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Evaluation of Water Vapour Assimilation in the Tropical Upper Troposphere and Lower Stratosphere by a Chemical Transport Model

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Abstract.

The present analysis deals with one of the most debated aspect of the studies on the Upper Troposphere/Lower Stratosphere (UTLS), namely the budget of the water vapour (H_2O) at the tropical tropopause. Within the French project "Multiscale water budget in the upper troposphere and lower stratosphere in the TROpics" (TRO-pico), a global-scale analysis has been set up based on space-borne observations, model and assimilation techniques. The MOCAGE-VALENTINA assimilation tool has been used to assimilate the Aura Microwave Limb Sounder (MLS) version 3.3 H_2O measurements within the 316–5 hPa hPa range from August 2011 to March 2013 with an assimilation window of 1 hour. Diagnostics are developed to assess the quality of the assimilated H_2O fields depending on several parameters: model error, observation minus analysis and forecast. Comparison with an independent source of H_2O measurements in the UTLS based on the spaceborne Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) observations and with meteorological ARPEGE analyses are also shown. Sensitivity studies of the analyzed fields have been performed by: 1) considering periods when no MLS measurements are available and 2) using another MLS version 4.2 H_2O data. The studies have been performed within 3 different spaces in time and space coincidences with MLS and MIPAS observations and with the model outputs and at 3 different levels: 121 hPa (upper troposphere), 100 hPa (tropopause), and 68 hPa (lower stratosphere) in January and February 2012. In the MLS space, the analyses behave consistently with the MLS observations from the upper troposphere to the lower stratosphere. In the model space, the analyses are wetter than the "true" atmosphere as represented by ARPEGE and MLS in the upper troposphere (121 hPa) and around the tropopause (100 hPa), but consistent with MLS and MIPAS in the lower stratosphere (68 hPa). In the MIPAS space, the sensitivity and the vertical resolution of the MIPAS data set at 121 and 100 hPa prevent to assess the behaviour of the analyses at 121 and

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100 hPa particularly over intense convective areas as the Southern American, the African and the Maritime continents but, in the lower stratosphere (68 hPa), the analyses are very consistent with MIPAS. Sensitivity studies show the great improvement on the H_2O analyses in the tropical UTLS when assimilating spaceborne measurements of better quality particularly over the convective areas.

1 Introduction

Water is constantly cycling through the atmosphere. It evaporates from the earth's surface and rises on warm updrafts into the atmosphere. Then it condenses into clouds, is blown by the wind, and then falls back to the Earth's surface in form of rain or snow. This cycle is one important way to transfer the heat and energy from the surface of the Earth to the atmosphere, and transported from one place to another on the globe. Water vapour (H_2O) is also one of the dominant greenhouse gas in the Earth's atmosphere. Unlike other greenhouse gases, the additional water vapour in the atmosphere was not put there directly by humans. The increase in water vapour occurs because the climate is warming, and the increase then contributes to further warming. This process is referred to as a positive feedback. The effect of water vapour as a greenhouse gas on climate change is a key parameter due to its positive feedback on the earth radiative budget. The concentration of water vapour in the atmosphere ranges from 3% of volume in wet tropical areas to a few parts per million by volume (ppmv) in the stratosphere. Water vapour mixing ratio in the lower stratosphere is generally very low (2.5–5.3 ppmv) (Panwar et al., 2012).

Brewer (1949) postulated that the observed stratospheric air must have passed through the cold tropopause region observed over the tropics. The evolution of H_2O in the Upper Troposphere and Lower Stratosphere (UTLS) is still not well understood irrespective of numerous space- and balloon-borne data now available. One of the challenging region is the tropical tropopause layer (TTL). The layer is maintained by a complex interplay between large and small-scale circulation patterns, deep convection, clouds and radiation (Randel and Jensen, 2013). H_2O is also a key constituent in atmospheric chemistry. It is the source of hydroxyl (OH), which controls the lifetime of shorter-lived pollutants, tropospheric and stratospheric ozone, and other longer-lived greenhouse gases such as methane (Seinfeld and Pandis, 2006). Furthermore, H_2O has an important influence on stratospheric chemistry through its ability to form ice, which offers a surface for heterogeneous chemical reactions involved in the destruction of stratospheric O_3 via polar stratospheric clouds. It is noteworthy that despite the importance of water vapour, there seems to be only little skill in representing water vapour distributions in current chemistry-climate models specially in extratropical UTLS (Hegglin et al., 2010), as well as in climate models such as used for the IPCC climate assessments (Jiang et al., 2012) and reanalyses (Jiang et al., 2010) in these regions. Combining models and measurements together to understand the interannual and long-term behaviour of stratospheric water vapour, even in the lower stratosphere, as presented in Heggling et al. (2014) can help characterizing biases in observations and also the physical processes responsible for the long-term trends in water vapour.

The lack of progress in representing UTLS water vapour in models may partially be explained by inconclusive observational records, to which the models are compared (SPARC CCMVal, 2010). It is not trivial to accurately measure water vapour in the TTL, and satellite measurements, as well as in situ correlative data, have been shown to exhibit large absolute differences (SPARC WAVAS, 2000). In particular, the current lack of an accepted standard from in situ correlative data precludes a conclusive assessment of the performance of available satellite water vapour measurements (see Weinstock et al., 2009). To cope with this issue, the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) international reference observing network has been designed to fill an important gap in the current global observing system, providing long-term, high-quality climate data records (including H_2O) from the surface, through the troposphere, and into the stratosphere (see e.g. http://www.dwd.de/EN/research/international_programme/gruan/home.html).

Around the tropopause, large gradients in H_2O and interplay of transport processes between troposphere and stratosphere, mainly due to rapid change in H_2O by deep convection, are highly challenging for an accurate representation of H_2O in global models.

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The most advanced Numerical Weather Prediction (NWP) models use sophisticated data assimilation systems to better represent H_2O in the UTLS based on direct (e.g. radiosonde) and indirect (e.g. satellite radiance) observations. For instance, at the European Centre for Medium-range Forecast (ECMWF), state-of-the-art assimilation systems are operationally used to provide some of the best forecasts, analyses, and reanalyses among the NWP centres around the world (http://apps.ecmwf.int/wmolcdnv/).

Recently, Kunz et al. (2014) carried out a comprehensive assessment of the UTLS H_2O in the most recent ECMWF analyses and reanalyses. The authors compared the operational analysis and ERA-Interim reanalysis datasets to a 10-year climatology of H_2O measurements in the UTLS from the Fast In Situ Stratospheric Hygrometer (FISH, Zoger et al., 1999). FISH instruments have been used between 2001 and 2011 in 10 international airborne campaigns from polar regions to the tropics, including the Tropical Convection, Cirrus and Nitrogen Oxides Experiment (TROCCINOX) campaign in 2005 which was specifically dedicated to the study of deep tropical convection (Schiller et al., 2009).

ERA-Interim reanalyses benefit from the 12-hour sequential 4D-Var data assimilation scheme at T255 spectral resolution (80 km) and 60 hybrid levels based on the operational Integrated Forecast System (IFS) (version Cy31r2) operationally used at ECMWF between 2006 and 2007. Note that beyond the tropopause, no direct humidity observation is assimilated and all supersaturation is suppressed, which means that, in the stratosphere, the humidity distribution is mainly controlled by troposphere-to-stratosphere exchange, advection, and methane oxidation schemes in IFS. Specifications of the forecast model, data assimilation system, and assimilated datasets are thoroughly described by Dee et al. (2011).

Unlike the reanalyses, which are based on a single version of the data assimilation system and forecast model, the operational analyses have benefited from significant modifications of the IFS and the 12-hour 4D-Var data assimilation system over the period

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2001-2011. The changes mostly impacted H_2O fields over this period are: a revised convection scheme, introduced in 2007 (Cy32r3), the better account for ice supersaturation in 4D-Var in 2009 (Cy35r3), and a new cloud scheme in 2010 (Cy36r4). The horizontal resolution of the analyses is also higher than that of the reanalyses, with T511 spectral resolution (39 km) and 61 vertical levels from 2001 to 2006, increased to T1279 (16 km) and 91 levels in 2010. Note that, at the present time, ECMWF high resolution model produces analyses thanks to a new cubic octahedral grid of Tco1279 horizontal resolution (9 km) and 137 vertical levels (Cy41r2). Documentation related to model changes is available online at the following address: http://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model.

Compared to FISH measurements, about 30% of the ERA-Interim reanalyses were found to be in very good agreement (deviation from the model < 10%), both in very dry and very wet conditions, and another 57% have been defined as in fairly good agreement with the model (deviation < 50%). Only 13% of the data were showing large positive or negative biases (deviation > 50%). The authors also analyzed the data in function of their geographical repartition, i.e. in the tropics, in the subtropics and in the extratropics, using the height of the thermal tropopause as proxy. In the LS, at all latitudes, the deviation of FISH observations from ERA-Interim is very small, which means that there is no lower stratospheric wet bias as suggested in previous studies (Oikonomou and O'Neil, 2006; Luo et al., 2007; Flentje et al., 2007; Schafler et al., 2010). Only the extratropical tropopause region (±4 km around the thermal tropopause) and tropical UT were shown to have deviations up to 10 times to the observed values.

Focusing on the H_2O amount and transport from UT to LS, Jiang et al. (2015) show that the reanalyses from ECMWF and from NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA) and its newest release (MERRA2) overestimate annual global mean UT H_2O by up to ~150% compared to MLS observations. Substantial differences in H_2O transport that impact on H_2O budget are also found between the observations and reanalyses. H_2O transport across the tropical tropopause in the reanalyses is faster by up to ~86% compared to MLS observations. In the tropical LS, the mean vertical transport from ECMWF is 168% faster than the MLS estimate, while MERRA and MERRA2 have vertical transport velocities within 10% of MLS values.

The comparison of operational analyses with FISH measurements presents similar patterns. The overall good agreement is contrasted by wet biases in the extratropical tropopause regions and dry bias in the tropical UT of similar order that those found in the reanalyses. Nevertheless, the authors pointed out that those biases were reduced by up to a factor 2 in the operational analyses towards the end of the period of study (2011) with respect to ERA-Interim. This highlights the impact of the improvements of both the IFS and the assimilation system. In summary, the consistent biases found both in ERA-Interim and operational analyses emphasize the difficulty to properly account for dynamical processes, especially deep tropical convection, in the assimilation system and model to accurately represent the water vapour distribution in the UTLS.

The present study is intended to address one of the most debated aspects of the TTL and the LS, the budget of water vapour (H_2O), and aspires to be a baseline for further studies related to the “Multiscale water budget in the upper troposphere and lower stratosphere in the TROpics” (TRO-pico) project (www.univ-reims.fr/TRO-pico). One of the TRO-pico aims is to monitor H_2O variations in the TTL and the LS linked to deep overshooting convection during field campaigns, which took place in the austral summer of 2012 and 2013 in Bauru, Sao Paulo state, Brazil, involving a combination of balloon-borne, ground-based and space-borne observations and modelling. TRO-pico’s objectives are to evaluate to what extent the overshooting convection and involved processes contribute to the stratospheric water vapour

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entry. Small- and medium-size balloons were launched as part of two field campaigns (2012 and 2013) held during the convective period in Bauru, Sao Paulo state, Brazil. Flights carrying Pico-SDLA (Tunable Laser Diode Spectrometer; Durry et al., 2008) and Flash-B (Yushkov et al., 1998) hygrometers were launched early morning and late evening while radiosondes were launched up to 4 times a day during the most convective period. The measurements, still under analysis, are matched with space-borne and model data.

