to marked maxima of the water vapour mixing ratio in the summer hemisphere around 80 km ( $\sim 7.5$  ppmv). A considerable decrease of mesospheric water vapour is observed in the winter hemispheres. Maximum values in the tropics are observed at higher altitudes than in the 488.9 GHz band, visible for example in April and October when the meridional circulation reverses and the water vapour maximum is found in the tropics. We attribute this inconsistency to systematical too low values, both in the Chalmers-v2.0 556.9 GHz retrievals below 60 km and in the *CTSO-v223* 488.9 GHz data above 65 km (see discussion in Section 4).

## 6. Summary and conclusions

We have described Odin/SMR limb measurements of middle atmospheric water vapour and presented results for selected observation days in 2002. Odin observes thermal emission lines of the main isotope at 488.5 and 556.9 GHz since November 2001 on the basis of about four observation days per month. The retrieved vertical profiles cover altogether an altitude range from about 20 to 100 km with a typical altitude resolution of about 3 km. Measurements of the water isotopes HDO and  $\text{H}_2^{18}\text{O}$  between 20 and 70 km are performed along with the measurements of the main isotope using two bands around 489 GHz. The Odin/SMR water data set is completed by measurements of the isotope  $\text{H}_2^{17}\text{O}$  at 552.0 GHz (one day per month since November 2003). Zonal mean distributions show a strong variability of the water vapour volume mixing ratio in the stratosphere and mesosphere, governed by the seasonal variation of the global meridional circulation. Preliminary validation results indicate too low mixing ratios in the *CTSO-v223* 488.9 GHz band retrievals below  $\sim 25$  km and above  $\sim 65$  km as well as systematically too low mixing ratios in the Chalmers-v2.0 556.9 GHz retrievals below  $\sim 60$  km, but reasonable agreement with correlative measurements elsewhere. Future versions of the Odin/SMR level-2 products for the different water vapour bands are expected to provide an improvement with respect to identified problems by improving the calibration scheme and by better parameterisation of the instrumental characteristics in the forward model of the retrieval code.

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