Remote sensing of atmospheric water vapor using the Moderate Resolution Imaging Spectroradiometer (MODIS)

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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 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 Radiometer at the ARM SGP site for a 10 month period in 2002 showed a rms deviation of $1.7kg/m^2$ and a bias of $0.6kg/m^2$. A comparison with radio soundings in central Europe from July 2002 to April 2003 showed a rms deviation of $2kg/m^2$ and a bias of $-0.8kg/m^2$.

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 CLOUDMAP2 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, e.g. the cloud mask, cloud top pressure, etc., the International MODIS/AIRS Processing Package (IMAPP) software was implemented at the Plymouth Maritime Laboratory. The IMAPP processing package is a NASA-funded, freely distributed software package which 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 build 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 *Seemann et al.* [2003] and *King et al.* [2003] showed a rms deviations of around $4kg/m^2$ and a significant slope (0.77), while a validation for MOD05 presented in *Gao und Kaufman* [2003] showed a rms deviation of $1.16kg/m^2$ 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 Validation).

As a consequence, the decision was taken to develop an independent algorithm based on the experiences gained with ESA's Medium resolution Imaging spectrometer MERIS and DLR's Modular Optoelectronical Scanner MOS, for which similar algorithms already had been developed (*Bennartz und 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 und Goetz* [1990]; *Frouin et al.* [1990]; *Kaufman und Gao* [1992]; *Gao et al.* [1993]; *Bartsch und Fischer* [1997]; *Bouffiès et al.* [1997]; *Tahl und v. Schoenermark* [1998]; *Vesperini et al.* [1999]; *Albert et al.* [2001]; *Bennartz und Fischer* [2001]; *Gao und 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 look-up table, regression methods or an artificial neural network. Previous results from the application of this technique to satellite data are published in *Tahl und v. Schoenermark* [1998] and *Bennartz und 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 instrument (POLDER) and in *Gao und Kaufman* [2003] and *King et al.* [2003] for MODIS.

The lay-out of the radiative transfer simulations for this work, i.e. the choice of atmospheric profiles and the radiative transfer model used follows the way chosen for the MERIS instrument which is described in *Bennartz und 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 2 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 look-up 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 look-up tables (*Gao und Kaufman* [1998, 2003]). A different approach was followed here by using an artificial neural network which 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 vapour from radiances reduces to a matrix multiplication which can be performed at great speed. Avoiding the use of look-up-tables leads to a very short time delay between measurements and results. Variations in surface reflectivity between different channels is 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 $1.24nm$, problems with the radiometric calibration have been reported [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 pseudo-spectral intervals within the radiative transfer simulations. This approximation is necessary, as 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 und Fischer* [1999]) 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 explicitely 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 vapour value of all simulations was $2.4 kg/m^2$, 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 $2.9 kg/m^2$ and $4.6 kg/m^2$. Finally, using a neural network with the following radiance ratios (the numbers give the central wavelengths in nm 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 $2.4 kg/m^2$, 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 und 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 ARM-SGP site in Oklahoma / USA (*Han und Westwater* [1995]) and to radio soundings over central Europe.

Concerning the MWR data, ARM data was collected for a 10 month period from January 1^{st}, 2002 to October 31^{th}, 2002. MODIS level1b data was ordered via the NASA-DAAC webservice and converted to atmospheric water vapor using the described algorithm. The differentiation between cloudy and cloud free pixels was done based on the MODIS cloudmask provided with the appropriate MOD05 files which were also downloaded for this period. For each day where MWR and MODIS data was 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 match-ups were found. In Figure 1 a scatter plot of MWR vs. MODIS data is shown. The error bars in y-direction represent the theoretically expected regression error of $2.5kg/m^2$. The error bars for the MWR are based on estimations provided by David Tobin (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 $0.1kg/m^2$. The results show a very high degree of agreement between the MWR and MODIS with a rms deviation of $1.7kg/m^2$ and a bias of $0.6kg/m^2$. The mean MWR water vapor column amount over all measurements was $18kg/m^2$, resulting in relative rms deviation and bias of 9.4% and 3.3%, respectively.

