NOTES AND CORRESPONDENCE

Remote Sensing of Atmospheric Water Vapor Using the Moderate Resolution Imaging Spectroradiometer

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ABSTRACT

This paper presents first validation results for an algorithm developed for the retrieval of integrated columnar water vapor from measurements of the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on board the polar-orbiting *Terra* and *Aqua* platforms. The algorithm is based on the absorption of reflected solar radiation by atmospheric water vapor and allows the retrieval of integrated water vapor above cloud-free land surfaces. A comparison of the retrieved water vapor with measurements of the Microwave Water Radiometer at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site for a 10-month period in 2002 showed an rms deviation of 1.7 kg m^{-2} and a bias of 0.6 kg m^{-2}. A comparison with radio soundings in central Europe from July 2002 to April 2003 showed an rms deviation of 2 kg m^{-2} and a bias of -0.8 kg m^{-2}.

1. Introduction

Satellite-based observations of atmospheric properties are available with a very high spatial coverage and resolution and reasonable temporal resolution. Therefore, their use in the work of forecasters and in data assimilation schemes of numerical weather prediction models continuously increases. One aim of the European Sub-Gridscale Parameterisation through the Validation and Data Assimilation of Cloud Properties for Weather Prediction and Climate Modelling from Fusion of EO and Ground-Based Instruments (CLOUDMAP)2 project (http://www.cloudmap.org) is to establish a framework for the delivery of satellite-retrieved atmospheric properties to potential end users in near–real time (NRT). For the cloud products—for example, the cloud mask, cloud top pressure, etc.—the International Moderate Resolution Imaging Spectroradiometer (MODIS)/Atmospheric Infrared Sounder (AIRS) Processing Package (IMAPP) software was implemented at the Plymouth Maritime Laboratory. The IMAPP processing package is a National Aeronautics and Space Administration (NASA)-funded, freely distributed software package that allows any ground station capable of receiving direct broadcast from *Terra* or *Aqua* to produce calibrated and geolocated radiances and a variety of environmental products (Huang et al. 2004). It is built from the operational NASA algorithms for the retrieval of the different atmospheric products. Two operational NASA algorithms exist for the retrieval of atmospheric water vapor, namely, MOD05 using near-IR radiances and MOD07 using IR radiances instead. Their results are not available in near–real time. Only one algorithm, following the MOD07 approach, is currently included in the IMAPP package. The advantage of MOD07 is that it allows measurements during day- and nighttime; however, the accuracy of the near-IR retrieval, which is limited to daytime measurements, is expected to be higher. A validation of MOD07 results presented in

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Seemann et al. (2003) and King et al. (2003) showed rms deviations of around 4 kg m^{-2} and a significant slope (0.77), while a validation for MOD05 presented in Gao and Kaufman (2003) showed an rms deviation of 1.16 kg m^{-2} and a slope of 0.96. Both validations were performed against microwave radiometer measurements. With regard to MOD05, the authors mention a possible larger systematic overestimation of MOD05 compared to the microwave radiometer for water vapor values greater than 35 kg m^{-2}. This was confirmed in our work presented here (see section 3).

As a consequence, the decision was made to develop an independent algorithm based on the experiences gained with the European Space Agency's (ESA's) Medium Resolution Imaging Spectrometer (MERIS) and Deutschen Zentrum für Luft- und Raumfahrt's (DLR's) Modular Optoelectronical Scanner (MOS), for which similar algorithms already had been developed (Bennartz and Fischer 2001).

In this paper, we describe this algorithm and the results of first validation activities.

2. Algorithm development

The method used for the retrieval of integrated water vapor from reflected sunlight is based on the "differential absorption technique" (e.g., Fischer 1988; Gao and Goetz 1990; Frouin et al. 1990; Kaufman and Gao 1992; Gao et al. 1993; Bartsch and Fischer 1997; Bouffiès et al. 1997; Tahl and von Schoenermark 1998; Vesperini et al. 1999; Albert et al. 2001; Bennartz and Fischer 2001; Gao and Kaufman 2003). Briefly, the integrated water vapor is related to the transmission in a spectral channel affected by water vapor absorption. As the transmission is not measured directly, it is estimated by the mean of the radiance ratio of measured radiances in the absorption channel and one or more window channels. The actual relation between the measured radiance ratio and the integrated water vapor is calculated a priori using a radiative transfer model for a large variety of different atmospheric profiles. The inversion is performed with either a lookup table, regression methods, or an artificial neural network. Previous results from the application of this technique to satellite data are published in Tahl and von Schoenermark (1998) and Bennartz and Fischer (2001) for measurements of the Modular Optoelectronic Scanner (MOS), in Vesperini et al. (1999) and Albert et al. (2001) for data from the Polarization and Directionality of the Earth Reflectances (POLDER) instrument, and in Gao and Kaufman (2003) and King et al. (2003) for MODIS.

