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# Evaluation of balloon and satellite water vapour measurements in the Southern tropical UTLS during the HIBISCUS campaign

N. Montoux<sup>1,3</sup>, A. Hauchecorne<sup>1</sup>, J.-P. Pommereau<sup>1</sup>, G. Durry<sup>1,2</sup>, B. Morel<sup>3</sup>,  
R. L. Jones<sup>4</sup>, F. Lefèvre<sup>1</sup>, and H. Bencherif<sup>3</sup>

<sup>1</sup>Service d'Aéronomie, Centre national de la recherche scientifique, Institut Pierre-Simon Laplace, Université ParisVI, Université de Versailles Saint-Quentin, Verrières-le-Buisson cedex, France

<sup>2</sup>Groupe de Spectroscopie moléculaire et Atmosphérique, CNRS and Université de Reims Champagne-Ardenne, Reims cedex, France

<sup>3</sup>Laboratoire de l'Atmosphère et des Cyclones, UMR Université de La Réunion-CNRS-Météo France, St-Denis de La Réunion, France

<sup>4</sup>Center for Atmospheric Science, University Chemical Laboratory, University of Cambridge, Cambridge, UK

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Correspondence to: N. Montoux (nadege.montoux@aerov.jussieu.fr)

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## Abstract

Among the objectives of the HIBISCUS campaign was the study of water vapour in the tropical upper troposphere and lower stratosphere (UTLS) by balloon borne in situ and remote sensing, offering a unique opportunity for evaluating the performances of balloon and satellite water vapour data available at the southern tropics in February-April 2004. Instruments evaluated include balloon borne in situ tunable diode laser spectrometer ( $\mu$  SDLA) and surface acoustic wave hygrometer (SAW), and remote sensing with a near IR spectrometer (SAOZ) flown on a circumnavigating long duration balloon. The satellite systems available are those of AIRS/AMSU (v4), SAGE-II (v6.2), HALOE (v19), MIPAS (v4.62) and GOMOS (v6.0). In the stratosphere between 20–25 km, three satellite instruments, HALOE, SAGE-II and MIPAS, are showing very consistent results (nearly constant mixing ratios), while AIRS, GOMOS and the SAOZ balloon are displaying a slight increase with altitude. Considering the previous studies, the first three appear the most precise at this level, HALOE being the less variable (5%), close to the atmospheric variability shown by the REPROBUS/ECMWF Chemistry-Transport model. The three others are showing significantly larger variability, AIRS being the most variable (35%), followed by GOMOS (25%) and SAOZ (20%). Lower down in the Tropical Tropopause Layer between 14–20 km, HALOE and SAGE-II are showing marked minimum mixing ratios around 17–19 km, not seen by all others. For HALOE, this might be related to an altitude registration error already identified on ozone, while for SAGE-II, a possible explanation could be the persistence of the dry bias displayed by previous retrieval versions, not completely removed in version 6.2. On average, MIPAS is consistent with AIRS, GOMOS and SAOZ, not displaying the dry bias observed in past versions, but a fast degradation of precision below 20 km. Compared to satellites, the  $\mu$  SDLA measurements shows systematically larger humidity although this conclusion may be biased by the fact that the balloon flights were carried out intentionally next or above strong convective systems where remote observations from space are difficult. In the upper troposphere below 14 km, all remote sensing measurements

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(except MIPAS of limited precision, and AIRS/AMSU) become rare, dry biased and less variable compared to ECMWF, but particularly HALOE and SAGE-II. The main reason for that is the frequent masking by clouds within which no remote measurements could be performed except by the AMSU microwave. Water vapour remote sensing profiles are representative of cloud free conditions only and thus dryer and less variable on average than ECMWF and AIRS/AMSU. Always in the upper troposphere, two in-situ instruments,  $\mu$  SDLA and SAW, flown on the same balloon agree each other, displaying water vapour mixing ratios 100–200% larger than that of HALOE and MIPAS, which could be explained by the large ice supersaturation of the layer up to the tropopause, hardly detectable from the orbit.

## 1 Introduction

Water vapour plays a key role in Upper Troposphere – Lower Stratosphere (UTLS) climate and chemistry. It strongly contributes to the stratospheric radiative balance via its greenhouse effect (Kiehl and Trenberth, 1997). And it is the main precursor of HO<sub>x</sub> radicals contributing to the catalytic destruction of ozone in the lower stratosphere (Wennberg et al., 1994; Hanson et al., 1996; Osterman et al., 1997). Finally, the formation of cirrus clouds in the upper troposphere, which also strongly impacts the radiative balance (Jensen et al., 1994), is very dependent on the concentration of water vapour and temperature (Jensen et al., 1996; Pfister et al., 2001). As a result, an increase of stratospheric water vapour of about 1–1.5% per year during the last twenty years as reported by Oltmans et al. (1995, 2000), would if globally representative, enhance the tropospheric warming and stratospheric cooling (Forster and Shine, 1999). However, although a slight water vapour increase has been reported from the HALOE measurements between 1992 and 1996 (Evans et al., 1998; Nedoluha et al., 1998), later observations do not confirm this evolution showing a decrease (0.5% per year) or constant concentration during the last decade (1992–2002) (Randel et al., 2004). In addition, neither changes in tropical temperatures nor surface CH<sub>4</sub> emissions appear

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sufficient to explain the magnitude of this increase (Kley et al., 2000). If confirmed, the trend would require an enhancement of the source of water vapour at the tropical tropopause or a lesser dehydration of air entering the stratosphere. However, the mechanism controlling this process, debated for 50 years, is still unclear (Sherwood and Dessler, 2000 and references herein). The main reason for that is the lack of information on water vapour concentration in the tropical UTLS, because of the very limited balloon and high altitude aircraft observations in the region as well as the difficulty of remote measurements from space at altitude levels of frequent presence of cirrus clouds.

The in situ and remote water vapour measurements from local and circumnavigating balloon flights available at the Southern Tropics from the HIBISCUS campaign in February–March 2004 (Pommereau et al., 2007), offer a unique opportunity for evaluating the performances of the satellite water vapour measuring instruments in operation during that period. After a brief description of the instruments and data sets in Sect. 2, the measurements will be compared in Sect. 3: (i) collocated in-situ and satellite observations; (ii) collocated satellite and long duration balloon profiles during the period of the balloon flight; and (iii) zonal mean and variability of the measurements at 10°–20° S and 20°–30° S in February–March 2004. The relative performances of all systems will be summarised in Sect. 4.

## 2 Water vapour data

The measurements available are those of two balloon borne in situ instruments: a tuneable diode laser spectrometer ( $\mu$  SDLA) and a Surface Acoustic Wave (SAW) hygrometer used on short duration flights at Bauru (22.36° S, 49.02° W), Brazil. Measurements of a near IR spectrometer for solar occultation flown onboard an IR Montgolfier and launched from the same location for a 39-day circumnavigating flight are also available. For the satellites, the SAGE-II, HALOE, GOMOS, MIPAS and AIRS profiles recorded at the Southern Tropics in February-April 2004 are used. A summary of the

technical characteristics of each instrument is provided in Table 1.

