# DUE GLOBVAPOUR

## Summary report on existing algorithm comparison and validation reports

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# 1 Introduction

## 1.1 Purpose

The purpose of this document is to briefly review both existing techniques and algorithms for the retrieval of atmospheric water vapour using satellite instruments, and corresponding existing water vapour products. This also includes a short review on inter-comparison studies conducted.

## 1.2 Definitions, acronyms and abbreviations

| | |
|---|---|
| 1D-VAR | One-dimensional variational data assimilation |
| AIRS | Atmospheric Infrared Sounder |
| AMSR | Atmospheric Infrared Sounder |
| AMSU | Advanced Microwave Sounding Unit |
| ATOVS | Advanced TIROS Operational Vertical Sounder |
| ATSR | Along-Track Scanning Radiometer |
| AVHRR | Advanced Very High Resolution Radiometer |
| COSMIC | Constellation Observing System for Meteorology, Ionosphere and Climate |
| DOAS | Differential Optical Absorption Spectroscopy |
| GEWEX | Global Energy and Water Cycle Experiment |
| GMS | Geostationary Meteorological Satellite |
| GOME | Global Ozone Monitoring Experiment |
| GPS | Global Positioning System |
| GRAS | GNSS (combined GPS and GLONASS positioning systems) Receiver for Atmospheric Sounding |
| IASI | Infrared Atmospheric Sounding Interferometer |
| IR | Infrared |
| MERIS | Medium Resolution Imaging Spectrometer |
| MSG | Meteosat Second Generation |
| NWC-SAF | Satellite Application Facility on Nowcasting and Very-Short Range Forecast |
| NWP | Numerical Weather Prediction |
| NOAA | National Oceanic & Atmospheric Administration |
| SCIAMACHY | Scanning Imaging Absorption Spectrometer for Atmospheric Chartography/Chemistry |
| SEVIRI | Spinning Enhanced Visible and Infrared Imager |

| | |
|---|---|
| SSM/I | Special Sensor Microwave/Imager |
| TOVS | TIROS Operational Vertical Sounder |
| TRMM | Tropical Rainfall Measuring Mission |
| UTH | Upper Tropospheric Humidity |

## 1.3 Applicable Documents

[AD-1] ESRIN Statement of Work. EOEP-DUEP-EOPS-SW-09-0003, issue 1 revision 1, dated 13 May 2009.

[AD-2] European Cooperation for Space Standardization: Space Engineering Software; ECSS-E-ST-40C, Part 1B, 6 March 2009; available from http://www.ecss.nl.

[AD-3] DUE GLOBVAPOUR Proposal, issue 1 revision 3, dated 9 July 2009.

[AD-4] DUE GLOBVAPOUR Clarification Note, issue 1, revision 1, dated 29 October 2009.

[AD-5] DUE GLOBVAPOUR Technical Specification Document; issue 1, revision 0, 11 May 2010

[AD-6] DUE GLOBVAPOUR Product Validation Plan; issue 1, revision 0, 26 July 2010

[AD-7] DUE GLOBVAPOUR Validation Data Document; issue 1, revision 0, 27 July 2010

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## 1.5 Structure of the document

Section 2 reviews existing retrieval algorithms for total column water vapour and water vapour profile, and describes satellite retrieval inter-comparison efforts carried out in the past. Section 3 gives an overview over existing validation efforts using ground-based observations. The evaluation of climate models and model based reanalysis is presented in section 4. Comparison techniques and existing water vapour products from satellite observations for climate applications are introduced in sections 5 and 6, respectively.

# 2 Existing algorithms for the retrieval of water vapour from satellite observations

Water vapour strongly varies in space and time leading to the necessity of its global monitoring from satellites. Today, a large number of scientific and operational satellites are capable of providing information on atmospheric water vapour. Various spectral ranges and retrieval techniques are utilised, each having its own particular advantages and disadvantages.

## 2.1 Applicable satellite sensors

Absorption lines of water vapour are present in almost every part of the electromagnetic spectrum. Space-borne sensors are used to retrieve atmospheric profiles of humidity or the column amount even if they were not designed specifically for it. The great variety of sensor types is due to the interaction of radiation with water vapour in the different parts of the spectrum (microwave, infrared, visible). Additionally, the observation geometry (nadir view, limb scanning, occultation, day or night) and different orbit orientations of the orbit planes increases the number of instruments available to observe the whole globe. The content of this chapter is restricted to tropospheric water vapour observation systems.

