Chapter 4

Validation of satellite-based water vapour measurements

The validation of the satellite-based retrievals of atmospheric water vapour above land was performed with three different sources of in-situ measurements: measurements of integrated columnar water vapour taken by the Microwave Water Radiometer (MWR) on the ARM-SGP[1] site in Oklahoma / USA, by ground-based GPS stations in Germany as well as by radio soundings over central Europe. Radiosonde data only was additionally used for the validation of MERIS measurements of columnar water vapour above clouds in combination with cloud top pressure measurements.

4.1 Validation with the ARM-SGP Microwave Water Radiometer

The MWR is a microwave radiometer designed to measure the emissions by atmospheric water vapour and liquid water (cloud droplets, rain) at specific frequencies of 23.8 GHz and 31.4 GHz [25]. Measurements of sky brightness temperatures at these two frequencies are converted into total precipitable water vapour and integrated cloud liquid water path [28]. The MWR at the ARM-SGP site measures

[1] Atmospheric Radiation Measurement Program - Southern Great Plains Site

Figure 4.1: The Microwave Water at the ARM-SGP site. Image courtesy of the ARM program.

the sky brightness temperature with a temporal resolution of 20 seconds; 5 minutes averages of precipitable water vapour were used for the comparison with satellite measurements. Figure 4.1 shows a photograph of the MWR instrument taken from the ARM web page[2].

The MWR measurements were compared to water vapour products derived from MERIS and MODIS using the algorithms described above and to the official MODIS water vapour product (MOD05) [21] provided by NASA-DAAC[3]. MERIS level1b data above the ARM-SGP site was provided for 61 overpasses by ESA for the period August 2002 to September 2003, MODIS level1b and the corresponding MOD05 data was ordered via the NASA-DAAC web service[4] for a 10-month period from January to October 2002. As the satellite retrieval of integrated water vapour above land is only possible for cloud free pixels, a cloud mask is a necessary prerequisite for each comparison. For MERIS, a cloud mask developed at the Institut für Weltraumwissenschaften (Rene Preusker, personal communication), for MODIS, the cloud mask provided with the MOD05 data was used.

For each day where MWR and MERIS or MODIS data, respectively, was available and the satellite pixel closest to the ARM site was classified as cloud free, the

[2]http://www.arm.gov/docs/instruments/static/mwr.html
[3]National Aeronautics and Space Administration - Distributed Active Archive Center
[4]http://daac.gsfc.nasa.gov/data/dataset/MODIS/