## 2.1 $\mu$ SDLA tunable diode laser spectrometer

The  $\mu$  SDLA (Micro Spectromètre à Diodes Laser Accordables) is a near-infrared tunable diode laser spectrometer (Durry and Megie, 1999; Durry et al., 2004), which measures in-situ  $\text{H}_2\text{O}$ ,  $\text{CO}_2$  and  $\text{CH}_4$  concentrations. Three InGaAs diode laser beams are directed into a 28 m absorption path using an open optical multipass-cell. Gas concentrations are retrieved from the in situ absorption spectra using the Beer-Lambert law and a molecular model.  $\text{H}_2\text{O}$  atmospheric spectra are recorded in the  $1.39 \mu\text{m}$  spectral region (Durry et al., 2005). The technique provides concentrations at high temporal resolution ranging from one to four samples per second, achieving a spatial resolution of the order of ten meters. The dynamical range of the measurements is of four orders of magnitude, allowing observations in both the lower stratosphere and the upper troposphere. The accuracy is estimated to 5 to 10% (Durry et al., 2004). During the HIBISCUS campaign, the  $\mu$  SDLA instrument was flown twice on board small short duration Open Stratospheric Balloons on 13 and 24 February (Durry et al., 2006; Pomereau et al., 2007). Water vapour was recorded during the slow (1.5 m/s) nighttime descent of the balloon (initiated by the day-night transition) to avoid contamination by outgassing from the gondola and the balloon envelope.

## 2.2 SAW hygrometer

The University of Cambridge (UCAM) Surface Acoustic Wave (SAW) instrument (Hansford et al., 2006) is an in-situ dew-/frost-point hygrometer based on a 250 MHz surface-acoustic-wave sensor. The physical principle is as follows. A quartz chip is cooled by a thermoelectric cooler until water vapour condenses into water or ice on it. Mass loading by water or ice on the chip is detected by its effect on the velocity and amplitude of the acoustic waves. A feedback control loop maintains a constant amount of condensate on the quartz chip surface and so equilibrium between the condensed

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phase and the vapour phase just above the surface is established. The water vapour pressure in the air is then equal to the saturated water vapour pressure at the temperature of the surface. Alternatively, the temperature of the SAW chip may be cycled above and below the dew- or frost-point temperature and the water vapour pressure deduced from the chip temperature at the onset of condensation; this method has the disadvantage of a much lower vertical resolution for balloon flights. Finally, the water vapour concentration is calculated from the measured surface temperature using the Wagner and Pruss formulation (1993) for liquid water (i.e. for temperatures above 273.16 K) and the Wagner et al. (1994) formulation for ice (i.e. for temperatures below 273.16 K). The accuracy of the temperature measurement is estimated to  $\pm 0.3^\circ\text{C}$  (Hansford et al., 2006). However, the water vapour accuracy and precision are difficult to estimate because they depend, among others, on the dew-/frost-point recorded and on the speed of the balloon. Here, each SAW data file gives the estimated errors in the vapour concentration, taking into account both the accuracy and the precision. During the HIBISCUS campaign, the instrument was flown aboard the same SF balloons as the  $\mu$  SDLA instrument.

### 2.3 SAOZ spectrometer

The instrument used here is a near-IR (400–1000 nm) extended version of the SAOZ (Système d'Analyse par Observation Zénithale) diode array UV-visible spectrometer (Pommereau and Piquard, 1994) designed for the measurement of O<sub>3</sub>, NO<sub>2</sub> and other species by solar occultation at sunrise and sunset. Water vapour is measured in three wavelength ranges: around 690 nm in the troposphere, around 760 nm between 10–15 km, and 945 nm above in the stratosphere, with a spectral resolution of 1.2 nm. The spectra are analyzed using the differential absorption technique (DOAS) using the HITRAN database absorption coefficients for water vapour. Trace gas profiles (O<sub>3</sub>, NO<sub>2</sub>, O<sub>4</sub> and H<sub>2</sub>O) are retrieved by the onion peeling technique after calculating the light path by ray tracing. The vertical resolution is 1.4 km corresponding to the half-width of the solar disk brightness, the vertical sampling is about 1 km, and the horizontal resolution

200 km. The altitude registration, checked by collocated lidar measurements during the overpass of the balloon is better than  $\pm 100$  m (Borchi et al., 2005). Data contaminated by clouds are removed by looking at the atmospheric extinction at 615 nm. The estimated precision of water vapour measurements is 5% at 17 km, degrading progressively at higher altitude (10% at 23 km). The accuracy of the current retrieval, limited by systematic errors in the spectroscopic analysis, is of the order of 20%. During the HIBISCUS campaign, the SAOZ instrument was flown on an Infra-Red Montgolfier (MIR) balloon for a 39-day flight (26 February–4 April) of one and half turn around the globe between 10–20° S, providing 68 water vapour profiles, half at sunrise, half at sunset (Borchi and Pommereau, 2006). Because of the diurnal cycle of the balloon altitude, the measurements are limited to altitudes below 24–25 km at sunset and 18–22 km at sunrise depending on the cloud cover. Thanks to the slow motion of the balloons compared to satellites, solar occultation measurements can be continued down to 8–10 km or cloud top in the troposphere by extending the duration of exposure. However, as all solar occultation systems, the observations are limited to cloud free areas. Water vapour number densities are converted into mixing ratios from ECMWF (European Centre for Medium-range Weather Forecasts) pressure and temperature at the location of the balloon measurements.

## 2.4 SAGE-II

SAGE-II (Stratospheric Aerosol and Gas Experiment II) is a sun-pointing photometer which measures the attenuated solar radiation through the Earth's limb in seven channels centred at wavelengths ranging from 0.385 to 1.02  $\mu\text{m}$ . SAGE-II was launched on 5 October 1984 on board the ERBS (Earth Radiation Budget Satellite) satellite (Mauldin et al., 1985) and provided measurements until 22 August 2005. The Version 6.2 of the retrieval used in this study, allows water vapour measurements from a spectral channel centred around 945 nm with a full-width half maximum of 33 nm (Thomason et al., 2004). The V6.2 version corrects the dry bias observed in older versions in the lower stratosphere and in the vicinity of the hygropause, i.e. the altitude of

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water vapour minimum (Taha et al., 2004; Chiou et al., 2004). The vertical resolution is approximately 1 km and the vertical sampling 0.5 km. The spatial resolution is 200 km along the light-of-sight and 2.5 km at right angles to the light-of-sight. The uncertainty of the version 6.2 products is the total uncertainty whose largest source is associated to the imperfect removal of the aerosol contribution (Thomason et al., 2004). Comparisons with ATLAS/ATMOS (Chiou et al., 2004), indicate that water vapour mixing ratio uncertainties are most probably overestimated by at least a factor of 2 to 3 especially in the lower stratosphere. Those comparisons along with the ones made by Taha et al. (2004) reveal agreement within 10–20% over an altitude range of 15–40 km between SAGE-II and other instruments. SAGE-II data are those available on the web site: <http://www-sage2.larc.nasa.gov/data/>.