The Advanced Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (ATOVS) suite of instruments (High resolution Infrared Radiation Sounder (HIRS), Advanced Microwave Sounding Unit (AMSU-A/B) and Microwave Humidity Sounder (MHS)) on NOAA and MetOp satellites represent infrared spectrometers and microwave radiometers where the combination of all three instruments contains enough information to derive atmospheric profiles of temperature and specific humidity. Since 2007 EUMETSAT’s MetOp satellite carries the Infrared Atmospheric Sounding Interferometer (IASI) instrument that represents a new class of infrared sounding, capable of observing about 15 independent pieces of information on the vertical profile by performing observations over a large part of the infrared spectrum (4 – 50 µm) (Simeoni et al., 1997). A similar instrument, the Atmospheric Infrared Sounder (AIRS) has flown since 2002 on NASA’s Aqua mission (Aumann et al., 2003) but does not cover the whole infrared spectrum. Infrared sounders are normally only utilised under cloud free conditions.

Microwave imagers have a long standing tradition to observe the radiation close to the 22 GHz water vapour absorption line that is closely related to the total column content of water vapour. These observations can only be used over oceans but also in cloudy conditions. Data from the conically scanning Special Sensor Microwave/Imager (SSM/I) on the DMSP satellites is available since 1987 and is continued with the Special Sensor Microwave Imager Sounder (SSMIS) instrument into the future. Among others this type of radiometer is flown on the US TRMM satellite (TRMM Microwave Imager (TMI)) and on the US Aqua mission (Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E)) (Kawanishi et al., 2003). The AMSU instruments also observe at this frequency but are cross track scanners (Ferraro et al., 2005).

While over water surfaces passive microwave remote sensing techniques provide accurate measures of the total water vapour content (Schlüssel and Emery, 1990), the retrieval above land surfaces is more sophisticated in terms of varying surface emissivities in the microwave as well as in the thermal spectral domain.

Measurements of the solar reflected radiation in the ρστ-$H_2O$ water vapour absorption band contain information on the water vapour content. Both, the Moderate Imaging Spectrometer MODIS as well as the Medium Resolution Imaging Spectrometer MERIS, have distinct bands to detect water vapour, however, with different approaches to account for the spectral wavelength dependence of the surface albedo (Kaufman and Gao, 1992; Bennartz and Fischer, 2001). In general, the brighter the surface the more accurate the water vapour can be retrieved. MERIS allow observations of small scale water vapour variability with a spatial resolution of 260 by 300 $m^2$. MODIS and MERIS are providing measurements of TCWV since 2000 and 2002, resp.

Algorithms for the estimation of the surface temperature have to correct for the influence on the varying water vapour and they are mainly based on the so-called split window technique, which rely on the different impact of water vapour on measured emitted radiances at 11 and 12 µm (Chesters et al., 1983). There are a few attempts to use the (A)ATSR thermal channels to estimate the total water vapour content (Li et al, 2003, Zhang et al., 2008). The impact of varying surface emissivity and absorbing aerosols are not deep enough investigated. A rigid validation study is missing. However, thermal measurements could be used day and night for the water vapour retrieval.

Infrared imagers such as the Meteosat Visible and Infrared Radiation Imager (MVIRI) and Spinning Enhanced Visible and Infrared Imager (SEVIRI) instruments in geostationary orbit observe radiation at 6.3 µm and 7.2 µm (only SEVIRI) and allow the retrieval of upper tropospheric humidity (UTH) with a very high temporal resolution (up to 15 minutes) that allows for studies of atmospheric dynamics (Tjemkes et al., 2001; Schmetz et al., 2002). Also in geostationary orbit humidity sounders similar to the HIRS instrument are flown on the US Geostationary Operational Environmental Satellites (GOES) but only cover a small area of the disk.

UV/VIS spectrometers such as the Global Ozone Monitoring Experiment (GOME) and Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (Sciamachy) allow for the retrieval of total column water vapour over land and ocean surfaces with approximately the same accuracy but only under daylight and clear sky conditions (Burrows et al., 1999; Bovensmann et al.,1999). The GOME-2 instrument in EUMETSATs MetOp-A satellite provides data since January 2007 with smaller ground pixel size and improved spatial coverage. Future European missions such as GMES Sentinel 4, Sentinel 5 precursor and Sentinel 5 will carry UV/VIS spectrometers that will extend the total column water vapour record.

Radio Occultation measurements, e.g., as performed by the GRAS (Loiselet et al., 2000) instrument onboard the MetOp satellite or the COSMIC fleet (Anthes et al., 2008), provide high-vertical resolution observations of the bending angle. Advantages are that the observations are independent of calibration efforts, therefore the intercalibration of different instruments over time is less demanding, and of high quality in the upper troposphere and lower stratosphere. A disadvantage is the relatively low spatial sampling and resolution. Furthermore, the bending angle is a function of temperature and water vapour, and a unique separation of the information is not always possible. Thus, Radio Occultation's main value is the determination of temperatures in the upper troposphere and lower stratosphere rather than tropospheric water vapour.