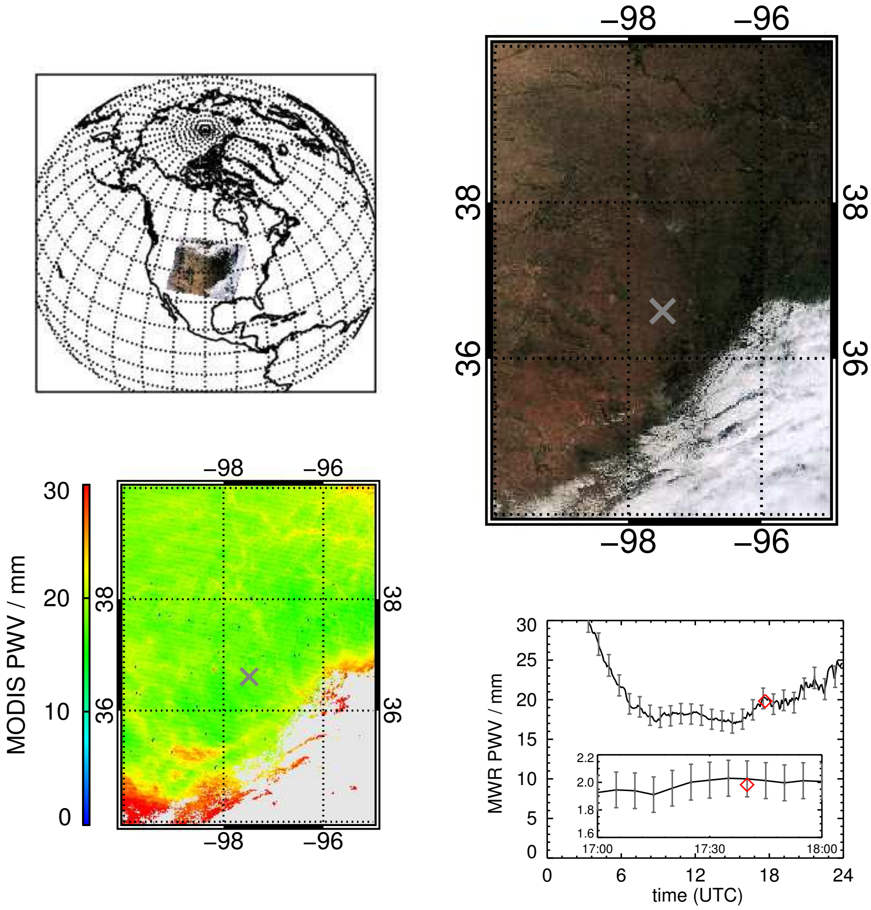

Figure 4.2: Upper panel: True colour image derived from a MODIS overpass over the ARM-SGP site / Oklahoma; USA, 14th August 2002. The left image shows a global overview, the right image is zoomed, the grey cross indicates the location of the ARM site. Lower panel: the left image shows the integrated water vapour over cloud free areas derived from the same MODIS scene, the right image shows the diurnal cycle of water vapour measurements from the MWR instrument. The red diamond indicates the MODIS measurements closest to the ARM site.

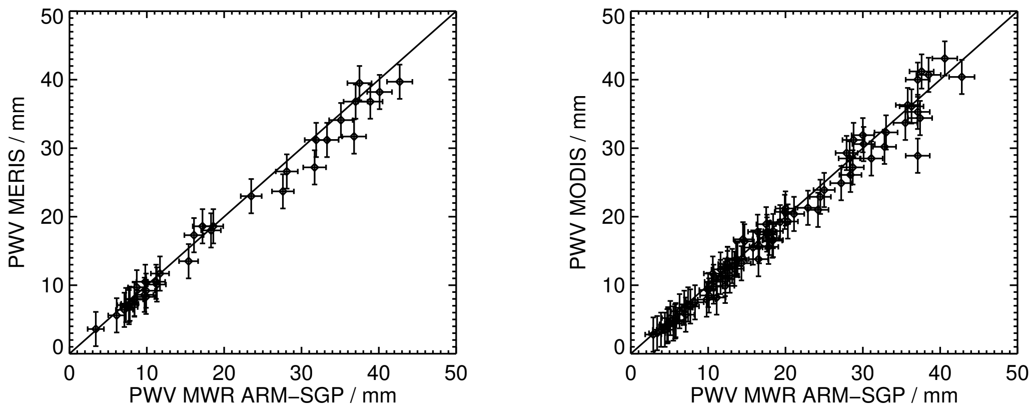

Figure 4.3: Scatter plots of integrated columnar water vapour from the Microwave Water Radiometer at the ARM-SGP site and from MERIS (left) and MODIS (right) measurements using the retrieval algorithms described in this work.

MWR measurement closest in time to the satellite overpass was compared to the water vapour value retrieved for this pixel. This is exemplarily illustrated in Figure 4.2 for a MODIS scene taken 14th August 2002. The upper two images show on the left hand side a global view with the location of the appropriate MODIS granule[5], on the right hand side this granule is enlarged, the grey cross showing the exact location of the ARM site. The lower two images show the atmospheric water vapour derived from the MODIS level1b data and the diurnal cycle of MWR water vapour measurements for this day, with the hour around the MODIS overpass enlarged. The red diamond gives the derived MODIS water vapour from the pixel closest to the ARM site. In total, 36 suitable overpasses were found for MERIS and 84 for MODIS. The resulting scatter plots are shown in Figure 4.3.