## 2.5 HALOE

HALOE (HALogen Occultation Experiment) is a solar occultation limb sounder launched on 12 September 1991 on board the UARS (Upper Atmosphere Research Satellite) spacecraft (Russell et al., 1993), which provided measurements until 21 November 2005. The broadband radiometry technique allows retrieving water vapour content between 10 and 85 km from a channel centred on  $6.61 \mu\text{m}$ . The data used in this study are the version-19 retrieval products. They have been screened for cirrus cloud contamination as described by Hervig and McHugh (1999). The vertical resolution is about 2.3 km and the sampling 0.3 km. The horizontal resolution is 200–400 km along the light-of-sight and 10 km at right angles to the light-of-sight. Systematic and random errors are estimated to 10–14% and 7–9% respectively between 1 and 10 hPa, 14–19% and 8–14% between 10 and 40 hPa, and 19–24% and 13 % between 40 and 100 hPa as a latitudinal average (Kley et al., 2000; Harries et al., 1996). Intercomparisons with others instruments as made by Harries et al. (1996) indicate that the HALOE water vapour is accurate to within  $\pm 10\%$  or better in the height range 0.1–100 hPa with a precision of 5% or less in much of the stratosphere. The HALOE data are available on the web site: <http://haloedata.larc.nasa.gov/download/index.php>.

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## 2.6 MIPAS

The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) instrument is a limb-viewing mid-Infrared high-resolution Fourier transform spectrometer (Fischer et al., 2000). This instrument is operated on ENVISAT (ENVironmental SATellite) launched on 1 March 2002 (ESA, 1998). ENVISAT has a sun-synchronous polar orbit with a  $98.55^\circ$  inclination, a 100.5 min period and a 785 km altitude. The atmospheric limb emission spectrum is measured by MIPAS in the  $4.15\text{--}14.6\ \mu\text{m}$  spectral interval. The window used for the water vapour retrieval is around  $6.1\ \mu\text{m}$  (Weber et al., 2004). Water vapour profiles are obtained with a vertical resolution of 3–4 km and a horizontal resolution of 300–500 km along the orbital track. The precision estimated for the water vapour products is 5%, and the accuracy 5–10% (Pappalardo et al., 2004). The data used in this study are those of the ESA V4.62 retrieval algorithm of 3 km vertical sampling. The MIPAS data are those available from the web site <http://envisat.esa.int/object/index.cfm?fobjectid=1381&id=11>.

## 2.7 GOMOS

The Global Ozone Monitoring by Occultation of Stars (GOMOS) instrument is a UV-visible-near-Infrared spectrophotometer (Bertaux et al., 2001; Bertaux et al., 2004; Kyrölä et al., 2004) which was also embarked onto the ENVISAT satellite. It measures the radiation emitted by a star and absorbed by the Earth atmosphere in four disjointed spectral bands. The spectral band dedicated to the water vapour retrieval (i.e. the IR2 band) extends from 926 to 956 nm. GOMOS characteristics allow day and night measurements with 600 profiles recorded per day. The vertical resolution is better than 1.7 km and the horizontal resolution is about 150 km. The vertical sampling is of 400–500 m. The accuracy of the measurement depends on the star temperature (T) and on the star brightness (defined by its visual magnitude  $m_v$ ) with better accuracy for nighttime  $\text{H}_2\text{O}$  local densities being obtained for cold and low visual magnitude (bright) stars. The expected accuracy is better around 16–24 km ranging from 10%

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( $T=3000\text{ K}$ ,  $mv=1$ ) to 25% ( $T=11\ 000\text{ K}$  and  $mv=1$ ) or greater for hotter and dimmer stars (<http://envisat.esa.int/instruments/gomos/>). The accuracy is expected to degrade below and above the 16–24 km altitude range. The data used in this study are nighttime  $\text{H}_2\text{O}$  “local densities” profiles only issued from Antares and Toliman stars occultations, produced by the V6.0c.6.0f research retrieval algorithm.

## 2.8 AIRS/AMSU

AIRS (Atmospheric Infrared Sounder) is a nadir scanning sounder launched on 4 May 2002 on board the EOS (Earth Observing System) AQUA satellite. AQUA has a near-polar and sun-synchronous orbit of  $98.2^\circ$  inclination and 98.8 min period and at an altitude of 705 km (Parkinson, 2003). The infrared spectrum is measured in 2378 channels covering the spectral range  $3.7\text{--}15.4\ \mu\text{m}$  and 4 visible and near infrared channels covering the  $0.4\text{--}0.94\ \mu\text{m}$  spectral range. Among those channels, 66 are used for water vapour, the strongest absorption features being in the  $6.7\ \mu\text{m}$  water vapour band (Susskind et al., 2003). Nadir scanning allows sounding most of the globe twice daily with a horizontal spatial resolution of 13.5 km (geolocation accuracy of 1.7 km) in the infrared and of 2.3 km in the visible and near-infrared. In the vertical, the AIRS level 2 processing provides measurements for 1 km layers in the troposphere and 3–5 km layers in the stratosphere. AMSU-A (Advanced Microwave Sounding Unit A), also aboard the AQUA spacecraft, is a microwave temperature/humidity radiometer formed with two independent modules: AMSU-A1 (12 channels between 50–58 GHz and 1 channel at 89 GHz) and AMSU-A2 (2 channels at 23.8 GHz and 31.4 GHz) (Rosenkranz et al., 2001). Because microwave radiation, unlike infrared radiation, is not sensitive to clouds, nine AIRS 13.5 km footprint infrared data are combined with one 40 km AMSU footprint in the microwave, to provide a single “cloud-clear” infrared spectrum (Aumann et al., 2003, and Susskind et al., 2003, for more details). The water vapour profiles are then obtained over footprints of  $45\text{ km} \times 45\text{ km}$  with a horizontal resolution of 50 km. Each standard product profile is made of mean water vapour mixing ratio in 28 pressure layers from the surface to the mesosphere. Compared with in situ and aircraft measure-

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ments, the AIRS data showed agreement within 25% between 500 and 100 hPa and even better for more spatially (<50–100 km) and temporally restricted criteria (<1 h) (Hagan et al., 2004). Further comparisons between AIRS version 3 and aircraft measurements by Gettelman et al. (2004) confirmed the agreement of 25% for pressures greater than 150 hPa and water vapour mixing ratio greater than 10 ppmv, corresponding to the limit of sensitivity of AIRS, but showed a wet bias at pressure lower than 100–150 hPa. The data used in this study are those of the version-4 retrieval available on the web site: [http://disc.gsfc.nasa.gov/services/dods/airs\\_dp.shtml](http://disc.gsfc.nasa.gov/services/dods/airs_dp.shtml).