For the comparison with radio soundings, MODIS data from July 2002 to April 2003 was used. The level0 data was received by the Dundee Satellite Receiving Station in Great Britain or the German DLR-DFD in Oberpfaffenhofen, respectively, converted to level1b 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 cloudmask 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 (”wew”, not ”www”!). For the validation period, satellite overpasses between 10 and 14 UTC were compared to radio soundings valid at 12 UTC. The radio soundings were downloaded from the archive at the University of Wyoming 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 ($\pm$ 0.2°) of the radiosonde station. A scatter plot is shown in Figure 2. The error bars show $1kg/m^2$ 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 $2kg/m^2$ and $-0.6kg/m^2$, respectively. With a mean water vapor content for all measurements of only $9.4kg/m^2$, 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 e.g. 30 minutes would on the other hand mean spatially reducing the validation to Great Britain, as the MODIS equatorial crossing time is 10:30 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 Figure 3. Also shown is the range given by the 5% and 95% 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 $1.24nm$) but is not available within the IMAPP package, MOD07, making use of MODIS' IR channels, is included within IMAPP. Recently, validation results were published for both algorithms in *Gao und Kaufman* [2003] for MOD05 and in *Gao und Kaufman* [2003] and *Seemann et al.* [2003]; *King et al.* [2003] for MOD07. For MOD05, the same microwave radiometer measurements as 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 rms deviation and bias of $1.6 kg/m^2$ 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 figure 4. One can see a strong overestimation of MOD05 measurements with increasing water vapor values. The resulting rms deviation and bias are $3.1 kg/m^2$ and $1.8 kg/m^2$, respectively. If the data is restricted to water vapor values lower than $35 kg/m^2$ the resulting rms deviation and bias are $1.7 kg/m^2$ and $1.0 kg/m^2$, which is, at least for the rms deviation, comparable to the results presented in *Gao und Kaufman* [2003], where only very few measurements exceeded $35 kg/m^2$.

Finally, we compared our results also to MOD07 measurements. Only measurements colocated to the near-IR measurements were considered, i.e. only daytime overpasses. Due to reported problems with MOD07 measurements prior to 1 May 2002 [http://modis-atmos.gsfc.nasa.gov/MOD07_L2/qa.html], only data from May to October 2002 is considered here. The MOD07 data was not taken from an IMAPP installation but was also ordered via the NASA-DAAC web-service. The results are shown in figure 5. The rms deviation and bias are

$4.4 kg/m^2$ and $-3.9 kg/m^2$ which agrees well to the results presented in *Seemann et al.* [2003]; *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 a 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 a 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 vapour values has been considered in literature.

In the future, further efforts will be put into more extended validation studies including climate regions different to the mid-latitudes, i.e. Artic and Tropic regions. Also, the activities will be extended towards the validation of a similar algorithm for the retrieval of atmospheric water vapor above cloud tops in cloudy atmospheres.

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Figure Captions

Figure 1: Scatter plot of precipitable water vapor measured by the microwave radiometer on the ARM-SGP site and retrieved from MODIS measurements from January to October 2002.

Figure 2: Scatter plot of precipitable water vapor measured by radio soundings and retrieved from MODIS measurements over Central Europe from July 2002 to April 2003.

Figure 3: Upper panel: 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 Figures 1 and 2; lower panel: mean relative deviation; the grey lines indicate the values between the 5% and 95% percentiles, respectively.

Figure 4: Scatter plot of precipitable water vapor measured by the microwave radiometer on the ARM-SGP site and from MOD05 from January to October 2002.

Figure 5: Scatter plot of precipitable water vapor measured by the microwave radiometer on the ARM-SGP site and from MOD07 from May to October 2002.