The error bars in this Figure are for the MWR based on estimates provided by David Tobin (personal communication). They represent a combination of the absolute uncertainty of the sensitivity of the MWR water vapour measurements to increasing water vapour of 1.5% and the uncertainty in the offset of 1 mm. An absolute error of 2.5 mm was chosen for the error bars for MERIS and MODIS

[5] A MODIS granule is typically a small MODIS scene containing 5 minutes of measurements. Here, MODIS data ranging from 17:35 to 17:40 UTC is shown.

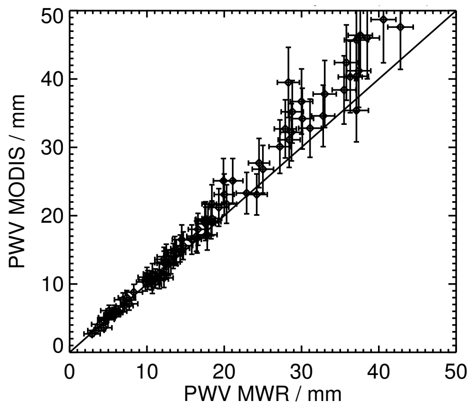

Figure 4.4: Integrated columnar water vapour from the Microwave water radiometer at the ARM-SGP site and from MODIS MOD05 (Version 3).

representing the theoretically expected regression error. Both comparisons show a very high agreement between the MWR and the satellite data. The *rms* deviation for MERIS is 2.0 mm with a bias of -1.1 mm, for MODIS the results are 1.7 mm and -0.6 mm, respectively. The mean MWR water vapour column amount over all measurements was 20.3 mm for the comparison with MERIS and 18.2 mm for MODIS resulting in relative rms deviations of 9.9 % and 9.3 % for MERIS and MODIS and biases of -5.4 % and -3.0 %.

The same scatter plot is shown in Figure4.4 for a comparison of the MWR measurements with the MODIS MOD05 results. A strong deviation of the two datasets is visible here. Nevertheless, it has to be mentioned that the MOD05 data for this period is of Version 3, while in the meanwhile Version 4 is released. A comparison with radio soundings over central Europe showed a great accuracy improvement for the new version (Ronny Leinweber, personal communication), however, MOD05 Version 4 is not available for the comparison period investigated for this work, yet.

4.2 Validation with GPS

A second validation was performed using ground-based GPS measurements of integrated columnar water vapour, provided by the GFZ Potsdam [22, 33]. Shortly,

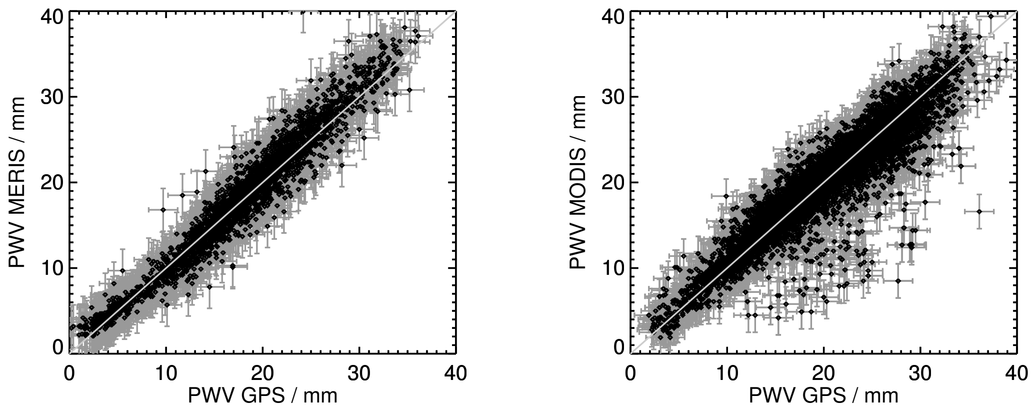

Figure 4.5: Scatter plots of integrated columnar water vapour from ground based GPS and from MERIS (left) and MODIS (right) measurements using the retrieval algorithms described in this work.