## 2.9 REPROBUS/ECMWF model

Also used in the study are the REPROBUS/ECMWF water vapour profiles. REPROBUS (REactive Processes Ruling the Ozone Budget in the Stratosphere) is a three-dimensional Chemistry-Transport Model (CTM) (Lefèvre et al., 1994 and 1998). This model calculates the densities of 55 species by means of 150 photolytic gas-phase and heterogeneous reactions. Among them, 40 individual constituents or chemical families are explicitly transported by the semi-lagrangian scheme with a time step of 15 min. The model extends from the surface up to 1 hPa on 42 hybrid levels and the horizontal resolution is 2° in latitude and longitude. Winds, temperatures and ground pressure provided by the T<sub>L</sub>511L60 6-hourly ECMWF operational analyses, interpolated to the model resolution, are used as input. In the model, water vapour concentrations from the ground up to 95 hPa level are directly those of the ECMWF analyses. Above that level, in the stratosphere, the water vapour concentration is calculated by the model initialized with climatological values of the Microwave Limb Sounder (MLS) of the UARS satellite. The simulations include the production of H<sub>2</sub>O by oxidation of methane. REPROBUS does not allow supersaturation (no supercooled water) when the temperature is below 273.16 K. The model provides profiles from the ground to 10 hPa with a vertical resolution of about 1 km near the tropopause and 1.3 km in the lower stratosphere.

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### 3 Water vapour profiles comparisons

Three different types of comparisons have been performed for evaluating the relative performances of the measurements: (i) individual collocated balloon in-situ and satellite water vapour profiles; (ii) mean collocated profiles and variability of long duration balloon and satellites instruments during the period of the balloon flight between 10° S and 30° S; and (iii) satellite zonal mean profiles in February–March 2004 between 10° S–20° S and 20°–30° S respectively.

#### 3.1 Individual collocated balloon in-situ and satellites profiles

Two SF balloons carrying the in situ  $\mu$  SDLA and UCAM-SAW instruments were flown from Bauru in the convectively active South Atlantic Convergence Zone, on 13 (SF-2) and 24 (SF-4) February 2004. The flights and the meteorological conditions within which they were performed are described by Durrý et al. (2006) and Pommereau et al. (2007). The two balloon profiles are compared to those of the closest satellite observations. The location and the distance of the satellite measurements from those of the balloons are given in Table 2 for SF-2, and in Table 3 for SF-4.

The first slow descent SF balloon flight of the HIBISCUS campaign (SF-2) was launched on 13 February 2004 at 20:18 UTC (17:18 LT) some 300 km east of a strong convective region over the west of the state of Sao Paulo (Pommereau et al., 2007). Among several instruments, it was carrying a SAW hygrometer and  $\mu$  SDLA at the bottom of the flight train 40 m below. The balloon ascended up to 20 km afterward it was left descending slowly after its cooling at sunset, down to 11.8 km where the payloads were separated. The two instruments performed during the daytime ascent in the troposphere and during the slow nighttime descent (after 22:00 UTC). Unfortunately, the SAW experienced some technical problems leading to oscillations in the measured frost-points and no data from this instrument are available for this flight. But the  $\mu$  SDLA performed well except between 12.774 and 13.385 km where there were no data because of technical problems. The closest satellite observations available are a HALOE

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sunrise profile at 09:19 UTC on the morning 475 km in the south-west direction and an AIRS profile 41 km from the balloon location at 16:52 UTC. The quality flag of the AIRS data indicates that the water vapour data were of highest quality.

The water vapour profiles of the three instruments in the altitude range 12–20 km are shown in Fig. 1 where the AIRS pressure coordinate was converted in altitude coordinate using the information of a GPS (precision  $\pm 20$  m) and a pressure sensor (accuracy  $\pm 1$  hPa) also carried by the balloon. The percent relative difference of  $\mu$  SDLA and HALOE in reference to AIRS is also shown in Fig. 1, where stars indicate the mean values at the middle of each AIRS layer.

The  $\mu$  SDLA profile displays the highest mixing ratio, between 3.5–7 ppmv in the lower stratosphere, a supersaturated layer extending a little above the tropopause (Marécal et al., 2007), and a moist troposphere (174 ppmv at 12 km). The sharp mixing ratio increase at the top of the profile (11.6 ppmv around 19.7 km) at the very beginning of the descent probably due to outgassing from the gondola and the balloon should be ignored (Durry and Megie, 2000). Compared to AIRS, the  $\mu$  SDLA shows a systematic wet bias of 40% around 18 km, increasing at lower altitude in the UT. The HALOE water vapour consistent with that of AIRS above 18 km, displays an increasing low bias at decreasing altitude in the troposphere, reaching 60% at 13.5 km. As noted by Kley et al. (2000), this dry bias in the upper troposphere could be attributed to the difficulties for the processing algorithm to accurately follow extremely sharp gradients, leading to a 40% low bias or even more below the hygropause. Another possible contribution to the large differences between the measurements is the high variability of water vapour mixing ratio in a region of active convection and intrusion of mid-latitude stratospheric air sampled 475 km apart and moreover at different local time during the day.

The second flight, SF-4, was performed in the presence of very active local convection (Pommereau et al., 2007). The balloon was launched at 20:03 UTC (17:30 LT) on 24 February carrying one SAW and the  $\mu$  SDLA at the bottom of the flight train. The closest satellite overpass are those of GOMOS at 03:08 UTC during the night, 768 km in the north-north west, AIRS at 16:35 UTC at 44 km and two MIPAS profiles on the

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following day at 01:00 UTC at 1205 km in the east-north east and at 16:46 UTC at 652 km in the south-west (Table 3). In the case of MIPAS, and because of the known error in the altitude coordinate (Fricke et al., 2004) of approximately 2 km, the pressure has been used instead, converted in altitude with the closest ECMWF analysis profile ( $\pm 12$  h and  $\pm 2.5^\circ$  in latitude and longitude). The measurements and the difference in reference to AIRS are displayed in Fig. 2.