Finally, the Microwave Limb Sounder (MLS) can be used to derive vertical profiles in the upper troposphere. With the MLS 183 GHz radiometer measurements useful water vapour profile data between 150 and 55 hPa can be produced (Read et al., 2004).

## 2.2 Retrieval algorithms

Generally, retrieval methods for water vapour have to correspond to the instrument spectral characteristics and observation geometry. Processes in the atmosphere complicate the retrieval task, e.g., the co-existence of the three thermodynamic phases of water on Earth, interaction with aerosols and uncertainties in surface emissivities and temperatures particularly over land. In addition to the different methods (e.g. statistical, physical based, neural networks), algorithms have been developed over time and different methods have been combined. In general, the number of retrieval algorithms is much larger than the number of sensors.

Additionally, retrieval methods generally depend on a-priori information. This could be the coefficients of a regression calculation of precipitable water for a microwave radiometer, the training set of a neural network or the atmospheric state from an NWP short range forecast. The quality of a retrieval depends on the applicability of the a-priori information to the prevailing environmental conditions. The error characteristics of the retrieval or analysis will also critically depend on the a-priori data used as shown by Rodgers (1990) and more recently by Eyre and Hilton (2010).

Retrieval methods can be separated into semi-physical and physical schemes. In both cases observations are simulated using a radiative transfer model. Input to the model is the atmospheric state vector (including surface characteristics) and instrument parameters (e.g. applicable spectral response). The semi-physical schemes retrieve the water vapour content by applying a statistical scheme (linear regression or neural networks) based on a training set of diverse atmospheric profiles. The physical schemes mostly use a first guess, often coming from a numerical weather forecast model (NWP), as the basis for the forward computation and then vary the guess profile until the computed set of radiances best matches the observed radiances (e.g., Wentz, 1997; English, 1999). The latter requires much more computer power but has generally replaced statistical methods in the past ten years.

*Total column water vapour*

Major instruments used for total column water vapour retrieval are microwave imagers such as SSM/I, AMSR-E and microwave sounders such as AMSU-B, MHS, SSM-T2 and radiometers sensing in the VIS/NIR spectral region such MERIS and GOME class instruments. Additionally, geostationary and polar orbiting imagers observing in the IR may be utilized (e.g. GOES, GMS, Meteosat, (A)ATSR, AVHRR, MODIS etc).

Retrieval schemes for the SSM/I and similar instruments can be distinguished in semi-physical and physical schemes. Input to the model is the atmospheric state vector and instrument parameters (e.g., Phalippou, 1996). The semi-physical schemes then retrieve the water vapour content by applying a statistical scheme (linear regression or neural networks) based on the training data (Alishouse et al., 1990; Schlüssel and Emery, 1990; Schulz et al., 1993).

The basic principle in GOME type retrievals is the DOAS (Differential Optical Absorption Spectroscopy) method to calculate the difference between the Sun normalized measured Earthshine radiance and absorption cross-sections at wavelengths where water vapour absorbs radiation, e.g., using the wavelength band from 614nm to 683nm, and relate this absorption-depth to the water vapour column concentration (e.g., Noel et al., 1999, Maurellis et al., 2000, Lang et al., 2003, Wagner et al., 2003). The DOAS method provides a global (land and ocean) completely independent data set, because it does not rely on any additional external information but is only available during the day.

Near infrared MERIS algorithms are based on radiative transfer simulations, where the radiance ratio between the MERIS channels 15 (900 nm) and 14 (885 nm) are used in an inversion procedure based on statistical regression (Bennartz and Fischer, 2001, Albert et al., 2001). Near infrared and infrared algorithms were also developed for the MODIS instrument by Huang et al. (2004), Albert et al. (2005).

*Water vapour profiles*

Profile retrievals mostly employ the so called 1D-VAR technique that uses the variational principle to solve the retrieval problem (Eyre, 1989). Such a scheme applied to TOVS/ATOVS observations (e.g., Li et al., 2000) performs an inversion of the radiances to retrieve simultaneously the temperature and humidity profiles, and surface temperature and cloud-top pressure and amount. It employs an iterative method which finds the maximum probability solution to a nonlinear retrieval/analysis problem. It can operate on cloud-free or in some cases cloudy radiances. The 1D-VAR retrieval is used for almost all atmospheric sounders measuring radiances such as AIRS and IASI. It also widely used by the GPS radio occultation community as the preferred method to obtain temperature and humidity profiles from the observed microwave refractivity profiles in the troposphere (Healy and Eyre, 2000; Ho et. Al (2008). For these applications, the a priori profile – or first guess profile – is usually a 6 hour forecast from e.g. ECMWF.