the technique makes use of the fact that the GPS signal emitted by satellites and received by ground stations is delayed in dependence on the atmospheric temperature and humidity profiles. The knowledge of the exact station location and the orbit parameters of the GPS satellites allow the calculation of the total path delay, knowledge of the station surface pressure and the mean atmospheric temperature allows the separation into a dry and wet path delay and finally the retrieval of the integrated columnar water vapour. The expected accuracy of this method is in the order of 1.5 mm. Along with the high accuracy GPS data has another advantage for the validation of satellite measurements, as comparisons are possible over a broader range of surface conditions than in the previous validation, where the ARM MWR always represented similar conditions.

For the validation, GPS-based water vapour retrievals were available from October 2002 to September 2003 for 150 ground stations in Germany. MERIS level1b data was again provided by ESA for the period October 2002 to September 2003, MODIS data was taken from the output of the near-real-time processing system described in chapter 3. For MODIS, only the period January to October 2003 was compared. Concerning the cloud mask, for MERIS the same cloud mask as in the previous section, for MODIS the official NASA cloud mask was used. The latter is processed and distributed in near-real-time within the European CLOUDMAP2 project by the Plymouth Maritime Laboratory / GB. For each day where MERIS or MODIS data was available, the satellite pixel closest to each station was used for the comparison if the pixel was identified as cloud free and the time difference between the MERIS overpass and the GPS measurement was less than 30 minutes. In total, 2769 and 10722 collocations between GPS measurements and cloud free MERIS or MODIS, respectively, were found during the validation period. The resulting scatter plots are shown in Figure 4.5. The error bars (plotted in grey) show 1.5 mm for the GPS and 2.5 mm for the satellite measurements. The agreement between the two datasets is very high, with a *rms* deviation and bias of 1.74 mm and 0.28 mm for MERIS and 2.27 mm and 0.02 mm for MODIS. A small overestimation by MERIS for very low and very high water vapour values must be further investigated. A small number of pixels show a strong underestimation of water vapour by MODIS, these deviations occur when a cloudy pixel is falsely detected as cloud free.

4.3 Validation with radio soundings

The last validation was performed with radio soundings. Also having the advantage of allowing comparisons over different surface types, radio soundings are generally expected to have a larger retrieval error for water vapour. However, the advantage here is that radio soundings perform vertically resolved measurements and can therefore be used for a validation of the algorithms for the retrieval of water vapour above clouds. For a comparison, these algorithms require the integration of the water vapour profile from top of the atmosphere down to the level of the cloud top.

In the first subchapter MERIS and MODIS measurements of total columnar water vapour are compared to radio soundings followed by the results from the validation of MERIS measurements of integrated water vapour above clouds.