As in the previous flight, the  $\mu$  SDLA water vapour profile displays a supersaturated upper troposphere up to 15 km surmounted by variable mixing ratio above. The relatively moist layer of 5 ppmv between 17–18 km, coincident with an enrichment of methane, is attributed by Durry et al. (2006) to a convective overshoot while the increase above 19 km could be due to outgassing at the very beginning of the descent when the vertical speed is very slow or to injection by convection of tropospheric air into the lower stratosphere as explained by Nielsen et al. (2007). The other in situ sensor, the SAW hygrometer, is in very close agreement with the  $\mu$  SDLA up to an altitude of 14 km, above which, its limited sensitivity at low temperature does not allow reliable measurements. AIRS is dry biased of around 20–30% as compared to  $\mu$  SDLA above 15 km, but two times dryer than the two in situ sensors around 13 km, although the comparison with the balloon measurements in a supersaturated and thus cloudy layer is little conclusive. Although separated by more than 1000 km and one day, the two MIPAS profiles are close to each other, both dry biased by 20–30% compared to AIRS in the TTL and by 40% in the upper troposphere. This low bias in MIPAS water vapour is consistent with the results of previous comparisons with aircraft measurements as well as lidar and radiosonde data (Oelhaf et al., 2004; Colavitto et al., 2004) with the MIPAS V4.61 version. Finally, GOMOS displays an unrealistic profile shape with a minimum mixing ratio ( $1.8 \pm 0.3$  ppmv) at 18.4 km, not seen by all others. The reason for that, identified by the GOMOS team, is the strongly non-uniform response of the CCD (Charge Coupling Device) detector in the spectral region of water vapour absorption, introducing distortions in the spectra.

In summary, although some differences, e.g. the HALOE and MIPAS low biases

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compared to AIRS and in situ measurements, are consistent with previous findings, it must be recognised that individual comparisons of water vapour concentrations in the tropical UTLS of more or less collocated observations, are not very conclusive. This is particularly true in a region of very active convection where humidity can vary by large amounts within short distances. The only reliable indication, which could be derived, is the relatively dry bias of satellite observations compared to  $\mu$  SDLA in the TTL, at least at altitude where the contamination of the in situ measurements by outgassing is limited.

### 3.2 Mean balloon and satellites collocated profiles between 10–30° S

All SAOZ long duration balloon and satellites collocated profiles available in February–April 2004 in the latitude range 10°–30° S have been compared to those of AIRS, the latter being selected as a reference because of its high space and temporal sampling compared to all other systems. The criteria for collocation are less than 6 h in time and  $\pm 2^\circ$  in both longitude and latitude (except  $\pm 1^\circ$  for MIPAS of higher sampling than others). The numbers of selected profiles of each instrument and the periods of acquisition are summarized in Table 4. AIRS providing water vapour values averaged in pressure layers, each layer has been subdivided into 10 pressure levels evenly spaced onto which the measurements of other instruments have been interpolated. The 10 values have been then averaged to provide a mean value directly comparable to AIRS.

For each of the instrument, a mean profile was calculated according to:

$$\overline{X^j} = \frac{1}{n} \sum_{i=1}^n X_i^j \quad (1)$$

where

$\overline{X^j}$  is the mean water vapour concentration at AIRS mean pressure layer j,

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$X_i^j$  the water vapour concentration of profile  $i$  at AIRS mean pressure layer  $j$  and

$n$  the number of measurements available at AIRS mean pressure layer  $j$

5 For each instrument, a relative mean difference with AIRS, called **Dev**, was calculated according to:

$$Dev_{Instr/AIRS}^j = \frac{\overline{X_{Instr}^j} - \overline{X_{AIRS}^j}}{\overline{X_{AIRS}^j}} \times 100 \quad (2)$$

and finally, a variability, **V**, associated to the mean profile following Eq. (3)

$$V^j = \frac{\sigma^j \times 100}{\overline{X^j}} \quad (3)$$

10 where  $\sigma$  is the 1-sigma root-mean-squared difference to the mean profile defined by:

$$\sigma^j = \sqrt{\frac{1}{n} \sum_{i=1}^n (X_i^j - \overline{X^j})^2} \quad (4)$$

The results of the statistical comparisons are displayed in Fig. 3 (SAOZ, SAGE II and HALOE) and Fig. 4 (MIPAS, GOMOS).

### 3.2.1 SAOZ/AIRS

15 38 collocated profiles are available at 20 km, reducing to 3 only at 25 km (at the beginning of the balloon flight when the helium still present in the balloon makes the altitude higher) and 7 at 12 km because of the frequent presence of clouds.

Overall, the SAOZ and AIRS profiles are very consistent showing a slight increase of water vapour mixing ratio in the lower stratosphere, except the highest AIRS data point

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displaying a drop but of little statistical significance. In the lower stratosphere between 16 and 22 km, the difference does not exceed 10–15% (0.5 ppmv), SAOZ being high bi-  
ased. The opposite is observed in the UT where SAOZ becomes dry biased compared  
to AIRS, but it should be remembered that AIRS is still performing in the presence of  
clouds where SAOZ is blind. The amplitude of the variability, which includes both at-  
mospheric variations and instrumental random errors, is larger (30–35%) in AIRS than  
(15–20%) in SAOZ in the stratosphere, indicative of a worse precision of AIRS.

### 3.2.2 SAGE-II/AIRS

In total, up to 41 coincidences are available at 25 km, reducing to 3 at 13 km because  
of the cloud limitation of the SAGE-II measurements. Two series of SAGE-II data are  
shown. The first (dotted line) was calculated by keeping only the water vapour data as-  
sociated with 1020 nm aerosol extinction not exceeding  $3.10^{-4} \text{ km}^{-1}$  as recommended  
by Thomason et al. (2004), while the second (solid line) results from an additional se-  
lection of water vapour uncertainty lower than 50% as proposed by Taha et al. (2004).

Mean SAGE-II and AIRS profiles are very consistent in the stratosphere above 17 km  
showing again a slight increase of water vapour with altitude, and a difference not ex-  
ceeding  $\pm 20\%$  (0.7 ppmv). In the UT, SAGE-II displays a 20–30% low bias, the lowest  
data point derived from a single coincidence being ignored. The SAGE-II variability is  
significantly smaller than that of AIRS, 5–10% in the stratosphere, 15% in the UT, for  
the best case. The main change between the two data sets selected for SAGE-II ap-  
plies to the variability. The selection of water vapour data of less than 50% uncertainty  
improves the variability, showing that this parameter is indeed a good indicator of the  
average random error.

### 3.2.3 HALOE/AIRS

More than 100 coincidences are available above 18 km, reducing to 57 around 13 km.  
The profiles of the two instruments are very consistent above 20 km (HALOE low bi-

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ased by 10–20%), but the agreement degrades rapidly below, HALOE becoming more and more dry biased at decreasing altitude. This feature is very similar to that observed between HALOE and SAOZ for ozone (Borchi and Pommereau, 2006) attributed to a growing altitude registration error in the UT. Note that in the case of comparison between mixing ratio and not number density as for ozone, the difference is even amplified by the division by an overestimated air density. The HALOE variability is of the same order of magnitude of that of SAGE-II above 18 km and is lower than that of AIRS in the UT except for the lowest data point but where two profiles only are available for the comparison.