GPS radio occultation measurements primarily provide near-vertical microwave refractivity profiles. These profiles have the advantage of a relatively high vertical resolution, on the order of 0.5 to 1 kilometer, but a somewhat lower horizontal spatial resolution, on the order of 100 to 300 kilometer. Using a priori information from ECMWF forecasts as input to a 1D-variational scheme, temperature and humidity profiles can be retrieved. From the observational and a priori error covariances, an estimate of the associated errors on the retrieved variables (i.e. temperature and humidity) is obtained. Due to the relatively low impact of small amounts of water vapour on refractivity, the information on humidity is largely restricted to the troposphere.

Semi-physical schemes such as neural networks can also be used to simultaneously retrieve temperature and water vapour profiles (Kuligowski and Barros, 2001; Scott et al., 1999). This retrieval technique is sometimes preferred for climate studies because it does not need a first guess from a NWP model. Thus, it is not influenced by the NWP model error. However, it is likely that fully physical schemes retrieve profiles with higher accuracy because the assumed model background better covers the variability of the global water vapour distribution compared to limited training data sets often used for the construction of statistical algorithms.

The NWC-SAF recently finished the development of a physical retrieval scheme to retrieve profiles of water vapour mixing ratio from SEVIRI observations (PGE13 ATBD, 2009) which is already installed at CM-SAF and fully tested. The MSG disc covers more than a full continent, namely Africa, with a temporal sampling of 15 minutes. Thus SEVIRI data are very much suitable for enhancing the temporal sampling but have the disadvantage of less accuracy in the retrieval and can only work in clear skies.

# 3 Evaluation of water vapour

## 3.1 Inter-comparison of water vapour products from satellite observations

Due to the relative low number of high quality ground- or aircraft-based reference measurements, satellite products are often compared amongst each other. Such comparison can also help to uncover specific instrumental and retrieval problems. For instance the comparison of the passive microwave AMSR-E and infrared AIRS estimates of total water vapour content revealed some systematic differences due to the treatment of clouds in the AIRS retrievals (Fetzer et al., 2006).

Fetzer et al. (2008) compared AIRS UTH with MLS data. The mean values agreed well within 10% and standard deviations of their differences were 30% or less. Differences in wet and dry regimes were found to be caused by different sensitivities of the two instruments, i.e., AIRS is not sensitive enough in the very dry regions whereas MLS overestimates in wet regions associated with deep convection.

Milz et al. (2009) compared monthly mean distributions of UTH products from AMSU-B, Humidity Sounder Brazil (HSB), and AIRS for January 2003. The UTH based on simulated AMSU-B channel 18 brightness temperatures from AIRS profiles has a slight moist bias of up to 4% relative humidity (RH) compared to the microwave instruments. The bias between AIRS and the AMSU-B on NOAA-16 is small compared to differences in UTH observed between radiosondes and nadir looking infrared sounders as presented by Soden and Lanzante (1996), which were in the range of 10 to 15%RH depending on the type of radiosondes. The mean errors are small compared to the large differences in UTH in different climate models (John and Soden, 2007). Thus, most of the existing datasets have already a potential to benchmark climate model representations of humidity but mostly because the models strongly differ.

GOME-2 TCWV is measured over sea and over land, on the illuminated side of a sun-synchronous orbit with equator crossing time at 9h:30 (GOME/ERS: 10h:30, SCIAMACHY: 10h:00). GOME-2 has daily a near-global coverage (with some gaps around the equator). Slant columns of H2O (the number of molecules in the effective lightpath) are expected to be accurate within 5%. The largest uncertainties arise when slant columns are converted to vertical columns, by the use of calculated “Airmass Factors” (AMF). The errors on the AMFs are difficult to quantify, as there may be compensating effects. E.g., high surface reflectivity as in the case of snow would lead to a much lower AMF-ratio of O2 to H2O – but above cold surfaces the tropospheric column of H2O is reduced, which has the opposite effect. The combined error can therefore be smaller than the error on each parameter separately. Preliminary AMF error estimates for clear sky are based on model calculations of various scenarios. Clouds may shield a major part of the total H2O column from the GOME-2 view. This effect is partly compensated for by using a “measured” AMF of O2, but errors remain which depend on cloud properties and on H2O vertical distribution. On the GOME-2 Level 2 product, cloudy conditions are flagged using a lower limit on the observed total column of O2.
A feature of the GOME-2 AMF calculation, is that it minimises the amount of external information which is fed into the algorithm. At present, only albedo information is used. This is applied as a multiplicative correction on the AMF, which for climate applications could easily be identified. The absence of detailed atmospheric input parameters leads to large uncertainties for a single measurement: errors on the AMF may be in the range 10-25% for clear sky observations, and 20-100% for cloudy observations. However, for long-term averages these uncertainties will to a large extend be averaged out.