To evaluate the local results obtained in Bauru with respect to a larger scale, comparisons with climatologies were necessary. Although seasonal and annual variations of H_2O have been extensively studied, few studies were devoted to the geographical and temporal variability of its diurnal cycle in the TTL. In Carminati et al. (2014), the impact of the continental tropical convection on the H_2O variability was debated by considering the 8-year Microwave Limb Sounder (MLS) H_2O, cloud ice-water content (IWC), and temperature data sets from 2005 to 2014. The interplays between these parameters and their role in the water vapour variability in the TTL were highlighted separately in the northern and southern tropics. The analysis from Carminati et al. (2014) adopted the Liu and Zipser (2009) philosophy to discuss the difference between daytime and night-time data sets with the aim of better apprehending the role of continental convection on hydrating and dehydrating processes in the TTL.

According to Carminati et al. (2014), in the tropical upper troposphere (177 hPa), continents, including the maritime continent, present the nighttime (01:30 local time, LT) peak in the water vapour mixing ratio characteristic of the H_2O diurnal cycle above tropical land. The western Pacific region, governed by the tropical oceanic diurnal cycle, has a daytime maximum (13:30 LT). In the TTL (100 hPa) and tropical lower stratosphere (56 hPa), South America and Africa differ from the maritime continent and western Pacific displaying a daytime maximum of H_2O. The MLS water vapour and cloud ice-water

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observations demonstrated a clear contribution to the TTL moistening by ice crystals overshooting over tropical land regions. The process was found to be much more effective in the southern tropics. Deep convection is responsible for the diurnal temperature variability in the same geographical areas in the lowermost stratosphere, which in turn drives the variability of H_2O.

Following results obtained by Carminati et al. (2014), we have used the opportunity of constraining CTM H_2O outputs with MLS H_2O measurements by using the assimilation techniques. The present paper intends to assess the quality of the assimilated H_2O fields to study troposphere to stratosphere transport in the tropics focusing on the H_2O budget. A companion paper will mainly deal with the scientific implications of the assimilated fields to trace the diurnal evolution of H_2O in the TTL (Carminati et al., 2016) with a temporal resolution of 1 hour.

Meteorological analyses from ARPEGE developed at Météo-France are more dehydrated in the UTLS region than the space-borne observations of the Aura Microwave Limb Sounder (MLS) instrument in the UTLS by 1 to 2 ppmv (Payra et al., 2014). Within the TRO-Pico project, the primary motivation of this study is to understand the dynamical and chemical processes affecting the H_2O budget in the tropical UTLS for the essential role in climate change through a Chemical Transport Model (CTM). The main issue is to critically diagnose and improve the CTM by the assimilation technique.

The present paper is structured as follows. Section 2 describes the observational data while section 3 presents the MOCAGE-VALENTINA assimilation system and section 4 the description of the experiments. The assimilated fields are analyzed in section 5 and validated in section 6. A sensitivity study is developed in section 7 and finally section 8 concludes the analysis.

2 Observations

2.1 Aura/MLS Water Vapour Observations

The MLS instrument on board the NASA's Earth Observing System (EOS) Aura satellite (Waters et al., 2006) provides global measurements of temperature, ice cloud, and 16 chemical species including water vapour from the upper troposphere to the upper stratosphere (Read et al., 2007; Lambert et al. 2007). The instrument measures ~3,500 vertical profiles per day in 5 spectral regions (118, 190, 240, 640 and 2500 GHz) along a sun-synchronous sub-orbital track with equatorial crossings at 01:30 AM and PM local times (LT). H_2O is retrieved from the 183-GHz H_2O rotational line spectrum within the 316 to 0.002 hPa pressure range. The present study was conducted using MLS H_2O Level 2 Version 3.3 (hereafter referred to as V3; Livesey et al., 2011) from August 2011 to March 2012. A sensitivity study has been performed in section 7 comparing the analyses with MLS H_2O V3 and MLS H_2O Level 2 Version 4.2 (hereafter referred to as V4; Livesey et al., 2015).

The H_2O profiles in V3 (V4) are characterized by a vertical resolution varying from 2 to 3.5 km (1.3 to 3.5 km) in the 316-1 hPa pressure range, and a precision greater than 20% (greater than 20%) for pressure greater than 147 hPa, 20-10% (20-7%) between 121 and 83 hPa, and less than 8% (less than 6%) between 68 and 1 hPa. The accuracy is greater than 15% for pressure greater than 147 hPa, 12-7% between 121 and 83 hPa, and less than 9% between 68 and 1 hPa for both versions (Livesey et al., 2011; 2015).

Hurst et al. (2014) reported agreement better than 1% between the National Oceanic and Atmospheric Administration (NOAA) frost point hygrometer and MLS V3 from 68 to 26 hPa over three tropical sites. At 83 and 100 hPa, statistically significant biases of 0.1 to 0.3 ppmv (3 to 8%) were found. Upper tropospheric pressure levels of 121 and 147 hPa were recently investigated in Hurst et al. (2015) in the tropics showing significant biases of 0.5 and 3.0 ppmv, respectively. MLS mean biases for MLS V4 are slightly smaller at 83, 100 and 121 hPa than for V3 (< 0.2 ppmv), but are larger at 147 hPa (~0.5 ppmv).

With a methodology approaching that of Carminati et al. (2014), we will consider in the following the 3 independent vertical layers in the TTL, at 121 hPa for the upper troposphere (UT), 100 hPa for the tropopause (TP), and 68 hPa for the lower stratosphere (LS). Figure 1 shows the monthly-averaged MLS H_2O V3 fields in the UT, TP and LS in January 2012. We clearly observe the 3 different tropical regimes depending on the layer considered. Maxima of H_2O are detected above the intense convective areas in the UT: Western Pacific, Africa and South America, and a minimum over the Maritime Continent. Minima of H_2O are detected when reaching the cold point tropopause in the TP: Western Pacific, Maritime Continent, Africa and, to a lesser extent, South America. And a zonally symmetric field of H_2O is measured in the LS with no imprint of convective activity from the UT or TP whatever the area considered.

The number of measurements per 5°×5° bin at 100 hPa is shown Figure 2 for MLS V3 H_2O fields in January 2012. We note that, in general, the tropical domain (30-50 measurements per bin) contains fewer measurements than the high latitude domain (40-60 measurements per bin) because of the sun-synchronous orbit of the AURA satellite. We also note that, in the tropics above South America, Africa and the Maritime Continent, the number of measurements per bin is less than 30 because of the presence of clouds that impacts both on the rejection of cloud-contaminated spectra and on the quality of the retrievals.

2.2 MIPAS

The limb-viewing Fourier transform spectrometer named Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) (Fischer et al., 2008) is onboard the ESA satellite Envisat. It has been designed to operate in the mid-infrared spectral region covering five spectral bands between 685 and 2410 cm−1 with an unapodized full spectral resolution of 0.025 cm^{-1}. The instrument was launched into a sun-synchronous orbit by ESA on 1 March 2002. It passes the Equator in a southwards direction 14.3 times each day at 10:00 local time. The Envisat mission, and consequently the MIPAS instrument, ended on 08 April 2012.

MIPAS run predominantly in its nominal measurement mode from July 2002 until the end of March 2004. Then, due to an instrument failure, it was operating with reduced spectral resolution (0.0625 cm^{-1}) for the benefit of an equivalent improvement in spatial sampling. The duty cycle of this so-called optimized resolution mode has been steadily increasing from 30% in January 2005 to 100% from December 2007 (Wetzel et al., 2013). MIPAS measures at 19 tangent points; tangent altitudes are latitude-dependent from 7 to 50 km over the poles and 13 to 56 km over the equator. A latitude dependent floating altitude-sampling grid is used in order to follow roughly the tropopause height along the orbit with the requirement to collect at least one spectrum within the troposphere but to avoid too many cloud-affected spectra (Chauhan et al., 2009). The instantaneous vertical field-of-view covers 3 km, i.e. oversampling is achieved in the troposphere and lower stratosphere. Due to its emission sounding capability, MIPAS records spectra of the atmosphere during day and night (Stiller et al., 2012). Retrieval of temperature and trace gases from the optimized-resolution nominal observation mode at the Institute of Meteorology and Climate Research (IMK) at the Karlsruhe Institute of Technology in cooperation with the Instituto de Astrofisica de Andalucia (IAA) is described in von Clarmann et al. (2009). The retrieval is based on constrained inverse modelling of limb radiances.

We present the results of a validation study of water vapour, version V5R_H2O_221, retrieved with the IMK/IAA (Institut für Meteorologie und Klimaforschung, Karlsruhe/Instituto de Astrofisica de Andalucia, Grenada) MIPAS scientific level 2 processor. Only valid profiles have gone into the analysis by considering a filter visibility equal to 1.

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The retrieval version is based on ESA level 1 spectra from version IPF 5. The MIPAS version V5R_H2O_221 H_2O water vapour has a vertical resolution of 2.3 km at 20 km and 6.9 km at 50 km, and the horizontal resolution is 206 km at 20 km and 436 km at 40 km. Single profile precisions are 0.2 ppmv at 10 km and 0.92 ppmv at 50 km (Tschanz et al., 2013).

Figure 1 shows the monthly-averaged MIPAS H_2O fields in the UT, TP and LS in January 2012. In the UT, MLS V3 and MIPAS H_2O fields are consistent over the tropics with maxima over the Eastern Pacific Ocean, the South of Africa, and the South of the Indian Ocean, and minima over the Maritime Continent, whilst 2 great differences occur above the Western Pacific and the South America with maxima in MLS field and minima in MIPAS field. In the TP, the Maritime Continent and Africa are strongly dehydrated (~2 ppmv) in the MLS V3 field whilst MIPAS H_2O field does not show any longitudinal gradient (~4 ppmv). Above, in the LS, MIPAS and MLS V3 H_2O fields are very consistent with each other showing a zonally symmetric field of ~4 ppmv.

The number of measurements per 5°×5° bin at 100 hPa is shown Figure 2 for MIPAS H_2O fields in January 2012. About 10-15 measurements per bin can be retrieved within the whole month, with no great differences above the continents except maybe above Africa (<10). Nevertheless, the MIPAS sampling in January 2012 (~8-15 per bin) is on average much less than the MLS V3 sampling (~30-60 per bin), and this, whatever the month considered from September 2011 to March 2012 (not shown).

3 The MOCAGE-VALENTINA assimilation system

In this study, the global atmospheric composition is simulated using MOCAGE (Modèle de Chimie Atmosphérique à Grande Echelle). It is a three-dimensional CTM developed at Météo-France (Peuch et al., 1999) which covers the planetary boundary layer, the free troposphere, and the stratosphere. It provides a number of optional configurations with

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varying domain geometries and resolutions, as well as chemical and physical parameterization packages. It has the flexibility to use several chemical schemes for stratospheric (e.g. El Amraoui et al., 2008a) and tropospheric studies (e.g. Ricaud et al., 2014), and has been validated using a large number of measurements during the Intercontinental Transport of Ozone and Precursors (ICARTT/ITOP) campaign (Bousserez et al., 2007).