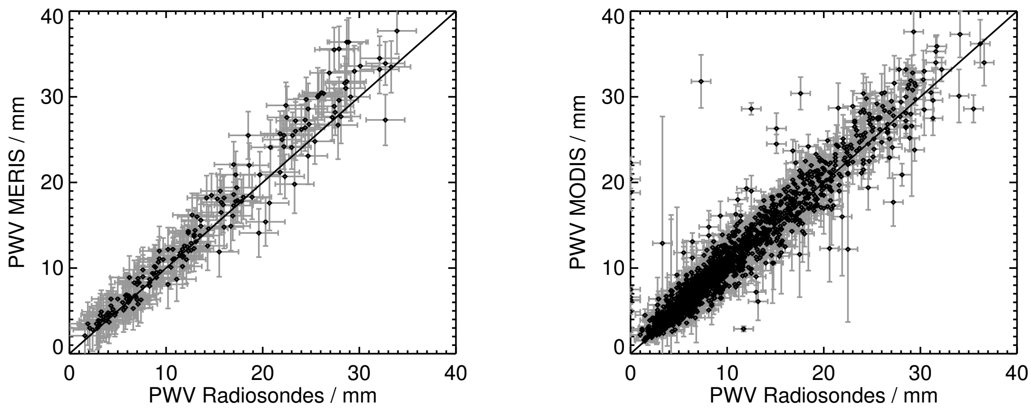

Figure 4.6: Scatter plots of integrated columnar water vapour from radio soundings and from MERIS (left) and MODIS (right) measurements using the retrieval algorithms described in this work.

4.3.1 Water vapour above land

The same satellite data as in the previous section was used for this comparison. Radio soundings were collected from the Department of Atmospheric Science, University of Wyoming / USA[6]. One problem with radiosonde measurements with regard to this comparison is the large time difference between the observations. Operational radiosondes are launched at 12 UTC while the MERIS and MODIS equatorial crossing times are 10:00 and 10:30 UTC, leading to time differences of up to 3 hours for central Europe. Therefore, the comparison for MODIS was performed twice, once for all available radio soundings and once for those cases only, where the satellite overpasses were less than 30 minutes before or after the radio soundings. The comparison statistics are very similar, though and only the results for all overpasses are shown here.

For each satellite overpass, the mean satellite water vapour column amount and the standard deviation was calculated for all cloud free pixels in the vicinity (distance < 15 km) of each radiosonde station within the satellite scene. The resulting scatter plots are shown in Figure4.6. The error bars in y-direction (shown in grey)

[6]http://weather.uwyo.edu/upperair/sounding.html

are calculated from the standard deviation of water vapour measurements in the vicinity of the radiosonde station σ_{obs} and the theoretical regression accuracy σ_{reg} by $\sqrt{\sigma_{obs}^2 + \sigma_{reg}^2}$. A constant error of 2 mm was assumed for the radio soundings. This estimate is based on the technical description of the Vaisala RS-80 instrument [3].

The agreement between the satellite and the radiosonde measurements is again high, however, a significant deviation for increasing water vapour values can be observed. This result is in agreement with the findings published in [40]. The authors performed a long-term comparison between total precipitable water vapour obtained from radiosondes profiles and retrieved from collocated ARM-MWR measurements. The radiosondes were of the same type as the sondes used in this work (Vaisala RS80). The comparison revealed an approximate 5 % dry bias of the radiosondes. This compares well to the approximate 7 % dry bias between radiosondes and MODIS observed in this work. The bias between the radiosondes and MERIS is around 11 %, which requires further investigation.

4.3.2 Water vapour above clouds

The same database of MERIS and radiosonde data from the above subchapter was used for this comparison. The satellite-based measurements of columnar water vapour above clouds are only useful in combination with accurate measurements of cloud top pressure or cloud top height, as these provide the information down to which atmospheric level the measurements are performed. For MERIS, cloud top pressure was retrieved from the level1b data using the oxygen absorption technique described in [18]. Radiosondes can significantly travel horizontally during their ascent which therefore is representative for a larger area. Consequently, MERIS and radiosonde collocations were reduced to homogeneous cloud cases where the standard deviation of retrieved cloud top pressure varied less than 50 hPa within 15 km around the radiosonde station. For these cases, the mean water vapour above clouds in the vicinity of the radiosonde station was compared to the precipitable water vapour from the radio soundings, integrated from top of the atmosphere down to the mean MERIS cloud top pressure. Additionally, the mean MERIS cloud top