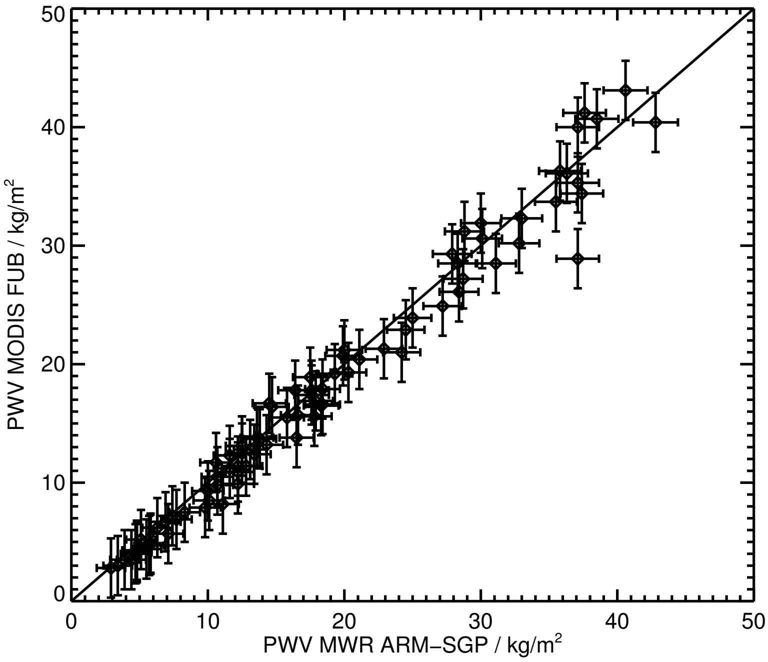

Figure 1. Scatter plot of precipitable water vapor measured by the microwave radiometer on the ARM-SGP site and retrieved from MODIS measurements from January to October 2002

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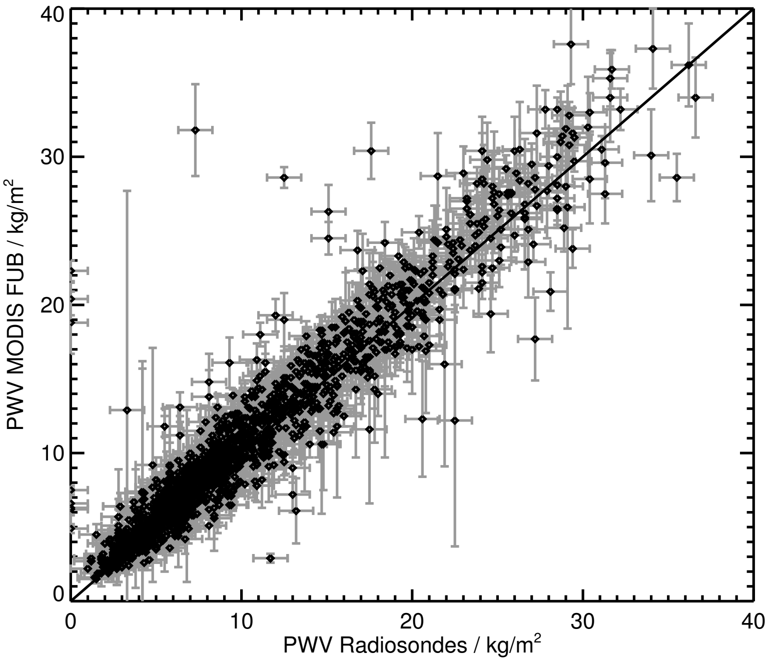

Figure 2. Scatter plot of precipitable water vapor measured by radio soundings and retrieved from MODIS measurements over Central Europe from July 2002 to April 2003

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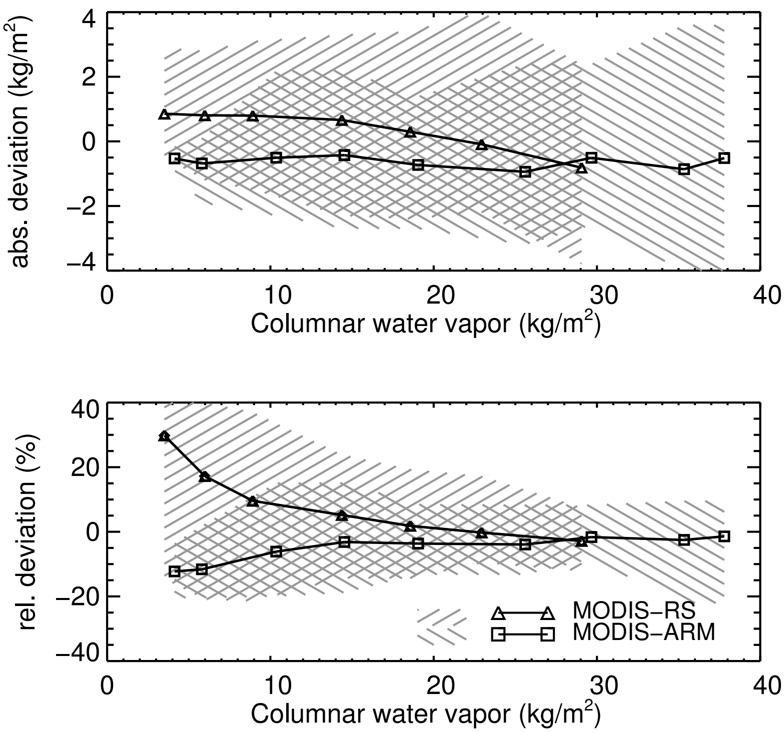