MOCAGE uses a semi-Lagrangian transport scheme and includes 47 sigma-hybrid vertical levels from the surface up to 5 hPa. It has a vertical resolution of about 800 m in the vicinity of the tropopause and in the lower stratosphere. For our study, we have used a global model configuration with an horizontal resolution of 2° both in latitude and longitude, driven dynamically every 3 hours by wind, temperature, pressure, surface pressure and specific humidity fields issued from ARPEGE analyses (Courtier et al., 1991). Surface anthropogenic emission is prescribed using the Monitoring Atmospheric Composition and Climate (MACC) emission database, and fire events are accounted for by using the Global Fire Emissions Database (GFED) version 3 inventory (Randerson et al., 2013).

To sum up, the microphysical, the dynamical and the radiative schemes are all treated by ARPEGE. MOCAGE only considers the chemical scheme. Consequently, water vapour in MOCAGE is treated as a chemical species when its value is less than 10 ppmv (roughly near 150 hPa) otherwise it is treated as a meteorological parameter from ARPEGE. However, to achieve the goal of our study, namely to constrain MOCAGE H_2O as chemical species by using MLS observations, we have modified this initial treatment by enlarging the vertical domain where H_2O is considered as chemical species. More precisely, we have taken the pressure level of 135 hPa as a separating limit: i) for pressures greater than 135 hPa, H_2O is calculated directly from ARPEGE specific humidity, and ii) for pressures less than 135 hPa, the H_2O distribution is fully controlled by MOCAGE. Figure 3 gives a schematic representation of the H_2O vertical profiles used in the current study. It depicts the separating limit between ARPEGE constraints and MOCAGE chemical species.

The assimilation system used here to incorporate MLS H_2O observations in MOCAGE, is the VALENTINA system, which was initially developed in the framework of the ASSET (ASSimilation of Envisat daTa) project (Lahoz et al., 2007a), and has been used in numerous atmospheric chemistry data assimilation studies (Massart et al., 2009; El Amraoui et al., 2010; Barret et al., 2012). It is developed jointly by Météo-France and CERFACS (Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique). Herein, we used a 3D-FGAT formulation (3D-Variational in the First Guess at Appropriate Time variant; Fisher and Andersson, 2001) with an assimilation window of 1 hour to assimilate MLS H_2O observations. The VALENTINA system has the capability to include the effect of the averaging kernel, which takes into account vertical variations of the sensitivity of the retrieval to the actual H_2O mixing ratios. This technique has already produced good quality results compared to independent data especially for O_3 and CO (see e.g., El Amraoui et al., 2010; Claeyman et al., 2011).

In VALENTINA, the background error covariance matrix (B) formulation is based on the diffusion equation approach (Weaver and Courtier, 2001) and can be fully specified by means of a 3D standard deviation field (diagonal of B) and 3D fields of horizontal (L_x and L_y) and vertical (L_z) local correlation lengths. This technique has already produced good quality results compared to independent data sets, especially for O_3 and CO (see e.g., Abida et al., 2016; El Amraoui et al., 2010; Claeyman et al., 2011).

4 Description of the experiments

It is worth pointing out that H_2O as a chemical species in MOCAGE (135-5 hPa pressure range) is suffering from a strong systematic bias in the UTLS region, especially in

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the tropics. Hence, in order to reduce the magnitude of this bias, we performed a relatively long assimilation run of 6-month duration using MLS V3 (and also MLS V4) observations from 1 August 2011 to 31 January 2012.

The most crucial ingredient in a variational assimilation procedure is the background error covariance matrix, B, which spreads out information extracted from observations in the vertical and horizontal directions in space and weights the importance of the *a priori* state. For this study, we used a simple parameterization for the B matrix. The horizontal correlation lengths (L_x and L_y) are taken to be homogeneous and equal to about 200 km. The vertical correlation length L_z is set to one vertical model grid point. Similarly to Emili et al. (2014), the background standard deviation 3D field (model error) is parameterized as a vertically varying percentage of the background profile. Roughly, it is set to 45% up to 135 hPa, 35% in 135-50 hPa, and to 15% in 50-5 hPa.

The long-run experiment is initialized on 1 August 2011 at 00:00 UTC from a climatological state. In the assimilation process, only MLS H_2O measurements which are in the 316-5 hPa pressure range are used (Figure 3). When taking into account MLS averaging kernels in the assimilation procedure, we found unrealistic values in some regions. Hence, only H_2O measurements and their associated errors are incorporated in our 3D-FGAT assimilation process. Note that the MLS observations will constrain only the model in 135-5 hPa pressure range where H_2O is freely evolving as a chemical species. In contrast, in 316-135 hPa pressure range, the information extracted from the observations is completely lost each time the MOCAGE H_2O field is updated by the ARPEGE constraint (Figure 3).

Figure 4 shows the temporal evolution of Observations-minus-Forecast (OmF) during the whole long-run assimilation experiment at three MLS pressure levels 121.15, 100, and 68.13 hPa. The MLS assimilated observations minus their model-equivalent values are averaged over the tropics (30°S-30°N) for each hour. The model forecast is initially high

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biased with respect to MLS observations, from about –4 ppmv at 121 hPa, about -2 ppmv at 100 hPa and ±0.1 ppmv at 68 hPa on 1st August 2011. The OmF magnitude decreases gradually with time over the whole long-run experiment time period. It takes about four months of assimilation to reach a model forecast state with minimum values of OmF reduced to: ±0.2 ppmv at 121 hPa, ±0.1 ppmv 100 hPa and ±0.05 ppmv at 68 hPa by December 2011. This emphasizes the extreme difficulty of constraining MOCAGE H_2O field, which is marked by important biases, by assimilating only MLS measurements.

On 1 December 2011 at 00:00 UTC, a free model simulation (without assimilating MLS observations) is performed by initializing from the obtained analysis state. The H_2O field analyses is compared with those from the free run in order to quantify the corrections brought by the MLS measurements in the model.

5 The assimilated fields

The analyses are produced from 1st November 2011 to 31st March 2013; however, the study concentrates on monthly-averaged H_2O fields in January and February 2012. Three levels will be studied in detail: 121 hPa (UT), 100 hPa (TP) and 68 hPa (LS). Because we used different data sets calculated or measured at different times and locations not necessarily consistent within all the data sets, the analyses will be presented within 3 spaces in time and space coincidences with MLS and MIPAS observations and with the model outputs.

5.1 Vertical profiles in the tropics

In order to highlight the quality of the different data sets used in our study around the tropical tropopause, Figure 5 shows the vertical profiles of zonally-averaged H_2O in January 2012 over the tropical UTLS (30°N–30°S) in the MLS observation space from background, MLS, MIPAS, ARPEGE and the assimilated field (MLS analyses). First of all, it is noted that the vertical distribution of the MLS analyses is consistent with the MLS data. The background field is wetter than the MLS analyses in the UT (~1.5 ppmv at 150 hPa) and is consistent with the MLS analyses in the LS above 80 hPa. The ARPEGE field although wetter in the UT (~1.5 ppmv at 150 hPa) is drier than the MLS analyses around the tropopause from 120 to 50 hPa with a minimum of ~2.5 ppmv at 80 hPa. Finally, it is noted that the MIPAS field is drier by 1.5 ppmv than the MLS analyses below 130 hPa, wetter by 1 ppmv from 130 to 70 hPa, and drier by 0.5 ppmv from 70 to 40 hPa.

Because of the great longitudinal variability of H_2O in the tropics, we have separated all the data into 4 main boxes, namely Eastern Pacific (30°S-21°N, 176°W-114°W), Southern America (30°S-12°N, 86°W-30°W), Southern Africa (30°S-12°N, 2°E-46°E) and the Maritime Continent (30°S-18°N, 90°E-160°E). Figure 6 shows the same fields as in Figure 5 but separated into the 4 above-mentioned areas. The 5 data sets show the same general features, namely a wet UT, a dry LS, and an hygropause (minimum of H_2O) around the tropopause whatever the box considered. Although all the data sets are consistent in the LS (40-60 hPa), some differences are worthwhile discussing. Among all the 4 domains, the Maritime Continent shows, on average, the wettest UT (10.5-12.5 ppmv at 140 hPa for all the data sets except MIPAS), and the driest hygropause (less than 2 ppmv for ARPEGE) because the tropopause is the coldest over this domain compared to all the other domains. In the UT, MIPAS data is on average much drier than all the other data sets by 4-7 ppmv, except over the Eastern Pacific. The fact that MIPAS behaves very differently compared to all the other data sets above the Maritime Continent might be a consequence of the systematic presence of clouds over this area. Since cloud contaminated spectra are discarded in the MIPAS analysis, a sampling bias towards a drier atmosphere might be generated. Around the tropopause, the hygropause is located either at 100 hPa (MLS and MLS analyses) or 80 hPa (ARPEGE, MIPAS, background). A local maximum is systematically detected around 60 hPa over the 4

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geographical domains in the MLS, MLS analyses and background data sets, although absent in the MIPAS and ARPEGE data sets.

5.2 Global distribution in the MLS space

The data sets are now studied at global scale along 3 different pressure levels: 121 hPa (UT), 100 hPa (TP) and 68 hPa (LS). In this study, we will mainly analyze the tropical band (30°S-30°N). The monthly-averaged H_2O fields representative of January 2012 in the MLS space (namely in time and space coincidence with the MLS observations) from the Free Run (MOCAGE), ARPEGE, MLS analyses and the background are displayed in Figures 7-9 at 121, 100 and 68 hPa, respectively.

At 121 hPa (Fig. 7), all the data sets show local maxima above the South American and the African continents, the Central Pacific, and the Maritime Continent, namely where convective systems are the most intense and the most efficient to bring high humidity from the lowermost to the uppermost troposphere. Both the Free Run and the background data sets are highly hydrated with maxima around or greater than 8 ppmv whilst the MLS analyses and the ARPEGE data sets show maxima of about 5-6 ppmv. ARPEGE should represent the "true" world in the UT. Although all the other data sets are wetter than ARPEGE, the analyses are drier than the background by about 1 ppmv consistently with the MLS data field (Fig. 1), underlining the positive impact of the assimilation technique to constraint the background by the observations.

At 100 hPa (Fig. 8), the 4 H_2O fields tend to show different behaviours. ARPEGE and the analyses exhibit a dehydrated tropopause (< 3 ppmv) whilst the background shows some local maxima above the continents (5-6 ppmv) and the Free Run a highly hydrated tropopause with values much greater than 8 ppmv above the continent sand the Indian Ocean. The Free Run, namely MOCAGE, cannot reproduce the dehydrated tropopause since it does not contain any microphysical processes to transform supersaturated air into ice particles over convective continental and ocean areas. The background field is not as hydrated as the Free Run as a consequence of the assimilation process but is nevertheless wetter than the "true" atmosphere as represented by ARPEGE. The assimilation technique efficiently constraint the background by the MLS observations to produce analyses much drier by 2-3 ppmv than the background fields, although slightly wetter than ARPEGE by about 1 ppmv but with consistent local minima above the South American, African and Maritime continents, as in MLS (Fig. 1).

At 68 hPa (Fig. 9), the Free Run and ARPEGE data sets strongly differ to each other but also differ to MLS analyses and background with a wet atmosphere in the Free Run (5-8 ppmv), a dry atmosphere in ARPEGE (1-4 ppmv) and a moderately dry atmosphere in the analyses and background around 4 ppmv. The Free Run data set is too much affected by the tropospheric injection of wet airmasses and cannot cope with supersaturation as explained at 100 hPa. ARPEGE tends to systematically show a dry lower stratosphere probably because of the impact of a dry bias in the meteorological soundings above the tropopause. The background and the analyses are very consistent to each other and to MLS (see Fig. 1), underlining the fact that the assimilation technique has produced a H_2O field very close to the MLS observations.