Noël et al. (2005) compared SCIAMACHY results from the AMC-DOAS algorithm to SSM/I. They found for clear sky situations SCIAMACHY H2O columns typically 2 $kg/m^2$ lower than SSM/I, with a typical scatter of the data of around 5 $kg/m^2$. A similar comparison was carried out by Mieruch et al. (2010). They analysed the clear sky bias which is mainly caused by the cloud clearing scheme applied in the AMC-DOAS algorithm but also influenced by systematic differences between in-cloud and clear sky water vapour observations.
Slijkhuis (2008) and Slijkhuis et al. (2009) performed an initial inter-comparison of GOME retrieval algorithms, and comparison to SSM/I data. Comparisons among different retrieval algorithms from GOME show a very tight correlation with an offset of 3 $kg/m^2$ and a difference in slope of 7%. The offset error compared with SSM/I is around 0-3 $kg/m^2$ (GOME lower), the error on the slope is generally within 20% for clear or partially clouded conditions, but may be much higher for cloudy conditions.

Leinweber (2010c) has performed a multi-annual inter-comparison of MERIS and MODIS-TERRA TCWV measurements over European land areas between 2005 and 2009, finding a high agreement between both satellite retrievals. On average, the MODIS-derived TCWV values were found to be slightly higher than those of MERIS with an overall bias of 1.2 mm and a root mean square deviation of 1.7 mm. Both retrievals were found to similarly represent the seasonal cycle and spatial distribution of TCWV above Europe. A very high agreement was found above Central Europe whereas higher deviations between both satellite retrievals occurred in the Mediterranean area.

## 3.2 Validation of water vapour products from satellites using ground-based observations

The conventional observation, i.e., mainly radiosonde observations, build the core of many validation efforts performed nowadays. As an example, CM-SAF performs validation analysis of its operational ATOVS products on an annual basis. For this purpose radiosonde data recorded at 173 Global Climate Observing System (GCOS) Upper-Air Network (GUAN) stations are allocated to the grid boxes and averaged over the day (if more than one radiosonde ascent is available in a grid box). CM-SAF reports in its annual validation report (ValRep, 2010) that bias is generally smaller than 1 kg/m2 (total column and layer integrated water vapour) and 1 K (layer averaged temperature). The accuracy for the ATOVS profile products has also been determined by Li et al. (2000) with 2 K for temperature and 3 to 6 K for dewpoint temperature at a vertical resolution of 1 km.

For SSM/I based retrievals, the most comprehensive comparison to radiosondes was performed by Sohn and Smith (2003). They study revealed that differences in statistical retrievals are mostly caused by different training data and hence a a priori information that has been used. It was also found that statistical algorithms outperform physical ones because of simplifying assumptions on tangential factors such as near surface wind speed, sea surface temperature and residual cloud liquid water. On a seasonal scale (3-month means) the differences between satellite and radiosondes are ~1 $kg/m^2$ bias and ~2.5 $kg/m^2$ rms.

IASI profile retrievals have recently been evaluated by Pougatchev et al. (2009). They found in comparisons to radiosondes a standard error of a single FOV retrieval is ~0.6 K between 800–300 hPa with an increase to ~1.5 K near the tropopause and ~2 K at the surface, possibly due to incorrect surface parameters and undetected clouds or haze. Bias against radiosondes oscillates within ±0.5 K between 950–100 hPa. For water vapour the standard error of a single FOV relative humidity retrieval is below 10% relative humidity in the 800–300 hPa range and the bias is within ±10% RH.