Figure 3. Upper panel: Mean deviation of columnar water vapor from MODIS and ARM-MWR (MODIS-ARM) and from MODIS and radio soundings (MODIS-RS) as a function of water vapor for the data shown in Figures 1 and 2; lower panel: mean relative deviation; the grey lines indicate the values between the 5% and 95% percentiles, respectively.

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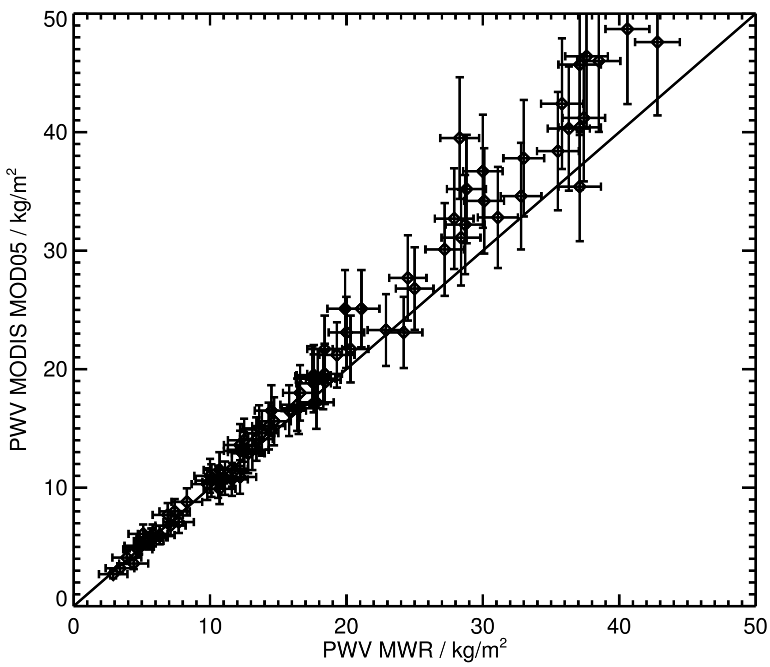

Figure 4. Scatter plot of precipitable water vapor measured by the microwave radiometer on the ARM-SGP site and from MOD05 from January to October 2002

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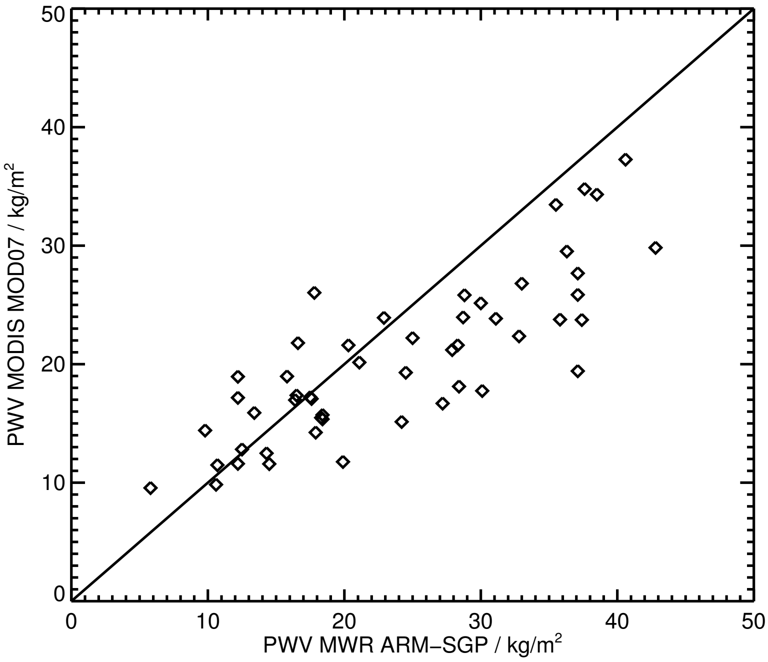

Figure 5. Scatter plot of precipitable water vapor measured by the microwave radiometer on the ARM-SGP site and from MOD07 from May to October 2002

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