5.3 Global distribution in the Model space

The monthly-averaged H_2O fields representative of January 2012 in the model space (namely in time and space coincidence with the MOCAGE and ARPEGE outputs) from the Free Run (MOCAGE), ARPEGE, MLS analyses and the background are displayed in Figures 10-12 at 121, 100 and 68 hPa, respectively. At 121 hPa (Fig. 10), a very wet atmosphere is calculated in the Free Run, the background and the analyses with local maxima above the

South American, the African and the Maritime continents (> 7 ppmv) although ARPEGE and MLS (Fig. 1) are much drier with local maxima of 5 and 6 ppmv, respectively. Since the background and the analyses are almost identical in the model space contrarily to what has been observed in the MLS space (see previous section), this means that the MLS observations are too sparse both in time and space to optimally constraint the background field. In other words, outside of the assimilation window and outside of the horizontal domain where MLS observations are taken, the assimilation system tends to converge to a background state strongly influenced by the too wet Free Run.

At 100 hPa (Fig. 11), the impact of the Free run to the background is less important since the tropical tropopause of the background and of the analyses (4-6 ppmv) is much less hydrated than the Free run tropopause (> 8 ppmv) but still wetter than both ARPEGE and MLS observations (< 3 ppmv). As at 121 hPa, the background and the analyses are almost identical in the model space.

At 68 hPa (Fig. 12), the background and the MLS analyses (~4 ppmv) are very consistent with the MLS observations (Fig. 1), whilst ARPEGE is much drier (< 2 ppmv) and the Free run is much wetter (> 6 ppmv). The assimilation system behaves nominally in the lower stratosphere since the background is no longer affected by the Free Run even outside of the assimilation window when and where the MLS observations are taken into account.

6 Validation of the assimilated fields

In order to validate the analyses, we have considered both the MIPAS data sets and the assimilated fields in the MIPAS space (namely in time and space coincidence with the MIPAS observations). The monthly-averaged H_2O fields representative of January 2012 in the MIPAS space from the Free Run (MOCAGE), ARPEGE, MLS analyses and the background are displayed in Figures 13-15 at 121, 100 and 68 hPa, respectively. At 121 hPa

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(Fig. 13), as in the model space, the analyses show a very wet upper troposphere (> 8 ppmv) above the continents consistently with the background and the Free run, but in contrast to ARPEGE (local maxima of 6 ppmv) and MIPAS observations (Fig. 1, maxima of ~7 ppmv). It nevertheless seems that the MIPAS observations above convective areas (Southern America, Africa and the Maritime continent) are dry biased compared to MLS observations (as already discussed in section 2.2). This is probably due to the impact of the cloud presence in the line of sight diminishing the number of available observations (see Fig. 2). Indeed, MLS microwave observations are in general less affected by clouds than the MIPAS IR observations, consequently the MIPAS H_2O field is given in a cloud-free atmosphere. The MLS and MIPAS measurements occur at two different local times (01:40 am/pm for MLS and 10:00 am/pm for MIPAS). Because of the diurnal cycle of the convective activity (Liu and Zipser, 2009) that differs above ocean (maximum in local morning) and continents (maximum in local afternoon), the MIPAS observations are probably more affected by upper tropospheric clouds than the MLS observations, both over the continent and the ocean. Chauhan et al. (2009) and Montoux et al. (2009) tried to clarify this cloud issue by different approaches but could not clearly identify a consistent picture except the strong effects of clouds within the presented comparison. They also suggested that the observed H_2O variability may be contaminated by the presence of clouds in the UTLS. Another issue is the altitude resolution of the MIPAS retrievals (Milz et al., 2005) in the lowermost layers at 121 and 100 hPa that may be too coarse (4.5-6.5 km) to allow a direct comparison without application of averaging kernels.

At 100 hPa (Fig. 14), the analyses are very consistent with the MIPAS observations (Fig. 1, ~4 ppmv) except above the South American, the African and the Maritime continents where the analyses are wetter by 1-2 ppmv. The background and the analyses are identical and differ from the wet Free run (> 8 ppmv) and the dry ARPEGE (< 2 ppmv) tropopause.

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The dehydration observed by MLS (Fig. 1) and by ARPEGE above the Maritime Continent is not reproduced by the analyses, probably because the Free run is far too wet (> 8 ppmv) above this area and the assimilation system cannot cope with such a difference with the sparse MLS observations.

At 68 hPa (Fig. 15), the analyses and the background are very consistent with the MIPAS observations (~4 ppmv) with no longitudinal gradient although the Free run and ARPEGE are wetter (~7 ppmv) and drier (< 2 ppmv), respectively. This tends to show that the assimilation system is working properly in the lower stratosphere, despite the fact that the MLS observations are sparse both in time and space.

To summarize, in the MLS space, the analyses behave consistently with the MLS observations from the upper troposphere to the lower stratosphere (121-68 hPa). In the model space, the analyses are wetter than the “true” atmosphere as represented by ARPEGE and MLS in the upper troposphere (121 hPa) and around the tropopause (100 hPa) but consistent with MLS and MIPAS in the lower stratosphere. In the MIPAS space, the sensitivity and the vertical resolution of the MIPAS data set at 121 and 100 hPa prevent to assess the behaviour of the analyses particularly over intense convective areas as the Southern American, the African and the Maritime continents but, in the lower stratosphere (68 hPa), the analyses are very consistent with MIPAS.

7 Sensitivity studies

We have used the opportunity of getting two versions of the MLS data to check the sensitivity of the assimilation technique to this parameter that affects both the quality of the data and the number of data available. But before, we have investigated the impact of some periods with no measurements onto the assimilated fields induced by the fact that, in this configuration, the background returns back to the Free run.

7.1 Periods with no measurements

We have already noticed that the H_2O analyses in the tropical UTLS in the model and the MIPAS spaces were very sensitive to the background and consequently to the Free run producing an atmosphere in the upper troposphere and in the tropopause wetter than in the MLS space. We investigate here the impact of periods of no MLS measurements on the H_2O analyses during the assimilation time frame of one month. Two consecutive months are very interesting to consider. In January 2012, MLS has been operating nominally and 31 days of measurements are available for the assimilation study. At the opposite, in February 2012, 4 days of measurements were unavailable, thus the assimilation process used MLS data over the time frame: 1-19 and 24-29 February.

The relative difference between the monthly-averaged H_2O fields from the observations and the assimilation in January and in February 2012 at 121, 100 and 68 hPa is shown in Figure 16. The impact of the missing data in February 2012 on the analyses compared to the January 2012 is clearly depicted since the Observation-minus-Analysis is, in absolute, greater in February than in January: -6% vs. -4% at 121 hPa, +4% vs. +2% at 100 hPa and –2% vs. +1% at 68 hPa in February vs. January 2012, respectively. When the MLS data are no longer available, the background field tends to be redirected towards the Free run, losing the memory of the MLS-driving information injected in the assimilation system.

7.2 Improvement of the data quality

In this section, we investigated the impact of using two versions of the MLS data on the assimilation fields because the version affects both the quality of the data and the number of data available. The MLS V3 and V4 are presented in section 2.1. Official documentation (Livesey et al., 2015) indicates an improvement in the cloud screening and first guess estimation from V3 to V4, which yielded better agreements with truth in simulation studies. As an example, Figure 17 shows for January 2012 the number of measurements per 5°×5° bin considering the MLS V4 data and the difference between the V4 and the V3 data. In the tropics, the number of measurements per bin in V4 is about 15 measurements per bin more than in V3, particularly over the Southern American, the African and the Maritime continents, and the Indian Ocean. This clearly shows a change both in the cloud treatment and in the data quality of V4 compared to V3.

In a similar way as performed with the MLS V3, the assimilation process has thus been conducted with the MLS V4 data from 1st November 2011 to 31st March 2013, namely with a background error set to 45% up to 135 hPa, 35% in 135-50 hPa, and to 15% in 50-5 hPa (see section 4 for the other parameters). The monthly-averaged analyses in January 2012 at 121, 100 and 68 hPa are presented in Figures 18-20 in the MLS, model and MIPAS spaces, respectively together with the difference between the V4 and the V3 analyses. In the MLS space (Fig. 18), both versions show the same structures (maxima at 121 hPa and minima at 100 hPa over the convective areas) in the upper troposphere and the tropopause whilst a zonally-symmetric field is detected in the tropical band in the lower stratosphere (68 hPa). However, V4 analyses compared to V3 analyses tends to show a much wetter atmosphere in the tropical upper troposphere and lower stratosphere by 10% and 15%, respectively and, at the tropopause, a slightly drier atmosphere by 2-3%. Consequently, the difference in the analyses between the two versions in the tropics is only significant at 121 and 68 hPa i.e. greater than the minimum measurable value of 0.1 ppmv estimated in Livesey et al. (2011, 2015).

In the model space (Fig. 19), the two analyses behave differently depending on the level and the area considered. Above the convective areas such as the Southern American, the African and the Maritime continents, the atmosphere is much drier in V4 compared to V3 by

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10%, 20% and 5% at 121, 100 and 68 hPa, respectively. Outside of these convective areas, the V4 compared to the V3 atmosphere is wetter by 10% at 121 hPa, and drier by about 5-10% at 100 and 68 hPa. This clearly shows the impact of V4 quality induced by cloud-screening methodology on the analyses over convective areas where the presence of clouds is prominent. Finally, in the MIPAS space (Fig. 20), the conclusions drawn for the model space are mainly the same: V4 analyses drier than V3 above the convective areas at the 3 levels considered and, outside of the convective areas, wetter V4 analyses at 121 hPa and drier above.

8 Conclusions

Water vapour (H_2O) in the tropical UTLS is known to play an important role in many aspects of meteorology, including radiation, dynamics, chemistry and climate change. Modelling of water in the UTLS is very challenging because it varies in space and time due to its rapid phase change (liquid, solid and gas). The representation of H_2O in the tropical UTLS from observations and from models does not necessarily converge since some caveats are detectable that impact on the measured or calculated H_2O fields, e.g. presence of clouds, in the observation, cloud microphysics in the model.

Within the French project "Multiscale water budget in the upper troposphere and lower stratosphere in the TROpics" (TRO-pico), a global-scale analysis has been set up based on space-borne measurements, model and assimilation techniques to study the time evolution of H_2O in the tropical UTLS. The MOCAGE-VALENTINA assimilation tool has been used to assimilate the Aura MLS version 3.3 H_2O measurements within the 316-5 hPa range with an assimilation window of 1 hour. The time period spans from 1st August 2011 to 31st March 2013 but the study concentrates on monthly-averaged H_2O fields in January and February 2012. Some diagnostics have been developed to assess the quality of the assimilated H_2O

fields depending on several parameters: model error, observation minus analysis and observation minus forecast. As a validation exercise, comparisons with 2 independent sources of H_2O in the UTLS have been performed based on the spaceborne MIPAS measurements and on the meteorological ARPEGE analyses. Sensitivity studies of the analyzed fields have been done 1) considering periods when no MLS measurements are available and 2) using another MLS version 4.2 H_2O data. The studies have been performed within 3 different spaces in time and space coincidences with the MLS and MIPAS observations and with the model outputs and at 3 different levels: 121 hPa (upper troposphere), 100 hPa (tropopause), and 68 hPa (lower stratosphere).