The layout of the radiative transfer simulations for this work, that is, the choice of atmospheric profiles and the radiative transfer model used, follows the method chosen for the MERIS instrument that is described in Bennartz and Fischer (2001) and will not be repeated here. The main difference between the MERIS and the MODIS instruments is that the latter has three absorption channels within the 900–950-nm water vapor absorption band and two adjacent window channels, while the former has one window and one absorption channel.

While for MERIS the relationship between the columnar water vapor and the radiance ratio of absorption and window channel can easily be described in a lookup table for different viewing geometries, different relations exist for different possible combinations of absorption and window channel in the case of MODIS. The NASA MOD05 algorithm for water vapor retrieval is based on the weighted average of three different water vapor column amounts retrieved individually from three different channel ratios by the use of lookup tables (Gao and Kaufman 1998, 2003). A different approach was followed here by using an artificial neural network that allows the simultaneous use of different radiance ratios during the inversion. This approach was motivated by two reasons: ease of use together with high inversion speed and a possible correction for variations in surface reflectivity between the different channels. Once the neural network is trained, the retrieval of water vapor from radiances reduces to a matrix multiplication that can be performed at great speed. Avoiding the use of lookup tables leads to a very short time delay between measurements and results. Variations in surface reflectivity between different channels are a major error source for this retrieval technique. If they are not properly accounted for, they will lead to false estimations of atmospheric transmission and thus to erroneous water vapor retrievals. Therefore, assuming a linear spectral variation of surface reflectivity, for MOD05, two window channels at both sides of the absorption band are used for the estimation of the (theoretical) transmission in the absorption channel in the absence of water vapor absorption (Gao und Kaufman 2003). However, for the (window) channel 5 at 1.24 nm, problems with the radiometric calibration have been reported (available online at http://modis-atmos.gsfc.nasa.gov/MOD05_L2/qa.html). A second problem associated with this channel is the fact that it is slightly affected by overlapping absorption of water vapor and carbon dioxide, which leads to problems with the proper approximation of atmospheric transmission using pseudospectral intervals within the radiative transfer simulations. This approximation is necessary because radiative transfer simulations with a spectral resolution resolving individual absorption lines would be far too time consuming. The modified k-distribution technique used here (Bennartz and Fischer 2000) showed a very high accuracy of the fitted transmissions for all other channels. Consequently, we decided not to use this channel in our retrieval scheme. However, a simple linear correction of the surface reflectivity in the absorption channel is not possible with only one window channel. Here, the use of the neural network proved to be advantageous. The assumption was that the concurrent use of different absorption channels (or radiance ratios of the absorption channels and the window channel at 865 nm) would provide some information about the spectral variability to the neural network. This was tested using radiative transfer simulations including measured surface reflectivities (Bowker et al. 1985). The highest theoretical retrieval accuracy can be achieved when the surface reflectivity in the absorption channels is made explicitly known to the retrieval scheme. Although this information is not available in real applications, it can be used as a benchmark for other approaches. Here, knowing the exact surface reflectivities, a theoretical retrieval error of 2.5 kg m^{-2} could be achieved. The mean water vapor value of all simulations was 24 kg m^{-2}; the accuracy is in the order of 10%. Individual regressions using single radiance ratios and excluding information about the surface reflectivity lead to retrieval errors between 2.9 and 4.6 kg m^{-2}. Finally, using a neural network with the following radiance ratios (the numbers give the central wavelengths in nanometers of the used MODIS channels)—905/865, 936/865, 940/865, and 936/905—and without any information about the surface reflectivity resulted in a regression error of 2.7 kg m^{-2} and a bias of 0.1 kg m^{-2}. With the mean simulated water vapor value of 24 kg m^{-2}, the expected accuracy of the neural network–based retrieval scheme is around 11%. The remaining retrieval error results from uncorrected variations of surface reflectivity as well as from the unknown aerosol optical thickness (Bennartz and Fischer 2001).

3. Validation

For validation purposes, MODIS measurements were compared to measurements of integrated columnar water vapor taken by the microwave water radiometer (MWR) on the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site in Oklahoma (Han and Westwater 1995) and to radio soundings over central Europe.