The IASI data are obtained in near real time from the EUMETCAST reception system. Only 1 in four of the pixels in the ASMU-A field of view is available. A subset of 183 channels are used in the 1DVAR retrieval optimised for both temperature and water vapour with 31 of the channels specifically picked in water vapour absorption bands. No near infrared channels are included to avoid the problem of solar reflection during the day. A cloud detection scheme is employed in the preprocessing to identify cloud-free fields of view. This makes use of only the IASI channels using the methodology described in Pavelin (2008). The first guess a-priori information used is from the NWP 6 hour forecast and the corresponding background error covariance of the forecast model is assumed. The 1DVAR retrievals are available globally in cloud free conditions. The retrievals are archived along with the measured radiances at the Met Office. The uncertainty estimates vary for different validation sites and so error estimates will be provided for each site. Typically they correspond to 10-20% in relative humidity. Errors will be larger over land and cloud due to the uncertainties in the surface emissivity or cloud top radiative properties which are inputs to the forward model in the 1DVAR retrieval.

The 1D-VAR retrievals of temperature and water vapour profiles from IASI are generated as part of the radiance assimilation process at the UK Met Office. The products are not validated routinely by comparison with the model as the radiances are actually assimilated into the NWP model not the retrieved profiles. However there have been a number of inter-comparisons of the profiles however during the JAIVEX campaign over the Gulf of Mexico which show they are close to other IASI retrievals from other centres.

An atmospheric sounding campaign in Sodankylä in 2009 has been performed to obtain accurate water vapour and ozone data in the upper troposphere and lowermost stratosphere using cryogenic chilled mirror hygrometers (CFH). The sonde launches were timed to Metop-A overpasses and have been used for validation of IASI satellite products. The comparison has evidenced that the average water vapour difference is of about 1000 ppmv at 900 hPa, 400 ppmv at 800hPa, and lower than 200 ppmv for the upper troposphere.

Total column water vapour has been validated to a high accuracy at selected sites (North Slope of Alaska-Barrow, NSA, Southern Great Plains-Lamont, SGP, and Tropical Western Pacific-Nauru, TWP) using microwave radiometers operated by DOE ARM. Note that total column water vapour constraints the accuracy of the water vapour profile retrieval because it is defined as the vertical integral of the retrieved vertical profile. Thus, errors in the total column water vapour can be attributed to errors in the retrieved profile. The relative errors of the IASI instrument are of about 20% at NSA, 25% at SGP and 10% at TWP. By contrast, the relative errors of the AIRS instrument are smaller than 5% for all sites. The large errors of the IASI instrument can be related to the bias tuning and/or cloud detection methods currently used.

A limited validation of SCIAMACHY data has been carried out above Ny Alesund, Spitsbergen (Palm et al. 2008).

In the framework of the O3M-SAF validation, Kalakoski et al. (2010) compared operational water vapour data from GOME-2 to radiosonde measurements from the Univ. Wyoming database archive (http://weather.uwyo.edu/upperair/sounding.html). They found that GOME-2 was systematically too high over high albedo surfaces. As a result, the operational water vapour algorithm was modified to include an albedo correction. A new validation has not yet been performed.

The MERIS TCWV product has been compared to a variety of water vapour data sets, namely ground-based GPS and microwave radiometer and radiosonde measurements (Albert et al., 2005 and Leinweber et al., 2010a) . In the validation study using ARM-SGP site MWR data, no bias and a root mean square deviation of 1.6 mm was found. A validation campaign based on TCWV from ground based GPS stations in Germany revealed a bias of 1 mm with a small root mean square deviation of 1.2 mm. Finally, an analysis of MERIS and radiosonde measurements of TCWV above Central and Western Europe showed a bias of 1.6 mm and a root mean square deviation of 2.6 mm between both data sets.

## 3.3 Evaluation of climate models and model based reanalysis

The radiative effect of absorption by water vapour is roughly proportional to the logarithm of its concentration, so it is the fractional change in water vapour concentration, not the absolute change, that governs its strength as a feedback mechanism. Randall et al. (2007) stated in the IPCC Fourth Assessment Report that calculations with GCMs suggest that water vapour remains at an approximately constant fraction of its saturated value (close to unchanged relative humidity (RH)) under global-scale warming. Under such a response, for uniform warming, the largest fractional change in water vapour, and thus the largest contribution to the feedback, occurs in the upper troposphere. In addition, GCMs find enhanced warming in the tropical upper troposphere, due to changes in the lapse rate. This further enhances moisture changes in this region, but also introduces a partially off setting radiative response from the temperature increase, and the net effect of the combined water vapour/lapse rate feedback is to amplify the warming in response to forcing by around 50%. The close link between these processes means that water vapour and lapse rate feedbacks are commonly considered together. The strength of the combined feedback is found to be robust across GCMs, despite significant inter-model differences, for example, in the mean climatology of water vapour.