In the MLS space, the analyses behave consistently with the MLS observations from the upper troposphere to the lower stratosphere. In the model space, the analyses are wetter than the “true” atmosphere as represented by ARPEGE and MLS in the upper troposphere (121 hPa) and around the tropopause (100 hPa) but consistent with MLS and MIPAS in the lower stratosphere. In the MIPAS space, the sensitivity and the vertical resolution of the MIPAS data set at 121 and 100 hPa prevent to assess the behaviour of the analyses particularly over intense convective areas as the Southern American, the African and the Maritime continents but, in the lower stratosphere (68 hPa), the analyses are very consistent with MIPAS. Sensitivity studies show the great improvement on the H_2O analyses in the tropical UTLS when assimilating spaceborne measurements of better quality particularly over the convective areas.

The analyses obtained from November 2011 (August-October 2011 is considered as a spin-up period) to March 2013 are being used to assess the impact of the continental convective activity on the diurnal cycle of H_2O in the tropical UTLS above the Southern American continent (Carminati et al., 2016) with a temporal resolution of 1 hour. The same methodology could be employed over the Indian Ocean, the Maritime continent and the

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Tibetan Plateau to quantify the impact of the cyclone, the maritime convection and the continental convection processes, respectively on the H_2O budget in the UTLS.

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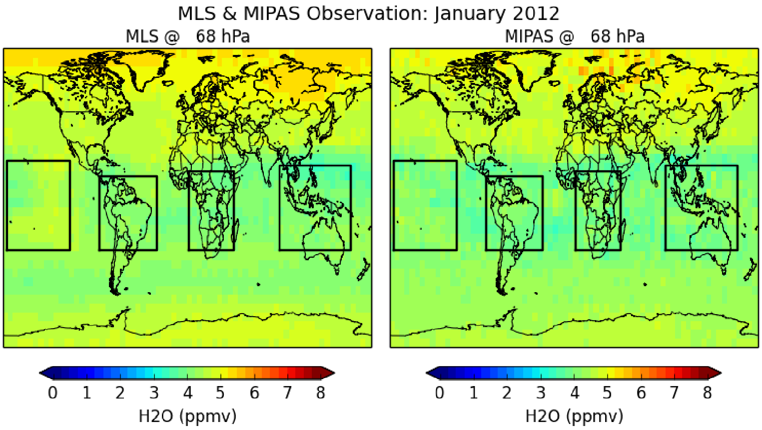
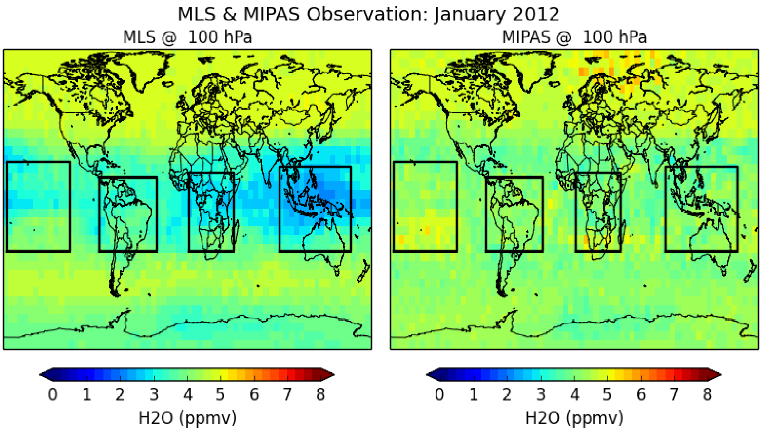
Figure Captions





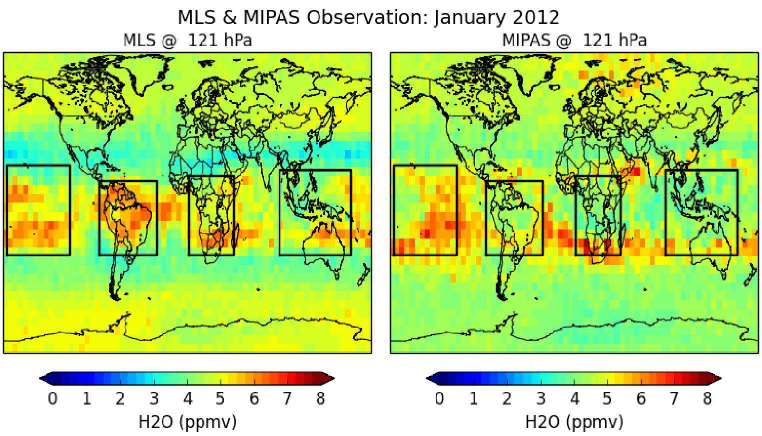


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Figure 1: (Upper panel) Monthly-averaged H_2O fields at 68 hPa in January 2012 in the MLS (left) and MIPAS (right) observation space (in space and time coincidence with MLS and MIPAS observations, respectively). (Middle Panel) Same as the upper panel but at 100 hPa. (Lower Panel) Same as the upper panel but at 121 hPa.

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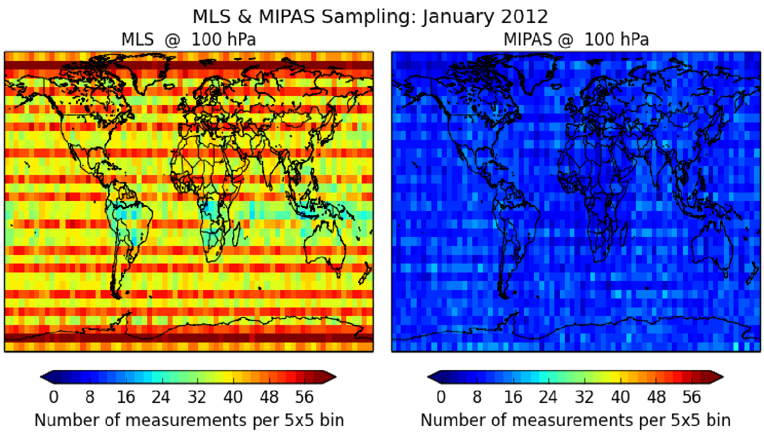

Figure 2: Number of measurements averaged within 5°x5° bins at 100 hPa in January 2012 in the MLS (left) and MIPAS (right) data sets.

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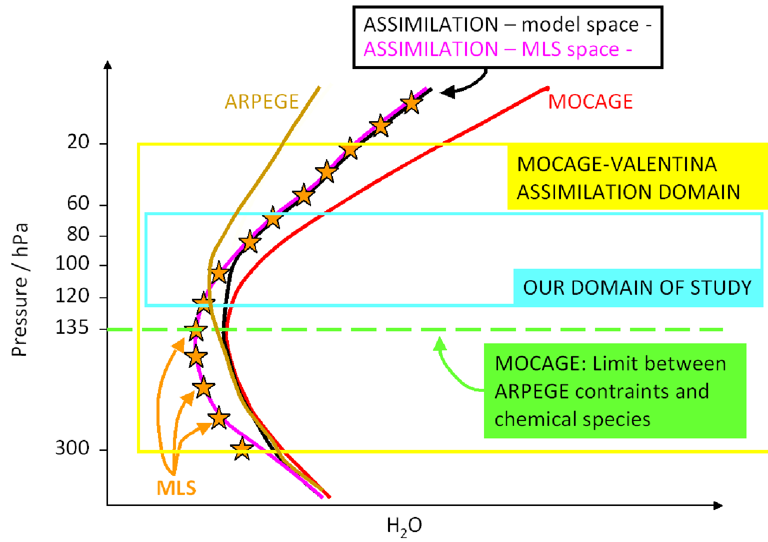

Figure 3: Schematic representation of the H_2O vertical profiles used in the present analysis: MLS (orange stars), MOCAGE (red line), ARPEGE (green line), assimilation in the MLS space (in time and space coincidence with MLS observations, pink line), and assimilation in the model space (in time and space coincidence with the model outputs, purple line). In MOCAGE, H2O is constrained to ARPEGE meteorological analyses below 135 hPa (horizontal dashed green line) and is considered as a chemical species above 135 hPa. MLS observations are assimilated from 300 to 20 hPa. Our domain of study relies from 121 to 68 hPa in the tropics.

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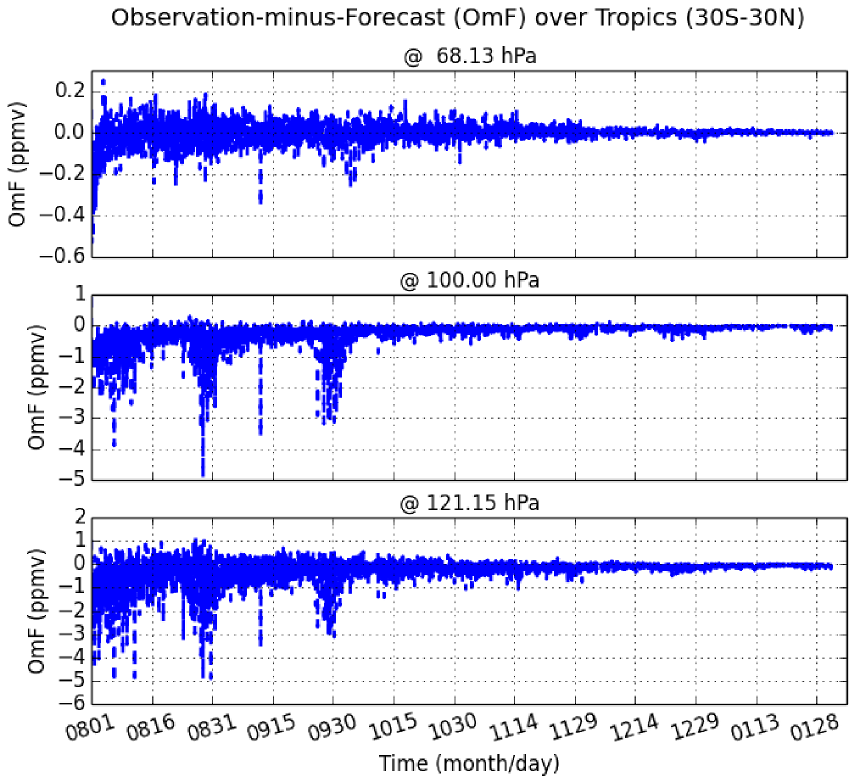


Figure 4: Observations minus forecasts zonally averaged over the tropics (30°S-30°N) from 1 August 2011 to 31 January 2012 at 121 hPa (bottom), 100 hPa (middle) and 68 hPa (top).