Concerning the MWR data, ARM data were collected for a 10-month period from 1 January 2002 to 31 October 2002. MODIS level-1b data were ordered via the NASA Distributed Active Archive Center (DAAC) Web service and converted to atmospheric water vapor using the described algorithm. The differentiation between cloudy and cloud-free pixels was done based on the MODIS cloud mask provided with the appropriate MOD05 files that were also downloaded for this period. For each day in which MWR and MODIS data were available and the appropriate MODIS pixel was classified as cloud free, the MWR measurement closest in time to the MODIS overpass was compared to the MODIS pixel closest to the ARM site. Over the whole period, 84 matchups were found. In Fig. 1, a scatterplot of MWR versus MODIS data is shown. The error bars in the *y* direction represent the theoretically expected regression error of 2.5 kg m^{-2}.

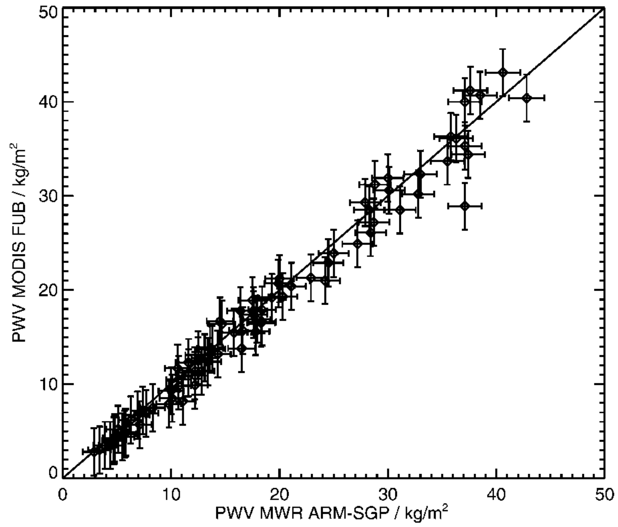

FIG. 1. Scatterplot of precipitable vapor measured by the microwave radiometer on the ARM SGP site and retrieved from MODIS measurements from Jan to Oct 2002.

The error bars for the MWR are based on estimations provided by D. Tobin (2003, personal communication). They are a combination of the absolute uncertainty of the sensitivity of the MWR water vapor measurements to increasing water vapor of 1.5% and the uncertainty in the offset of 0.1 kg m^{-2}. The results show a very high degree of agreement between the MWR and MODIS with an rms deviation of 1.7 kg m^{-2} and a bias of 0.6 kg m^{-2}. The mean MWR water vapor column amount over all measurements was 18 kg m^{-2}, resulting in a relative rms deviation and a bias of 9.4% and 3.3%, respectively.

For the comparison with radio soundings, MODIS data from July 2002 to April 2003 were used. The level-0 data were received by the Dundee Satellite Receiving Station in the United Kingdom or the DLR–German Remote Sensing Data Center (DFD) in Oberpfaffenhofen, Germany, respectively, converted to level 1b and transferred to the Institut für Weltraumwissenschaften in the framework of the CLOUDMAP2 project. The integrated water vapor was retrieved using the described algorithm and a cloud mask algorithm was applied to the data. (Images showing the current MODIS overpasses and the retrieved products are available at http://wew.met.fu-berlin.de/nrt). For the validation period, satellite overpasses between 1000 and 1400 UTC were compared to radio soundings valid at 1200 UTC. The radio soundings were downloaded from the archive at the University of Wyoming (available online at http://weather.uwyo.edu/upperair/sounding.html). For each MODIS overpass and each radio sounding, the mean MODIS water vapor column amount and the standard deviation were calculated for all cloud-free pixels in the vicinity (± 0.2°) of the radiosonde station. A scatterplot is shown in Fig. 2. The error bars show 1 kg m^{-2} for the radio soundings and the standard deviation of measurements in the vicinity of the radiosonde station for MODIS. The rms deviation and bias are 2 and −0.6 kg m^{-2}, respectively. With a mean water vapor content for all measurements of only 9.4 kg m^{-2}, this corresponds to relative rms deviation and bias of 21% and 6%.

The advantage of radio soundings is that they give validation measurements over a broader range of surface conditions. However, the allowed time interval between the satellite overpass and the radiosonde measurements is relatively large. Reducing the time interval to 30 min, for example would, on the other hand, mean spatially reducing the validation to the United Kingdom, as the MODIS equatorial crossing time is 1030 UTC.