Met Office Hadley Centre work using satellite data to evaluate moisture in their climate models has employed radiative fluxes and explicit retrievals of water vapour information, primarily total column moisture. This work encompasses both climate model evaluation studies (Allan et al., 2002) and examination of the quality of reanalyses (Allan et al., 2004) and often forms part of a wider evaluation of model performance (Martin et al., 2006). In addition to these 'conventional' types of analysis we have also developed methods to look at clouds and moisture from a dynamical perspective (Ringer and Allan, 2004) and now also employ direct simulations of water vapour sensitive radiance measurements to avoid ambiguities arising from the retrieval process (Allan et al., 2003).

The MERIS TCWV product has been used for a verification of COSMO-DE/EU TCWV analyses for the years 2006-2009 (Leinweber et al., 2010b). In general a good agreement of the data sets was found. Both representations of the water vapour field show similar seasonal cycles and spatial distributions. However, the COSMO-EU model analyses were found to show slightly higher TCWV values in the Eastern European regions and lower TCWV values elsewhere, as compared to MERIS TCWV. These deviations mainly occur during the winter season whereas there are hardly any differences during summer. For COSMO-DE a slight underestimation of TCWV ( ~1 mm) as compared to MERIS was found, not depending on the season.

CM-SAF compared almost 20 years of TCWV over global ice-free oceans from SSM/I to ECMWF operational forecast as well as ERA 40, ERA Interim, and JMA JCDAS-25 reanalysis. The global mean bias is lowest among SSM/I and ERA Interim as well as JMA reanalysis. The bias is ~1 mm and very stable in time (ValRep, 2009). The various updates to the operational system are visible in the time series of the difference to TCWV from SSM/I.

GlobVapour products will be used to evaluate the HadGEM2 climate model, which is the model the Met Office will be submitting to the next IPCC process (AR5/CMIP5). HadGEM2 will have both a standard atmosphere-ocean configuration but there will also be a full Earth System version (HadGEM2-ES), including the carbon cycle, ocean biogeochemistry, atmospheric chemistry and other processes. This model will be analysed in detail in preparation for IPCC AR5: many of the simulations for AR5 are already available and the GlobVapor products will be used for both general (overall model assessment and metrics) and specific (process evaluation and feedbacks) evaluation studies. This will involve making use of both total column water vapour and vertical profiles of moisture, including their relationships to the surface and top-of-atmosphere radiation budgets and to the large-scale circulation.

In addition, the Met Office is also developing its next generation model, HadGEM3, which has a specific focus on regional climate and seasonal-to-decadal forecasting. This model includes a new ocean model, new physics (including a new cloud scheme), higher vertical resolution (increasing from 38 to 85 levels), and higher horizontal resolution (increasing from N96 to N216). This model is key to the Met Office's aim of building a seamless (climate and NWP across a range of space and time scales) prediction system. The GlobVapour data will be assessed alongside the current set of observations used to assess HadGEM3 throughout the development process and then, if suitable, be integrated into the standard assessment/development software. Note that currently we use estimates of column water vapour from SSM/I and reanalyses, UTH from HIRS and reanalyses, and information on the vertical distribution of moisture from reanalyses.

The GlobVapour observations will also be examined to determine their suitability for inclusion in a set of observations being used to define metrics to assess the performance of HadGEM2 and HadGEM3 against previous Hadley Centre climate models and models from other global climate modelling centres.

The use of satellite simulators allows the actual satellite measurements (e.g. top of atmosphere radiance) to be simulated from the model fields, thus providing a direct comparison with the original measured quantities. For example the radiative transfer model RTTOV has now been interfaced to the simulation software COSP (see http://cfmip.metoffice.com/COSP.html) allowing direct comparisons of IASI (and also HIRS and MSU) water vapour channel radiances with simulated radiances from climate models. The results will be compared with the direct water vapour profile comparisons discussed above and any differences will be investigated. The water vapour data will also be used in conjunction with other information from models. One example of this is to combine the data with dynamical fields from re-analyses in order to examine the water vapour distribution in terms of 'dynamical regimes', e.g. areas of large-scale ascent and subsidence in the tropics.

# 4 Comparison techniques

After appropriate spatial and temporal collocation and/or sub-grid scale averaging the majority of evaluation/validation activities utilise bias and root mean square error (RMSE) as quality indicators. Typically (global) averages of such parameters are considered. Spatial and temporal distributions of such parameters have been found to be very helpful in the identification of systematic problems in the involved data sets (e.g., ValRep, 2009 and Mieruch et al., 2010). A clear definition of averaging processes involved in the generation of level 3 products is essential in order to avoid the presence of “artificial” biases.