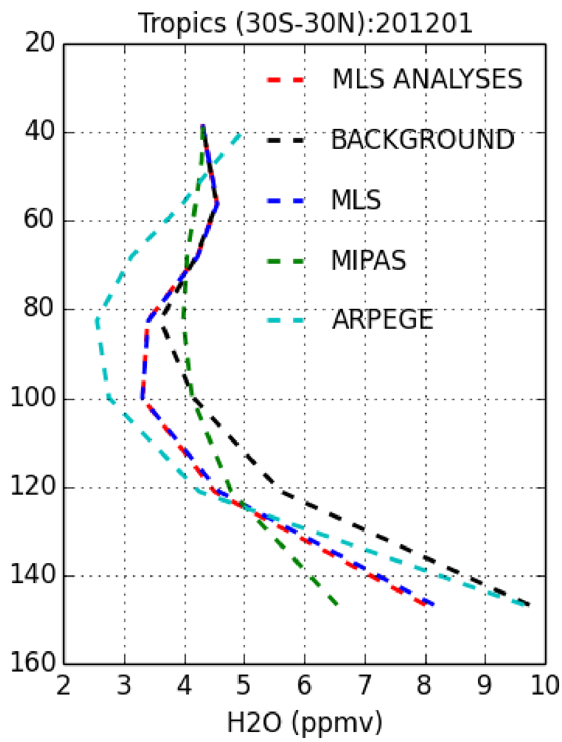
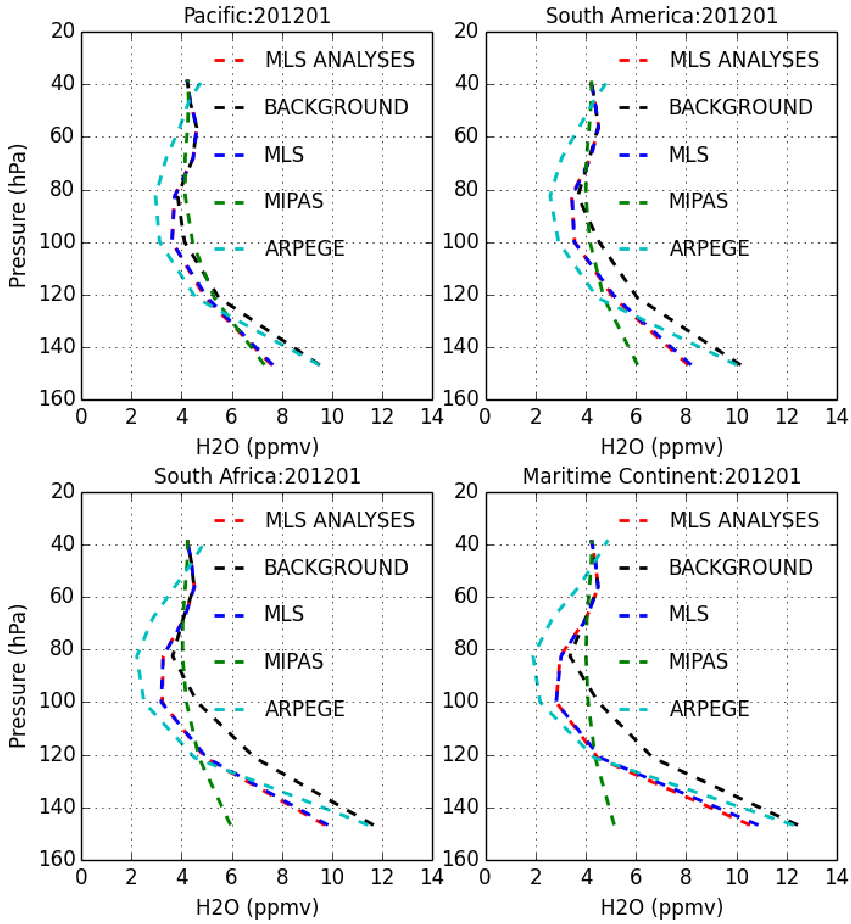


Figure 5: Monthly-averaged vertical profiles of H_2O in the tropical UTLS (30°S-30°N) in January 2012 in the MLS observation space from MLS analyses (red dashed line), Background (black dashed line), MLS (blue dashed line), MIPAS (green dashed line) and ARPEGE (light blue line).



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963 **Figure 6:** Monthly-averaged vertical profiles of H_2O in January 2012 in the MLS observation
964 space from MLS analyses (red dashed line), Background (black dashed line), MLS (blue
965 dashed line), MIPAS (green dashed line) and ARPEGE (light blue line) in four different
966 tropical areas (see Figure 1): Pacific Ocean (upper left), South America (upper right), South
967 Africa (lower left) and Maritime Continent (lower right).

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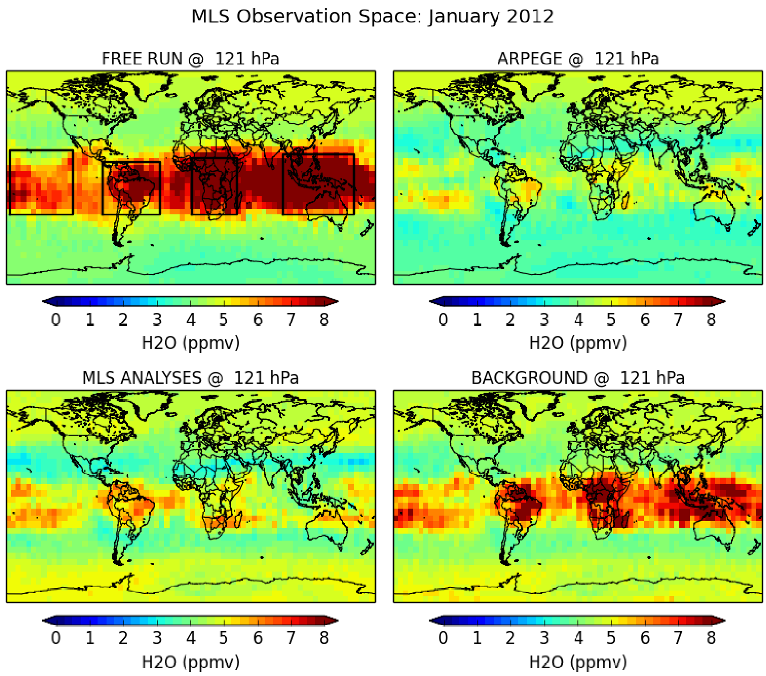

Figure 7: Monthly-averaged H_2O fields at 121 hPa in January 2012 in the MLS observation space (in time and space coincidence with MLS observations) from the Free Run (MOCAGE, upper left), ARPEGE (upper right), MLS analyses (assimilation, lower left) and the background (lower right).

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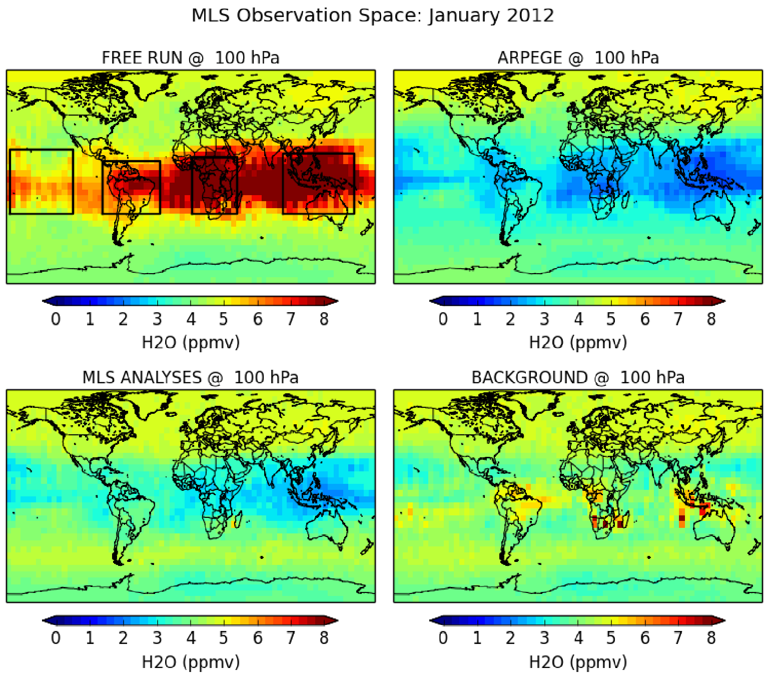

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978 **Figure 8:** Monthly-averaged H_2O fields at 100 hPa in January 2012 in the MLS observation
979 space (in time and space coincidence with MLS observations) from the Free Run (MOCAGE,
980 upper left), ARPEGE (upper right), MLS analyses (assimilation, lower left) and the
981 background (lower right).

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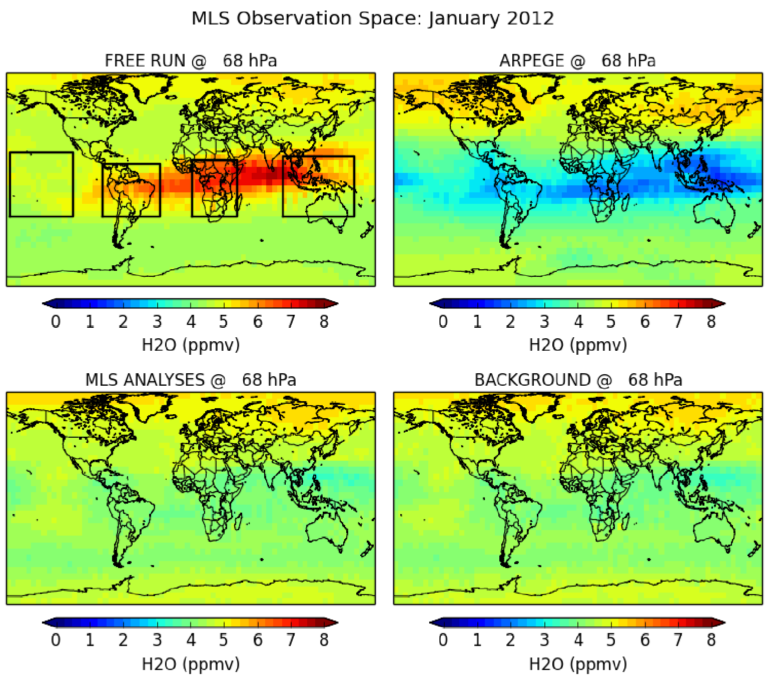

Figure 9: Monthly-averaged H_2O fields at 68 hPa in January 2012 in the MLS observation space (in time and space coincidence with MLS observations) from the Free Run (MOCAGE, upper left), ARPEGE (upper right), MLS analyses (assimilation, lower left) and the background (lower right).

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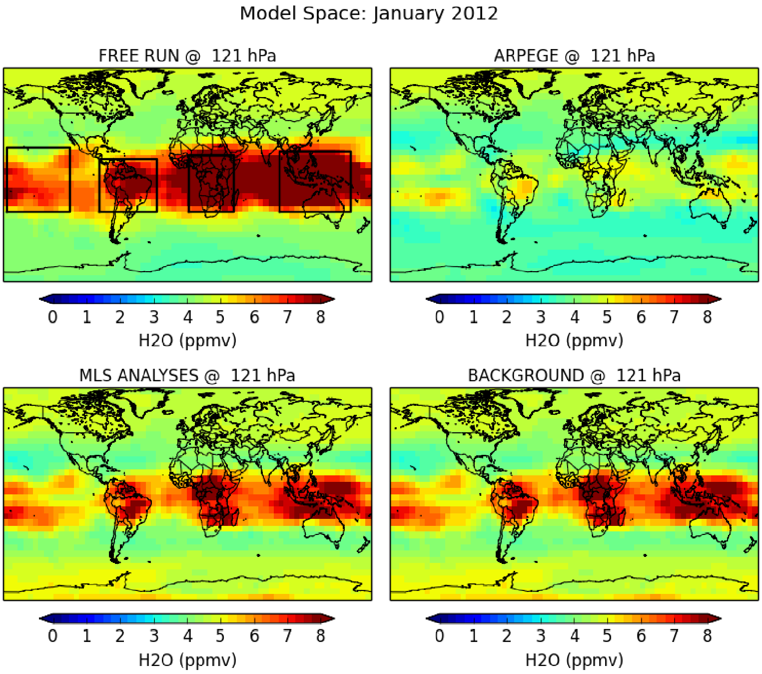

Figure 10: Monthly-averaged H_2O fields at 121 hPa in January 2012 in the Model space (in the Model grid and time samplings) from the Free Run (MOCAGE, upper left), ARPEGE (upper right), MLS analyses (assimilation, lower left) and the background (lower right).