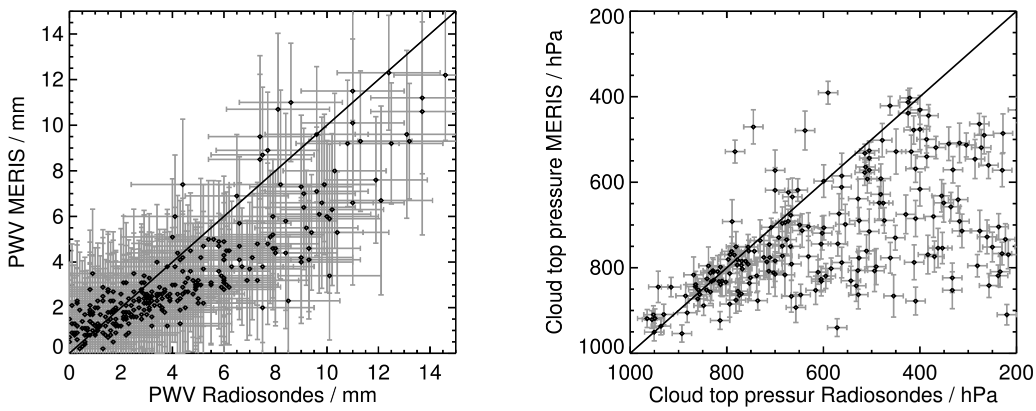

Figure 4.7: Left: Scatter plot of integrated columnar water vapour above clouds from radio soundings and from MERIS; right: scatter plot of cloud top pressure from radio soundings and from MERIS.

pressure itself was compared to the top of the highest cloud level identified in the radiosonde measurements using the cloud layer detection technique described in [13].

The results are illustrated in Figure 4.7 which shows in the left panel the scatter plot of retrieved water vapour and in the right panel the scatter plot of retrieved cloud top pressure. It is clear that the order of magnitude of the water vapour measurements is smaller compared to the previous comparisons as the largest water vapour densities typically are in the lower parts of the atmospheres and therefore below or within the clouds. Although the correlation between the radiosonde and MERIS water vapour measurements is good MERIS shows a strong underestimation especially for larger water vapour values. At the same time the MERIS cloud top pressure is very often below the highest cloud top pressure derived from the radio soundings. The latter is a well-known behaviour for multiple cloud layers. Given a two-layer cloud, the MERIS signal is a combination of photons being scattered upwards at the uppermost cloud layer and of photons penetrating through the upper layer and being scattered upwards at the lower cloud level. Effectively, a certain fraction of the absorber mass between the two cloud layers is shaded from the satellite view.

Therefore the measured absorption is smaller compared to an appropriate single-layer cloud with a cloud top at the height of the lower cloud level. As oxygen is very well mixed vertically in the atmosphere, the measured oxygen absorption is just related to air mass or cloud top pressure, respectively. Consequently, reduced absorption corresponds to a lower cloud top pressure (or higher cloud), and, for the two-layer cloud, the retrieved cloud top pressure is in between the two layers[7]. The same is in principle true for water vapour absorption, however, the different vertical profiles of oxygen and water vapour density have to be considered. While oxygen density is in good approximation a linear function of pressure, water vapour density typically decreases more quickly with height. If again a two-layer cloud is considered, the fraction of oxygen absorber mass above the upper cloud level will mostly be larger than the appropriate fraction of water vapour absorber mass. While approximately 30 % of the total oxygen absorber mass are located above 300 hPa, almost all water vapour is below this pressure level. Consequently, the shading of lower levels is more effective for water vapour than for oxygen, resulting in a stronger reduction of water vapour absorption than of oxygen absorption. As a result, the retrieved integrated water vapour associated with the MERIS cloud top pressure is mostly too small in cases of multi-layer clouds. The overall accuracy of the water vapour retrieval above clouds shows an *rms* deviation of 2.3 mm and a bias of -1.1 mm.

4.4 Validation summary

All validation results are summarized in Table 4.1. For each instrument and validation dataset, the *rms* deviation and bias are calculated twice, once for all available collocations and once after the removal of absolute differences larger than twice the standard deviation. The latter reflects the assumption that large outliers are rather due to e.g. deficient cloud masks than to erroneous retrievals. They can therefore be taken as a principally achievable retrieval accuracy. The dependencies of the observed absolute and relative deviations on the total precipitable water vapour above

[7]This assumption has been verified by several comparisons of MERIS cloud top pressure measurements with cloud radar data (Rene Preusker, personal communication).