### 3.2.4 MIPAS/AIRS

The number of coincidences exceeds 3000 above 20 km and still 1404 at 11 km. The mean profiles are consistent within  $\pm 20\%$  just showing a progressive growing MIPAS high bias at decreasing altitudes. But the largest difference with AIRS appears in the variability. Indeed, if a small variability of the order 10%, a little larger than that of SAGE-II and HALOE is found in the stratosphere, it increases rapidly below 20 km, reaching more than 100% below 16 km, suggesting that MIPAS water vapour measurements are little reliable in the UT.

### 3.2.5 GOMOS/AIRS

The number of coincidences exceeds 100 above the tropopause dropping to 61 at 11 km. With the exception of the highest data point at 25 km where the GOMOS uncertainty is known to increase, the two mean profiles are extremely consistent, GOMOS showing a systematic dry bias by 3–13% compared to AIRS at all altitude levels below. An important point to remember is that GOMOS because of its star occultation technique has the most precise altitude registration of all instruments, particularly when compared to the limb viewing systems. The large GOMOS variability of the order of 25% in the lower stratosphere is attributed to the known problem of non-uniform re-

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sponse of the CDD detector leading to an imperfect refraction correction algorithm.

### 3.3 Zonal mean profiles

The third approach used for evaluating the relative performances of all above water vapour measuring instruments, is to compare their zonal mean and their associated variability. Figure 5 shows the results of the calculations for the February–March period between 10–20° S (top) and 20°–30° S (bottom) and Tables 5 and 6 the number of profiles available from each instrument. The AIRS results are based on means of 1050 324 and 1063 165 profiles between respectively 10–20° S and 20°–30° S.

In the stratosphere above 20 km, the profiles could be grouped in two families: HALOE, SAGE-II and MIPAS showing an almost constant mixing ratio of 3.5–4 ppmv, and SAOZ, AIRS and GOMOS displaying a slight increase from 4 to 6 ppmv at 10°–20° S, AIRS being closer to the first family at 20°–30° S. Since the sensitivity of the three last is known to degrade at increasing altitude, it is very likely that the first group is more representative of atmospheric water vapour at these altitude levels. Compared to the measurements, the REPROBUS/ ECMWF model is significantly dry biased by 1 ppmv, which is not a surprise given the condensation and removal of water vapour at saturation in the model. But the comparison suggests the opposite in the TTL below 19 km, where HALOE and SAGE-II are seeing a minimum mixing ratio around the tropopause, and a strong dry bias in the UT not observed by all others, including ECMWF analyses.

The variability on the right side of the figures provides an indication of the random errors of the measurements very consistent with the conclusions of the comparisons of collocated measurements in the previous sections. In the stratosphere, the instrument displaying the largest random errors is AIRS (30–35%), followed by GOMOS (25–30%), SAOZ (20%), MIPAS (10–15%), SAGE-II when selected for errors smaller than 50% (solid lines) (5–10%) and HALOE (5%), compared to the REPROBUS model suggesting an atmospheric variability not exceeding 2–3%. The variability of all measurements increases below 19 km, that of SAOZ, GOMOS, AIRS and SAGE-II at 20–30° S, being close to the atmospheric variability suggested by ECMWF (around 50–60% at 12 km).

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That of MIPAS and SAGE-II at 10°–20° S (unselected since there is no more data if the 50% error selection is applied) increases rapidly, suggesting that their data are little reliable in the TTL. Finally, HALOE displays variability significantly smaller than that of ECMWF and other instruments.

#### 4 Summary and conclusion

Altogether, individual and statistical comparisons of balloon and satellites water vapour measurements available during HIBISCUS provide a clear picture of the performances of each in the UTLS. The biases compared to AIRS used as reference and the variability of retrieved concentrations indicative of precision, are summarized in Table 7.

In the stratosphere between 20–25 km, three satellite instruments, HALOE, SAGE-II and MIPAS, are showing very consistent results (nearly constant mixing ratios slightly dry biased by 5–15%, 0.5–0.9 ppmv, compared to AIRS), while AIRS, GOMOS and the SAOZ balloon are displaying a slight increase of water vapour with altitude. The first three appear also the most precise at this level, HALOE being the less variable (5%), close to the atmospheric variability shown by the REPROBUS/ECMWF model. The small wet bias of MIPAS compared to SAGE-II is consistent with the 4–12% estimated by Bracher et al. (2004) between 2.5 and 50 hPa. The three other instruments are showing significantly larger variability, AIRS being the less precise (35%), followed by GOMOS (25–30%) and SAOZ (20%). In contrast to the conclusions of Gettelman et al. (2004), it is suggested that AIRS may provide valuable measurements in the lower stratosphere although of lower precision than others.

Lower down between 14 and 20 km in the Tropical Tropopause Layer, the conclusions are different. HALOE and SAGE-II are reporting marked minimum mixing ratios around 17–19 km, not seen by all others. For HALOE, this might be related to a growing error of altitude registration at decreasing altitude as seen on ozone (Borchi and Pommereau, 2006). For SAGE-II, a possible explanation could be the partial persistence of the dry bias displayed by previous retrieval versions, not completely removed

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in version 6.2 in contrast to the conclusions of Thomason et al. (2004). On average, MIPAS is consistent with AIRS, GOMOS and SAOZ, not displaying the dry bias observed in previous version 4.61 (Schets et al., 2003; Colavitto et al., 2004; Oelhaf et al., 2004 in the lower stratosphere). The wet bias noticed by Gettelman et al. (2004) in AIRS from comparisons with aircraft measurements at pressure levels lower than 100–150 hPa is not seen. Compared to satellites, the  $\mu$  SDLA tunable laser balloon in situ measurements display systematically larger humidity although this conclusion may be biased by the fact that the balloon flights were carried out intentionally next or above strong convective systems where remote observations from space cannot be performed. Although, likely because of the frequent presence of cirrus clouds, the number of profiles available from remote sensing instruments decreases rapidly with altitude, the variability increases in all measurements, as in the REPROBUS/ECMWF model, but particularly in MIPAS compared to others suggesting that the water vapour measurements of this instrument are little reliable below 19 km.

In the upper troposphere below 14 km, all remote sensing measurements (except MIPAS of limited precision, and AIRS/AMSU) become rare, dry biased and less variable compared to ECMWF but particularly HALOE and SAGE-II. The main reason for that is the frequent masking by clouds within which no measurements could be performed except by the AMSU microwave sensor. Water vapour remote sensing measurements are representative of cloud free conditions and thus dryer and less variable on average than ECMWF and AIRS/AMSU. The two in-situ instruments,  $\mu$  SDLA and SAW, flown on the same balloon agree each other, displaying water vapour mixing ratios 100–200% larger than that of HALOE and MIPAS, which could be explained by the difference in space and time between the measurements and by the presence of clouds as shown by the supersaturation up to the tropopause, hardly detectable from the orbit.