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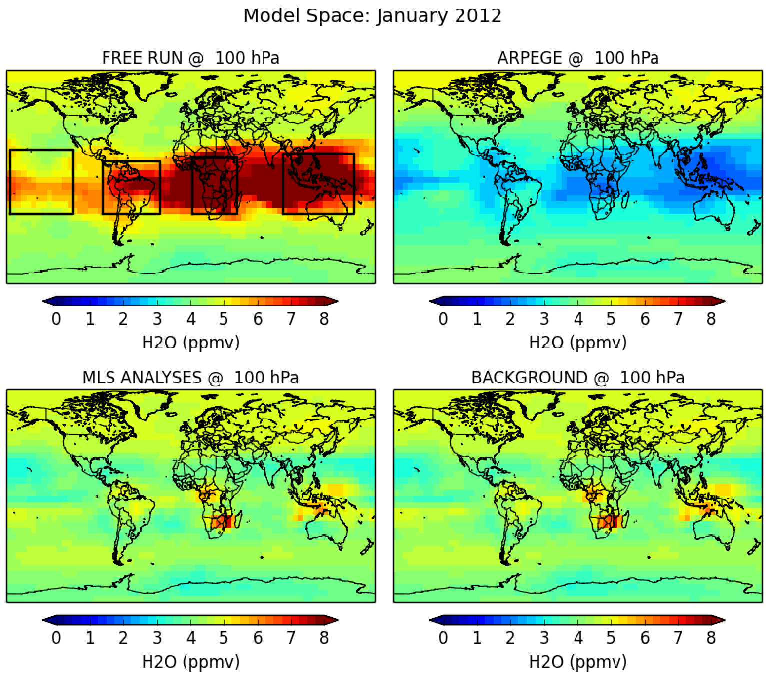

Figure 11: Monthly-averaged H_2O fields at 100 hPa in January 2012 in the Model space (in the Model grid and time samplings) from the Free Run (MOCAGE, upper left), ARPEGE (upper right), MLS analyses (assimilation, lower left) and the background (lower right).

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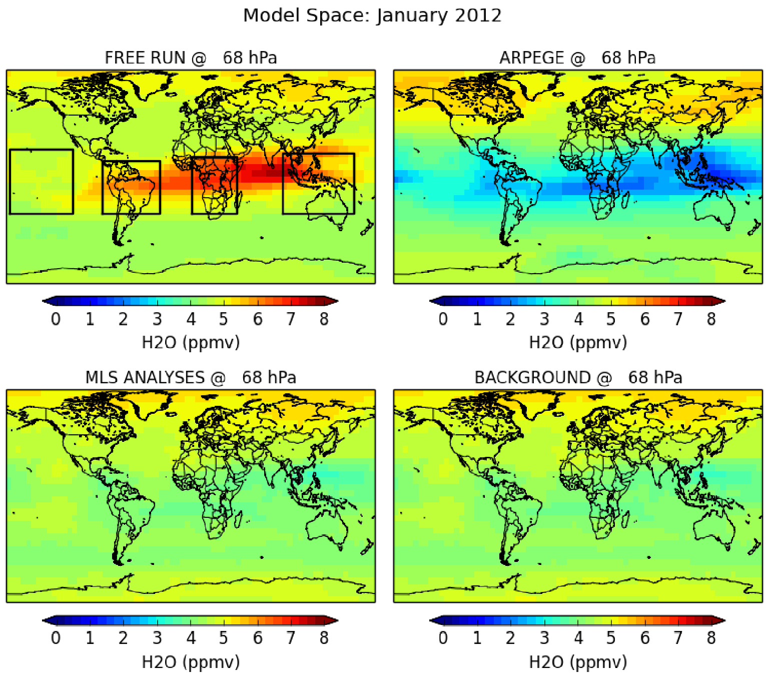
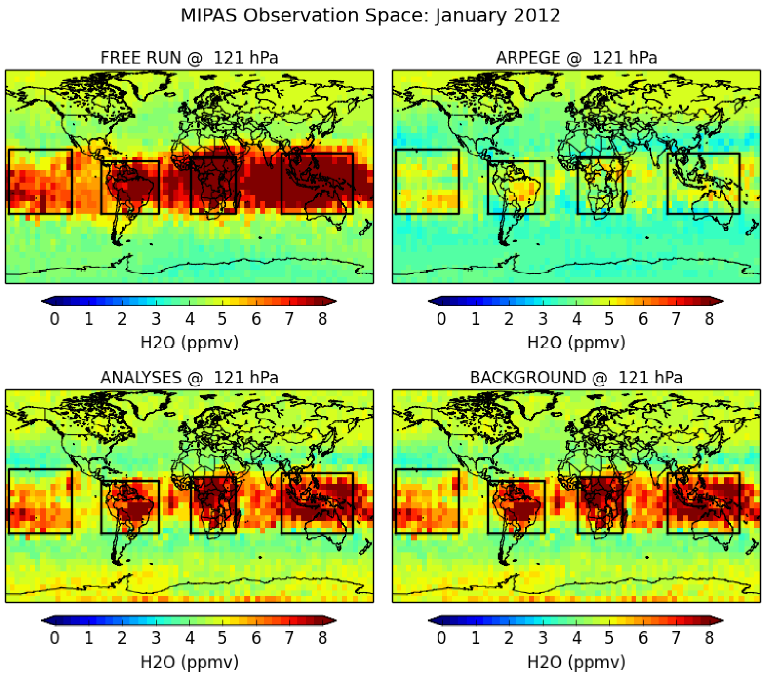


Figure 12: Monthly-averaged H_2O fields at 68 hPa in January 2012 in the Model space (in the Model grid and time samplings) from the Free Run (MOCAGE, upper left), ARPEGE (upper right), MLS analyses (assimilation, lower left) and the background (lower right).



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1004 **Figure 13:** Monthly-averaged H_2O fields at 121 hPa in January 2012 in the MIPAS

1005 observation space (in time and space coincidence with MIPAS observations) from the Free

1006 Run (MOCAGE, upper left), ARPEGE (upper right), MLS analyses (assimilation, lower left)

1007 and the background (lower right).

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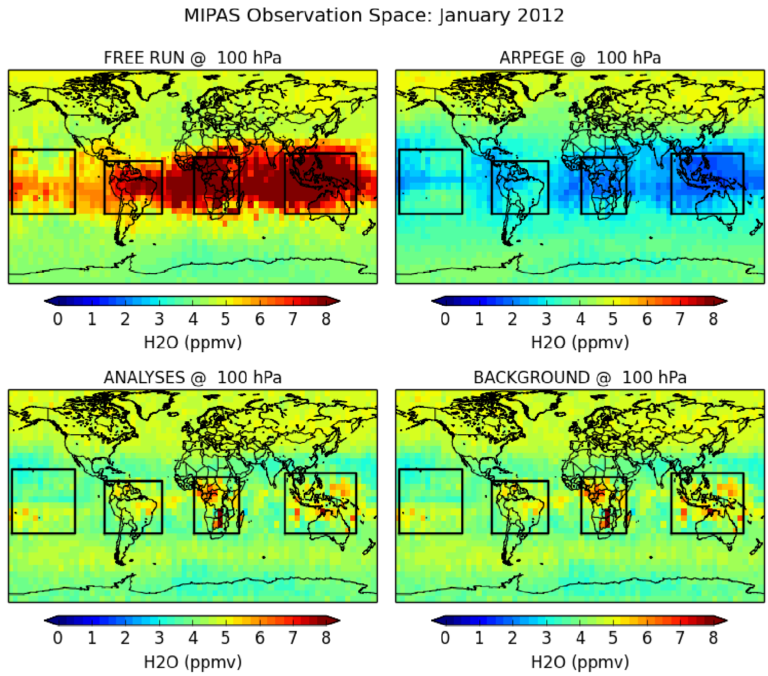

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1010 **Figure 14:** Monthly-averaged H_2O fields at 100 hPa in January 2012 in the MIPAS
1011 observation space (in time and space coincidence with MIPAS observations) from the Free
1012 Run (MOCAGE, upper left), ARPEGE (upper right), MLS analyses (assimilation, lower left)
1013 and the background (lower right).

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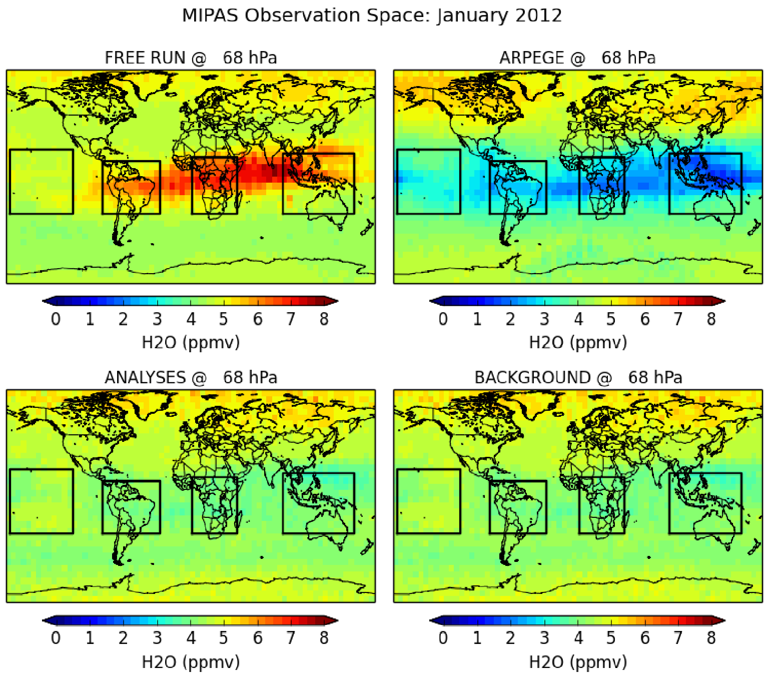

Figure 15: Monthly-averaged H_2O fields at 68 hPa in January 2012 in the MIPAS observation space (in time and space coincidence with MIPAS observations) from the Free Run (MOCAGE, upper left), ARPEGE (upper right), MLS analyses (assimilation, lower left) and the background (lower right).

