JP2.13 AN ANALYSIS OF THE SEASONAL AND DIURNAL VARIATION OF TOTAL PRECIPITABLE WATER VAPOR FROM SATELLITE AND GROUND-BASED INSTRUMENTS OVER THE ARM SGP AND TWP SITES

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1. INTRODUCTION

Total precipitable water (TPW) is defined as the amount of liquid water that would be produced if all of the water vapor in an atmospheric column were condensed. It is a very useful parameter for forecasters to determine atmospheric stability and the onset of convection and severe weather. Since water vapor is a greenhouse gas, the TPW of the atmosphere also plays a critical role in climate. The development of a climate record of water vapor is an important goal of the NASA NPOESS Preparatory Project (NPP). The Atmospheric Infrared Sounder (AIRS on Aqua) provides the capability to retrieve TPW at high vertical resolution, as well as monitor seasonal and diurnal trends of water vapor. The Cross-Track InfraRed Sounder (CrIS) will confirm this record on NPP and NPOESS.

The purpose of this study is to establish the absolute accuracy of the retrievals of TPW from a satellite-based high spectral resolution infrared sounding instrument (e.g. AIRS) using ground-based instruments such as the microwave radiometer (MWR). Results are presented that highlight both the seasonal and diurnal variability of TPW at two measurement sites, and the accuracy with which satellite algorithms are able to capture this variability.

2. ARM SITE INFORMATION

This study will focus on TPW comparisons over two ground-based observation sites operated by the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program. The ARM Tropical Western Pacific (TWP) site is located on the small island of Nauru. This is a maritime location located approximately 1200 miles northeast of Papua New Guinea. It is a useful site for validation because the surrounding ocean provides a well-known surface emissivity, relatively high levels of atmospheric water vapor, and little variation in moisture and temperature throughout the year. The TWP site at Nauru contains a MWR, which has been measuring TPW since 1998.

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The ARM Southern Great Plains (SGP) site is located in the central United States, near Lamont, OK. Unlike the TWP site, the SGP site exhibits strong seasonal and diurnal variability in water vapor. Among other instrumentation, the central ARM-SGP facility at Lamont contains a MWR, a GPS, and a RAMAN LIDAR. These instruments may be used to derive TPW.

The algorithm used to retrieve TPW from the MWR instruments at both the TWP and SGP sites is documented by Turner *et al.* (2007). This algorithm is an advanced statistical retrieval that is tuned to agree with physical retrievals, where the latter are only performed at rawinsonde launch times. Additionally, systematic biases in the MWR observations that are a result of the calibration variability of the instrument are removed prior to the retrieval. This results in improved accuracy over the original statistical approach used by ARM. Turner *et al.* (2007) document that the TPW derived from the ARM MWR using this method shows excellent agreement with TPW derived from a scanning Raman lidar, calibrated to a well-characterized chilled mirror water vapor hygrometer.

3. AIRS INFORMATION

AIRS is a hyperspectral, scanning infrared sounder that measures emitted infrared radiation in 2378 spectral channels, and reflected/emitted visible/NIR radiation in 4 spectral channels (Aumann *et al.* 2003). The IR spatial resolution at nadir is 13.5 km, and complete global coverage is attained every 2-3 days. AIRS travels aboard the polar-orbiting NASA satellite Aqua, along with AMSU-A (Advanced Microwave Sounding Unit A). Aqua was launched on May 4, 2002. This study examines AIRS level 2 version 5 moisture products, which are available beginning with September, 2002 (Susskind *et al.* 2003).

Due to its high spectral resolution in the IR, AIRS is extremely useful for determining vertical profiles of temperature, moisture, and trace gases. Infrared radiances, however, are highly affected by clouds and precipitation. To provide more uniform all weather capability, AIRS infrared measurements are combined with AMSU-A microwave measurements in cloudy conditions. AMSU-A is capable of providing profiles from the surface up to 40 km, even in the presence of clouds. A cloud clearing technique applied to data from these two unique instruments helps to provide temperature and moisture profiles in scenes that are up to 80% cloudy (Chahine 1974, 1977). It should be noted that a correction is applied to AIRS L2 data that reduces the impact of viewing zenith angle on the retrieval results. During the time period included in this study, no correlation was observed between AIRS/MWR agreement and viewing zenith angle. Additionally, the AIRS L2 TPW product contains an estimate of the retrieval error. This study is restricted to retrievals with an error estimate of 20% or less.

Several studies have confirmed that both the AIRS radiances and the AIRS clear-sky forward model have an absolute accuracy of around 0.2 K for the spectral channels used in temperature and water vapor retrievals (Fetzer *et al*. 2003 and Strow *et al.* 2006). Tobin *et al.* (2006) compared the AIRS version 4 temperature and water vapor retrievals to a "best estimate" product, derived by combining Vaisala RS-90 rawinsonde measurements with other ground based data during 3 dedicated rawinsonde launch phases between September 2002 and September 2004. The uncertainty in the "best estimate" water vapor profiles was estimated to be about 3% below 500 mb, and about 10% between 500 and 100 mb. While these profiles are useful for validating AIRS profiles of water vapor, when considering TPW only, the ARM SGP MWR derived product is better characterized for validation. Additionally, this study examines AIRS version 5 data, which include a number of improvements to both moisture retrieval quality and error estimation. The variables used in this study are the totH2OStd and totH2OStdErr from the AIRS L2_Standard_atmospheric&surface_product.