All water vapour products are unavoidably afflicted with variance. This variance leads to a pseudo bias when comparing two data sets even if the error distributions are Gaussian and unbiased (Stoffelen, 1998). However, the utilisation of three data sets offers a way to determine the error variance of each data set. Pre-requisites for an application of such a triple collocation approach are that the errors need to be uncorrelated and that the number of collocated triples is sufficiently large (Stoffelen, 1996; O’Carroll, 2008).

Pougatchev (2008) and Pougatchev et al. (2009) developed a model to account for differences in horizontal, vertical, and temporal resolution as well as noise level of the IASI instrument and radiosondes. Their approach further allows an assessment of the error information deduced from validation.

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# 5 Existing water vapour products from satellites for climate applications

Global single and combined sensor products are publicly available. In the framework of the GEWEX Water Vapour Project the NVAP total column water vapour product (Randall, 1996) was derived from a combination of SSM/I, TOVS and radiosonde data for the years 1988-2001. This product was partly renewed by the additional use of AMSU and TRMM data but this covers only the years 2000-2001. Over ocean total column water vapour derived from SSM/I is available from the EUMETSAT Satellite Application Facility on Climate Monitoring (CM-SAF) (Schulz et al., 2009) and from Remote Sensing Systems (Wentz, 1997). These data sets have successfully been used for climate analysis, the evaluation of climate models, model-based reanalysis, trend studies (Trenberth et al., 2005) and also investigations of the human impact on the water vapour distribution (Santer et al., 2007).

Global total column water vapour derived from GOME-2 will be provided operationally (by end of 2009) from the EUMETSAT Satellite Application Facility on Ozone and Atmospheric Chemistry Monitoring (O3M-SAF). Existing GOME/SCIAMACHY data sets have been used to compute trends of total column water vapour (Mieruch et al., 2008). The trend patterns over global oceans only partly agree with those found from SSM/I (Trenberth et al., 2005).

Datasets of atmospheric profiles of climate quality based on TOVS have been derived by Scott (1999). The connection to ATOVS profiles in climate quality is outstanding. Operationally processed data from ATOVS, AIRS and IASI exist at various places as NOAA, NASA, EUMETSAT, ECMWF and the CM-SAF. Currently, CM-SAF is providing daily and monthly mean merged products derived from all available ATOVS sensors from NOAA 15, NOAA 16 and NOAA 18 platforms (AD-6, AD-7). The following products are generated: Total column water vapour (TCWV) and integrated water vapour in five layers where surface pressure, 850, 700, 500, 300, and 200 hPa standard pressure surfaces are used as layer boundaries, mean values for temperature and relative humidity w.r.t. water for these layers and the original retrieval of temperature and mixing ratio at the layer boundaries to eventually support water vapour transport calculations. This data set is produced in a near-real time mode to provide climate departments in national meteorological services with early data for their routine analysis.
However, as inter-satellite biases are not corrected automatically a reprocessing of the data back to the start of the ATOVS sensor suite in 1998 is envisaged.
An objective analysis method (Kriging) is applied that provides a spatial distribution of mean values, their errors and the number of independent observations. The number of independent measurements from satellites is rather given by the number of satellite overpasses because individual pixels cannot be treated as independent measurements (Lindau and Schröder, 2010). As the method is also capable of handling retrieval errors and error covariances an improved error budget calculation is under development for IASI and will further enhance the quality of the operational products.

UTH datasets are derived from AMSU-B and described in Buehler et al. (2008). UTH data sets derived from geostationary satellites have been used for the evaluation of climate models (Brogniez et al., 2005).

# 6 Conclusions

In the past, many retrieval algorithm deriving atmospheric water vapour applied to various satellite-born instruments have been developed. Strengths and weaknesses of them have been assessed and lead to the following conclusions: Retrievals for satellite microwave radiometers work well for clear and cloudy skies but only over oceans whereas TCWV retrievals using infrared radiation are limited to

clear-sky regions since the radiations in the infrared is very sensitive to clouds. While TCWV retrievals schemes are applicable day and night inversion techniques applied to UV/VIS observations only provide valid retrievals during day. Retrievals for humidity sounding by the GPS radio occultation technique need – directly or indirectly – a-priori information on temperatures and the ionospheric electron density. However, the removal of the ionospheric effects on the signal using two GPS frequencies is well understood. From this review we conclude that the Technical Specifications (AD-5) do not need to be updated.
However, the application of water vapour retrievals to build global or regional long-term water vapour data sets is still underexplored. The GlobVapour project and the scientific lessons learned during the project will contribute to the progress in this particular scientific field. The applied water vapour retrievals will be state of the art and hence provide high quality water vapour products. A further scientific milestone will be to equip such product with estimates of their uncertainties.