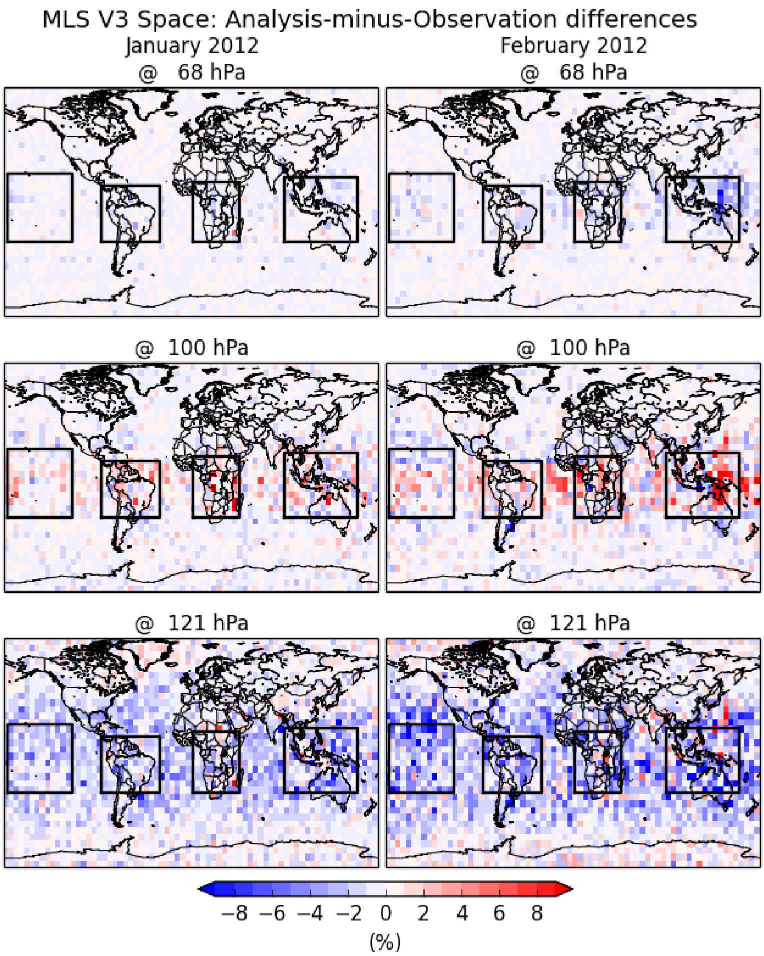

Figure 16: Relative difference between the H_2O fields from the observation and the assimilation in January 2012 (left) and in February 2012 (right) at 121 hPa (bottom), 100 hPa (middle) and 68 hPa (top).

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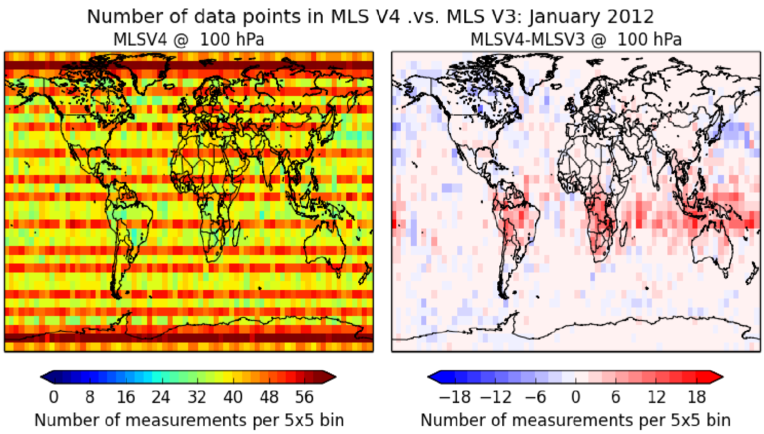

Figure 17: Number of measurements averaged within 5°x5° bins at 100 hPa in January 2012 in the MLS V4 data set (left). Difference between the number of measurements averaged within 5°x5° bins at 100 hPa in January 2012 in the MLS V4 and the MLS V3 data sets (right).

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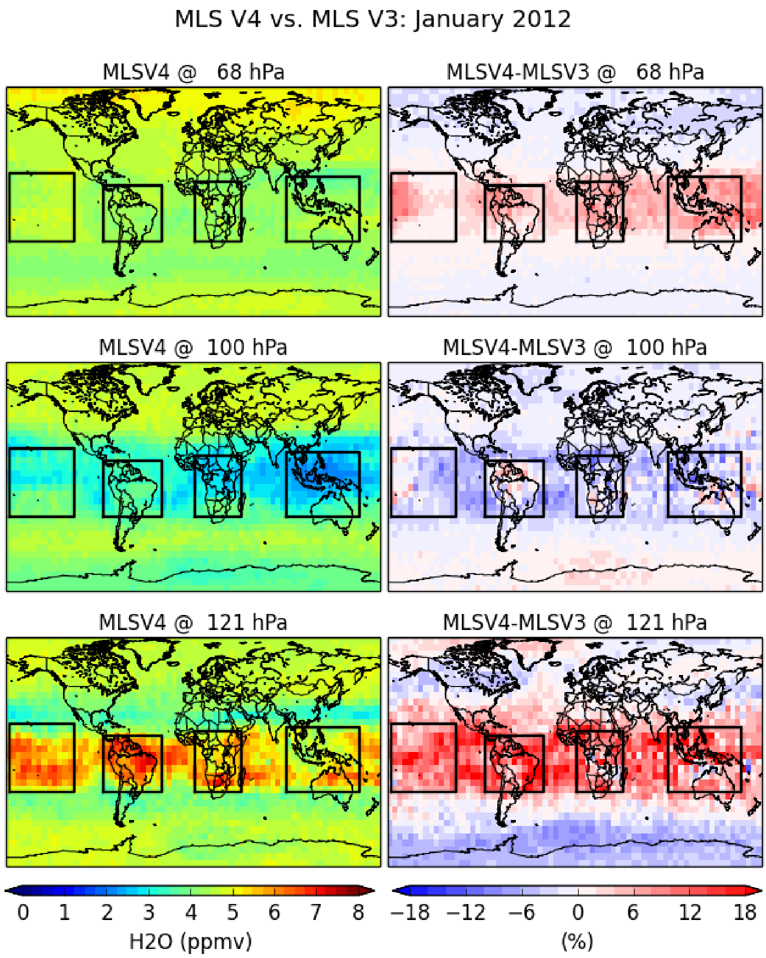

Figure 18: Monthly-averaged H_2O analyses in the MLS space in January 2012 using the MLS V4 data set (left) and relative difference between the MLS analyses using V4 and V3 data sets (right) at 121 hPa (bottom), 100 hPa (middle) and 68 hPa (top).

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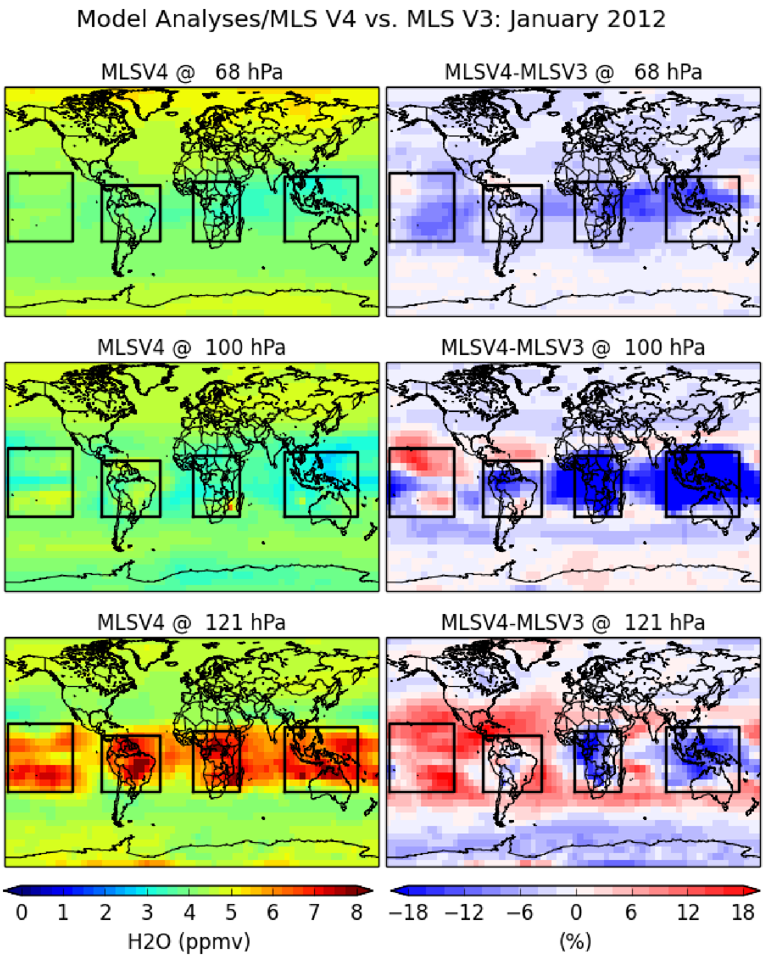
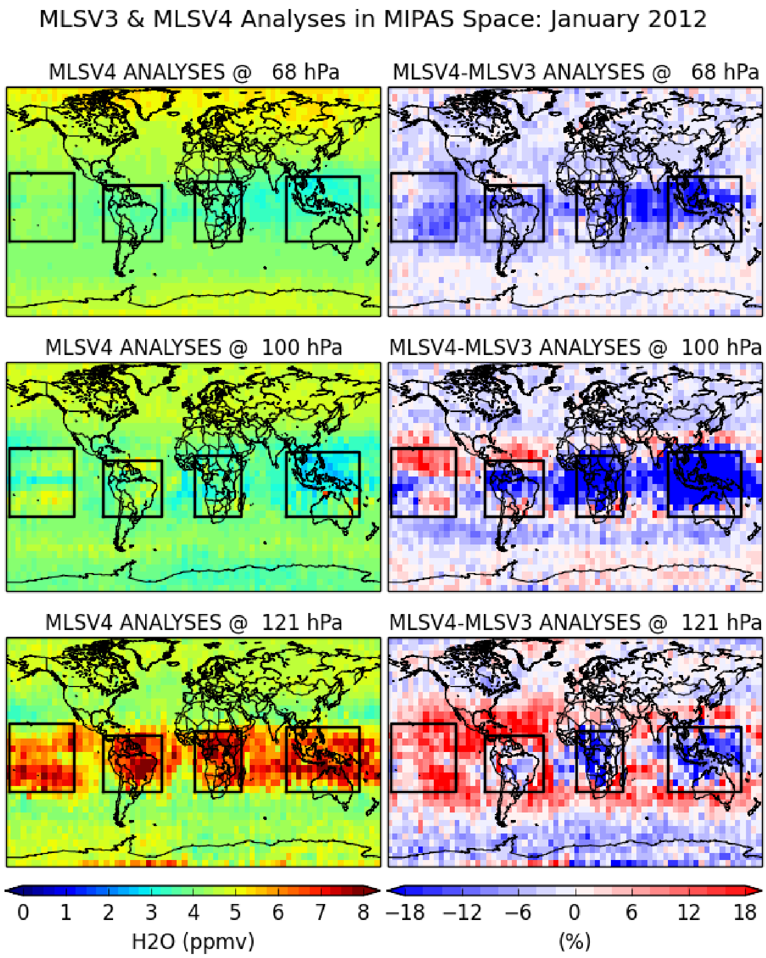


Figure 19: Monthly-averaged H_2O analyses in the model space in January 2012 using the MLS V4 data set (left) and relative difference between the MLS analyses using V4 and V3 data sets (right) at 121 hPa (bottom), 100 hPa (middle) and 68 hPa (top).



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1042 **Figure 20:** Monthly-averaged H_2O analyses in the MIPAS space in January 2012 using the MLS V4 data set (left) and relative difference between the MLS analyses using V4 and V3 data sets (right) at 121 hPa (bottom), 100 hPa (middle) and 68 hPa (top).

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