Table 4.1: Summary of validation results for the satellite-based retrieval of atmospheric water vapour. # denotes the number of collocations, rmsd the *rms* deviation of differences, <> the averaged value from the validation data. All water vapour values are given in mm. In the second table, the statistics are calculated after a 2σ elimination, i.e. after the removal of absolute differences larger than twice the standard deviation.

	MERIS				MODIS			
	#	rmsd	bias	<>	#	rmsd	bias	<>
ARM-MWR	36	2.0	-1.05	20.28	84	1.73	-0.57	18.20
GPS	2769	1.74	0.28	17.67	10722	2.27	0.02	19.77
RS land	181	2.44	1.13	14.31	2012	2.03	0.60	9.39
RS cloud	201	2.26	-1.10	4.41	-	-	-	-

	MERIS				MODIS			
	#	rmsd	bias	<>	#	rmsd	bias	<>
ARM-MWR	33	1.37	-0.67	18.41	82	1.45	-0.53	17.74
GPS	2615	1.38	0.21	17.42	10284	1.68	0.23	19.60
RS land	168	1.81	0.92	13.53	1946	1.37	0.48	9.20
RS cloud	195	1.71	-1.00	4.20	-	-	-	-

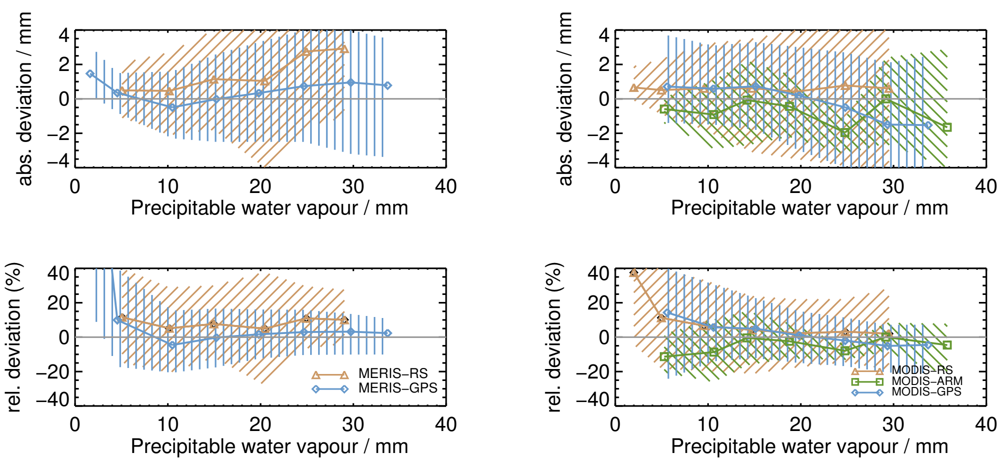

Figure 4.8: Absolute and relative deviations of measurements of columnar water vapour above land from MERIS and MODIS compared to microwave radiometer measurements, ground-based GPS data and radio soundings. The dashed areas indicate the range given by the 5% and 95% percentiles.

land are illustrated for the different validations in Figure 4.8. The mean absolute and relative deviations were calculated from the validation datasets in 5 mm intervals. For each interval, the 5% and 95% percentiles were also calculated. They are represented as dashed areas in Figure 4.8 . The comparison MERIS - ARM-MWR was omitted due to the small total number of observations.

The *rms* deviation of measurements is for both instruments smaller than the theoretically expected retrieval accuracy. In the future, especially the overestimation of water vapour by MERIS with regard to GPS for very low and very high water vapour values and the increasing negative deviation of MODIS water vapour measurements with regard to GPS have to be further investigated.