For both comparisons, the absolute and relative differences between MODIS and MWR and radio soundings, respectively, are shown as a function of water vapor column amount in Fig. 3. Also shown is the range given by the 5th and 95th percentiles. The agreement between MODIS and the MWR is better than between MODIS and radio soundings, which is in agreement with the expected higher absolute accuracy of the MWR measurements.

The results of this validation study must be compared to the results of the operational NASA algorithms for the retrieval of atmospheric water vapor, MOD05, and MOD07. While, as mentioned previously, MOD05 uses the same channels as the algorithm described here (and additionally channel 5 at 1.24 nm) but is not available within the IMAPP package, MOD07, making use of MODIS's IR channels, is included within IMAPP. Recently, validation results were published for both algorithms in Gao and Kaufman (2003) for MOD05 and in

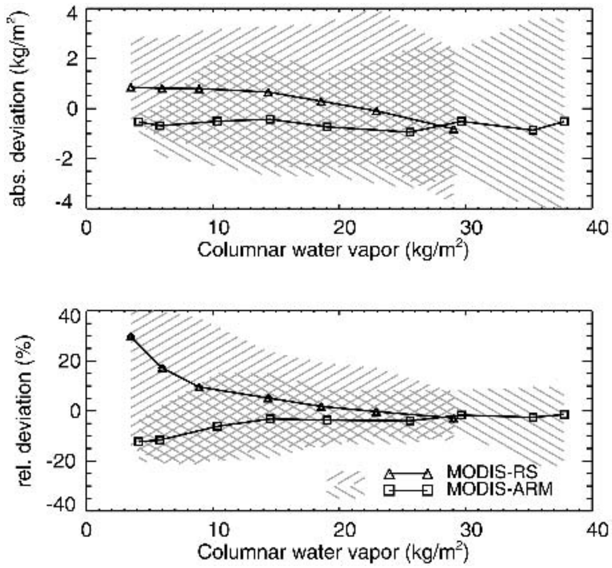

FIG. 3. (top) Mean deviation of columnar water vapor from MODIS and ARM–MWR (MODIS–ARM) and from MODIS and radio soundings (MODIS–RS) as a function of water vapor for the data shown in Figs. 1 and 2. (bottom) Mean relative deviation; the gray lines indicate the values between the 5th and 95th percentiles, respectively.

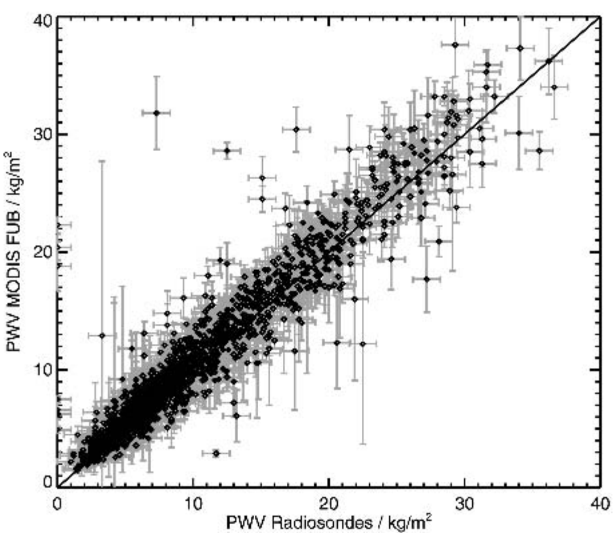

FIG. 2. Scatterplot of precipitable water vapor measured by radio soundings and retrieved from MODIS measurements over central Europe from Jul 2002 to Apr 2003.

Gao und Kaufman (2003), Seemann et al. (2003), and King et al. (2003) for MOD07. For MOD05, the same microwave radiometer measurements used here were used for the validation, albeit for a different time period (November 2000 to December 2001). When limited to water vapor values smaller than 35 kg m^{-2}, MOD05 shows a 3% overestimation and an rms deviation and a bias of 1.6 and 0.1 kg m^{-2}, respectively. When larger water vapor values are not excluded, the overestimation rises to 7% with similar rms deviation and bias. The authors mention a possible larger systematic overestimation of MOD05 compared to the microwave radiometer for water vapor values greater than 35 kg m^{-2}.

We performed a similar comparison with the MOD05 data and the microwave measurements for the time period covered in this work. The results are shown in Fig. 4. One can see a strong overestimation of MOD05 measurements with increasing water vapor values. The resulting rms deviation and bias are 3.1 and 1.8 kg m^{-2}, respectively. If the data are restricted to water vapor values lower than 35 kg m^{-2}, the resulting rms deviation and bias are 1.7 and 1.0 kg m^{-2}, which is, at least for the rms deviation, comparable to the results presented in Gao and Kaufman (2003), in which very few measurements exceeded 35 kg m^{-2}.