Finally, it must be recognised that the retrieval algorithms associated to the various systems investigated here are not at same stage of maturity. For most recent instruments, e.g. onboard ENVISAT, the data shown here are frequently those of research versions of the algorithms expected to receive improvements in the near future. It is

hoped that this analysis could contribute. The HIBISCUS data will remain available for that.

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**Table 1.** Summary of balloon and satellite water vapour measurements.

Platform	Instr.	Technique	Spectral Region	Vertical/Spatial resolution	Estimated Accuracy
Balloon	$\mu$ SDLA	In situ tunable diode laser spectro.	1.39 $\mu$ m	10 m/NA	5–10%
	SAW	In situ Surf Acoust Wave hygro.	NA		
	SAOZ	Near IR spectro Solar Occ	945 nm	1.4 km/200 km	Prec 0.2 ppm at 17 km, 0.4 ppm at 23 km; Acc: 20%
Satellite	SAGE–II V 6.2	Near IR Spectro Solar Occ	945 nm	1 km/200 km	10–20% (10–40 km)
	HALOE V.19	broadband phot. Solar Occ	6.61 $\mu$ m	2.3 km/200–400 km	Random 8–14% Syst. 14–24% (10–100 hPa)
	MIPAS V4.62	FTS Limb Thermal emission	6.1 $\mu$ m	3–4 km/300–500 km	Prec. 5% Acc. 5–10%
	GOMOS V6.0c.6.0f	Near IR Spectro Star Occultation	926–956 nm	1.7 km/ $\pm$ 150 km	10–25% (16–25 km)
	AIRS AMSU V4	IR/microwave Nadir	6.7 nm	2 km/50 km	25% P>100 hPa

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**Table 2.** SF-2. Instruments and location of water vapour measurements on 13 February.

Instrument	Date and Time UTC		Latitude	Longitude	Distance to $\mu$ SDLA (km)
$\mu$ SDLA & SAW	13 22:12 UTC	Feb	22.14° S	49.02° W	0
HALOE	13 09:19 UTC	Feb	25.22° S	52.59° W	~475
AIRS	13 16:52 UTC	Feb	22.35° S	48.93° W	~41

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**Table 3.** Same as Table 2 for SF-4 flight on 24 February.

Instrument	Date and Time UTC	Latitude	Longitude	Distance to $\mu$ SDLA (km)
$\mu$ SDLA & SAW	24 Feb 21:57 UTC	22.55° S	49.17° W	0
GOMOS	25 Feb 03:08 UTC	16.91° S	53.06° W	~768
AIRS	24 Feb 16:35 UTC	22.39° S	49.33° W	~44
MIPAS profile 1	26 Feb 01:00 UTC	17.02° S	39.40° W	~1205
MIPAS profile 2	26 Feb 16:46 UTC	24.16° S	55.37° W	~652

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**Table 4.** Number of selected collocated profiles and periods of observations.

Instruments	Numbers of profiles	Periods
SAOZ	40	28 February–1 April
SAGE-II	41	18–21 March (39) 30 April (2)
HALOE	110	10–14 February 8–11 April 23–25 April
MIPAS	3052	26 February–26 March
GOMOS	119	1 February (1) 17–29 February (118)

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**Table 5.** Number of measurements available for each instrument between 10–20° S. SAGE-II (1): 1020 nm aerosol extinction not exceeding  $3.10^{-4} \text{ km}^{-1}$ ; SAGE-II (2): plus water vapour uncertainty lower than 50%.

Altitude (km)	SAOZ/H <sub>2</sub> O	REPROBUS	SAGE-II (1)	SAGE-II (2)	HALOE	MIPAS	GOMOS
12	11	45	0	0	6	737	32
13	18	45	0	0	8	855	36
14	24	45	0	0	10	859	39
15	25	45	0	0	12	931	47
16	35	45	1	1	15	1246	53
17	42	45	1	1	17	1248	60
18	45	45	2	0	19	1399	72
19	43	45	10	1	25	2029	73
20	43	45	15	11	26	2029	73
21	39	45	17	14	26	2048	73
22	37	45	19	18	26	2077	73
23	28	45	20	18	26	2077	73
24	21	45	20	17	26	2077	73
25	17	45	20	20	26	2077	73

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**Table 6.** Same as Table 5 for 20–30° S.

Altitude (km)	SAGE-II (1)	SAGE-II (2)	HALOE	MIPAS	GOMOS
12	5	5	13	1236	49
13	8	8	19	1440	53
14	11	9	20	1472	57
15	18	11	21	1589	61
16	23	5	23	1884	66
17	25	14	24	1902	68
18	26	17	25	1916	68
19	27	23	26	2070	68
20	27	26	27	2071	68
21	27	27	27	2071	68
22	27	27	27	2075	68
23	27	27	27	2075	68
24	27	27	27	2075	68
25	27	27	27	2075	68

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**Table 7.** Summary of performance of all systems.

Instr.	Z>20 km		20>Z>14 km		Z<14 km	
	Bias %	Var. %	Bias %	Var %	Bias %	Var %
AIRS	0	35	0	30/40	0	40/70
$\mu$ SDLA	NA	NA	+20/+50	NA	>100	NA
SAW	NA	NA	NA	NA	>100	NA
SAOZ	+15	20	+10	20/40	-20	50
SAGE-II	-20	5/10	-30	10/30	-20	20-40
HALOE	-15	5	-10/-50	5/25	-60	25
MIPAS	-20/-10	5/15	+20	>100	+20	>100
GOMOS	-10	25	-10	25/35	-10	50

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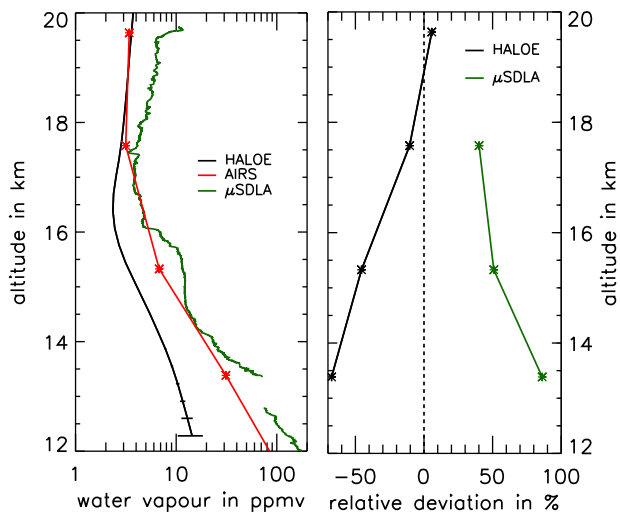
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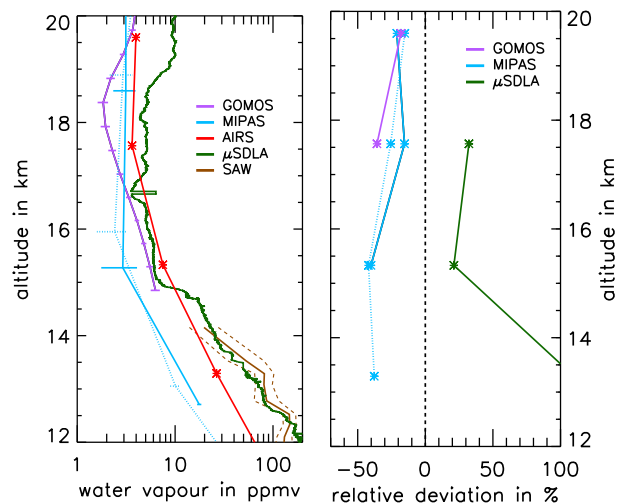


**Fig. 1.** Left: Water vapour profiles observed by  $\mu$  SDLA (green) during the SF-2 flight on 13 February, HALOE (black) and AIRS (red) water vapour data. Right: relative percent difference with AIRS at the AIRS vertical resolution.