Finally, we compared our results also to MOD07 measurements. Only measurements collocated to the near-IR measurements were considered, that is, only daytime overpasses. As a result of reported problems with MOD07 measurements prior to 1 May 2002

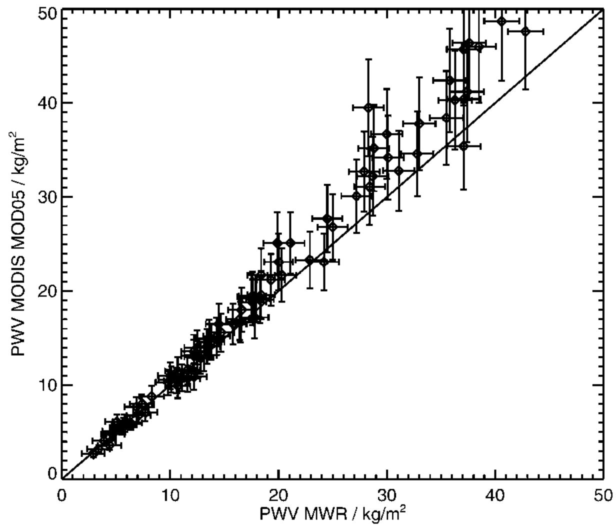

FIG. 4. Scatterplot of precipitable water vapor measured by the microwave radiometer on the ARM SGP site and from MOD05 from Jan to Oct 2002.

(http://modis-atmos.gsfc.nasa.gov/MOD07_L2/qa.html), only data from May to October 2002 are considered here. The MOD07 data were not taken from an IMAPP installation but were also ordered via the NASA DAAC Web service. The results are shown in Fig. 5. The rms deviation and bias are 4.4 and −3.9 kg m^{-2}, respectively, which agrees well with the results presented in Seemann et al. (2003) and King et al. (2003) and is significantly larger than the errors of the presented near-IR retrieval.

4. Summary and outlook

In this paper, we present validation results for a new algorithm for the retrieval of integrated water vapor from MODIS measurements based on the differential absorption technique. Retrievals are possible during daytime for cloud-free land pixels. The algorithm's accuracy was assessed using the microwave water radiometer on the ARM SGP site as well as radio soundings in central Europe. The agreement between MODIS and in situ measurements is high, with rms deviations of 1.7 kg m^{-2} for the MWR measurements and 2 kg m^{-2} for the radio soundings. A comparison of MOD05 near-IR measurements with the microwave measurements showed an rms deviation of 3.1 kg m^{-2}; the larger error is due to an observed strong overestimation of water vapor by MOD05 for larger water vapor values. A comparison of MOD07 IR measurements with the microwave measurements showed an rms deviation of 4.4 kg m^{-2}. The results for MOD05 and MOD07 agree well with previous publications, albeit for MOD05 only a small number of cases with large water vapor values have been considered in literature.

In the future, further efforts will be put into more extended validation studies including climate regions different from the midlatitudes, that is, Arctic and tropical regions. In addition, the activities will be extended toward the validation of a similar algorithm for the retrieval of atmospheric water vapor above cloud tops in cloudy atmospheres.

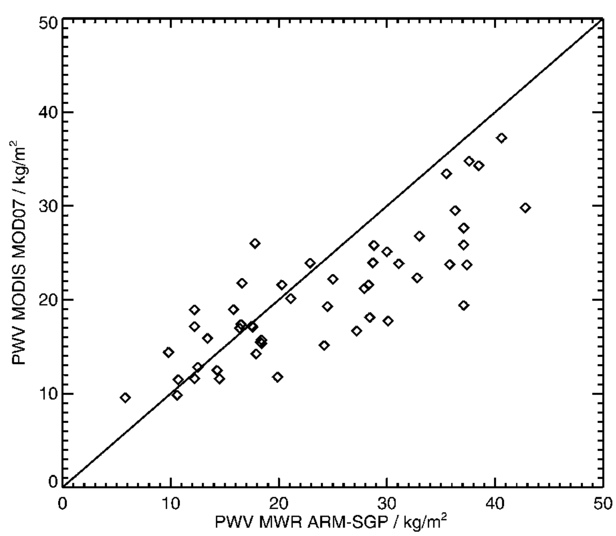

FIG. 5. Scatterplot of precipitable water vapor measured by the microwave radiometer on the ARM SGP site and from MOD07 from May to Oct 2002.

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