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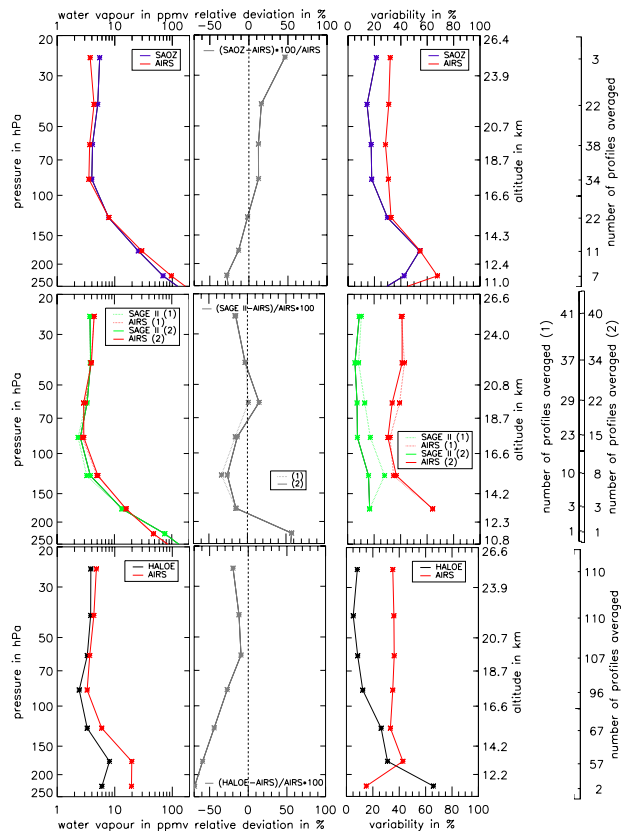


**Fig. 2.** Same as Fig. 1 for the SF-4 flight on 24 February  $\mu$  SDLA (green), SAW (brown), GOMOS (purple), MIPAS (light blue) and AIRS (red), including errors provided in the data files, when available.

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**Fig. 3.** Comparison of SAOZ (top), SAGE-II (middle) and HALOE (bottom) water vapour measurements to AIRS. Left panel: mean profiles; middle: difference with AIRS; right: variability. Left scale: pressure; right: altitude; far right: number of collocated measurements at each level.

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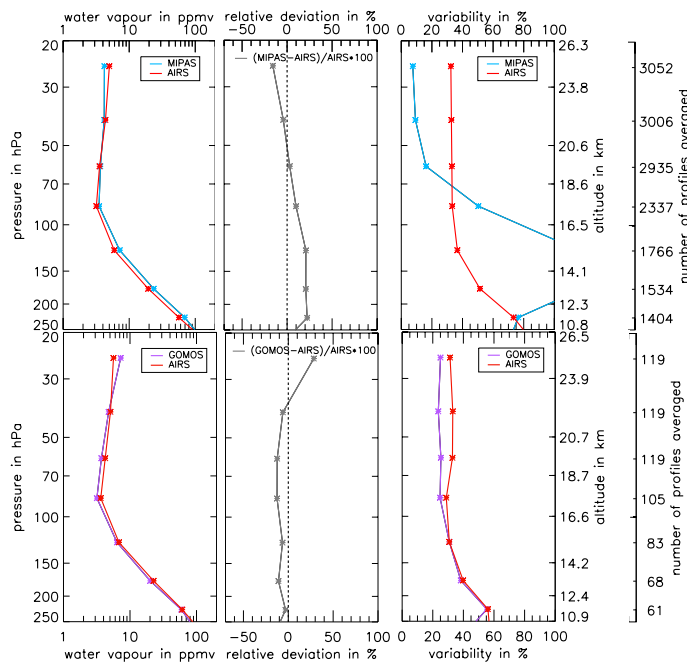
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**Fig. 4.** Same as Fig. 3 for MIPAS (top panel) and GOMOS (bottom panel).

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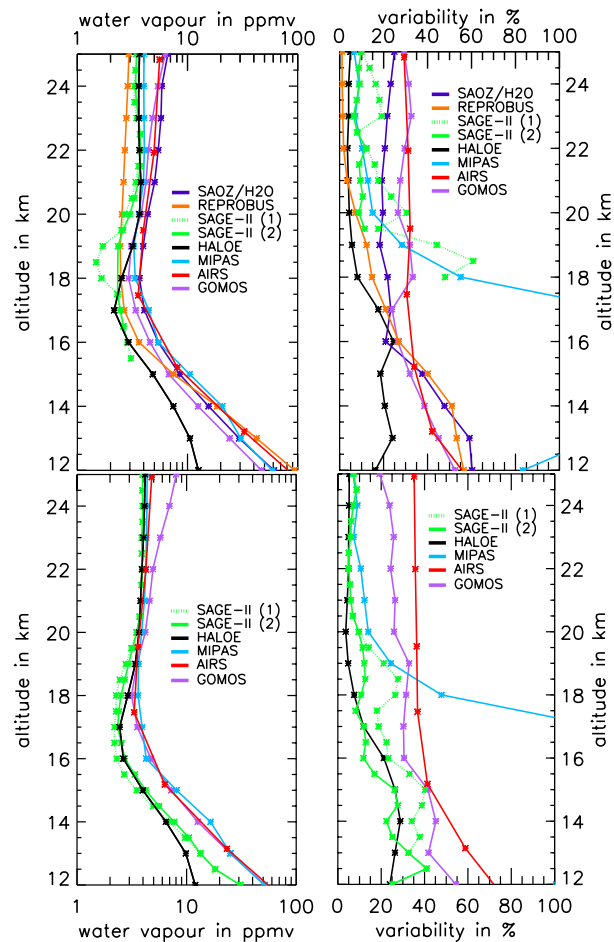
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**Fig. 5.** Zonal mean water vapour profiles (left) and variability (right). Top panel: 10°–20° S, bottom panel: 20°–30° S. 6075

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