4. SEASONAL AND DIURNAL TRENDS AT SGP

This study considers co-located AIRS and MWR retrievals of TPW over the ARM SGP site between September 2002 and August 2008. Matchups were limited to AIRS overpasses with estimated TPW retrieval errors of 20% or less, where the distance between the AIRS observation and the MWR observation was 100 km or less, and the AIRS reported cloud fraction was 80% or less. The closest AIRS retrieval to the ARM MWR location was selected for each satellite overpass. To reduce the impact of the difference in spatial resolutions of the two products, the MWR data were averaged over 10 minute intervals centered on the AIRS overpass time, and matches were excluded if the uncertainty in this mean exceeded 1%. This eliminated instances in which the atmospheric water vapor was changing rapidly around the AIRS overpass time.

During the time period examined, a total of 1068 AIRS overpasses of the SGP site met the given criteria. Of these, 534 were daytime observations and 534 were nighttime observations. Figure 1 shows the monthly mean daytime, nighttime, and diurnal difference (day-night) in TPW from both MWR and AIRS. The error bars shown on this plot indicate the uncertainty in each monthly mean, calculated by dividing the monthly standard deviation by the square root of the number of points for each month. Observations from both instruments indicate a significantly higher TPW during the daytime than at nighttime during the warmer months (May-September). The trend is opposite during the cooler months (October-April), with the nighttime TPW being slightly higher than the daytime. Compared to the MWR, AIRS overestimates the diurnal difference during the warmer months, by as much as 0.4 cm (in August). During the majority of the cooler months, AIRS slightly underestimates the diurnal difference, but the difference from the MWR is much smaller than in the summer.

Figure 2 shows the percent difference between AIRS and MWR monthly mean TPW. Positive values indicate that the AIRS TPW exceeds the MWR TPW. The daytime data show a near-zero or positive bias throughout the year, while the nighttime data show a positive bias during the cooler months, and a negative bias during the warmer months. It is this tendency of the AIRS retrieval to be too dry during the nighttime in the summer that leads to the overestimation of the diurnal TPW difference that is shown in figure 1.

Figure 3 shows a scatter plot of daytime (red) and nighttime (blue) TPW data, for June, July, and August only. The AIRS data shows a slight positive bias during the daytime and a larger negative bias at nighttime. The linear fit for the daytime (nighttime) data has a slope of 0.87 (0.83), and an intercept of 0.55 cm (0.28 cm). This indicates good general agreement between the two instruments, but supports the previous conclusion that some statistically significant differences exist.

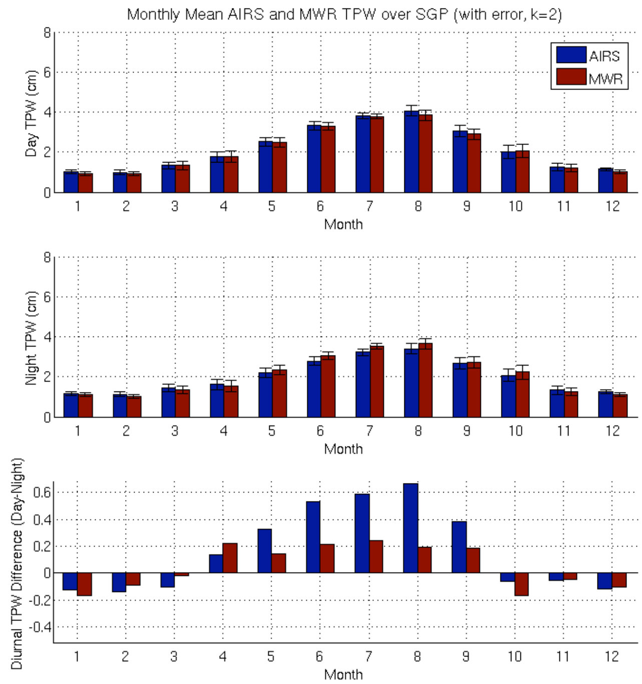

Figure 1. Monthly mean daytime, nighttime, and diurnal difference (day-night) in TPW from MWR and AIRS.

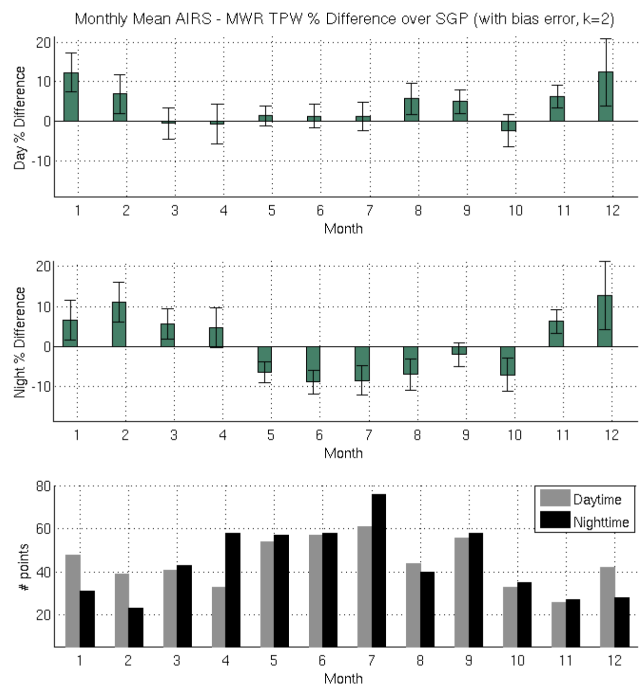

Figure 2. Monthly mean percent difference between AIRS and MWR TPW over SGP. Positive values indicate that the AIRS TPW exceeds the MWR TPW. Error bars indicate the uncertainty in the AIRS-MWR difference.

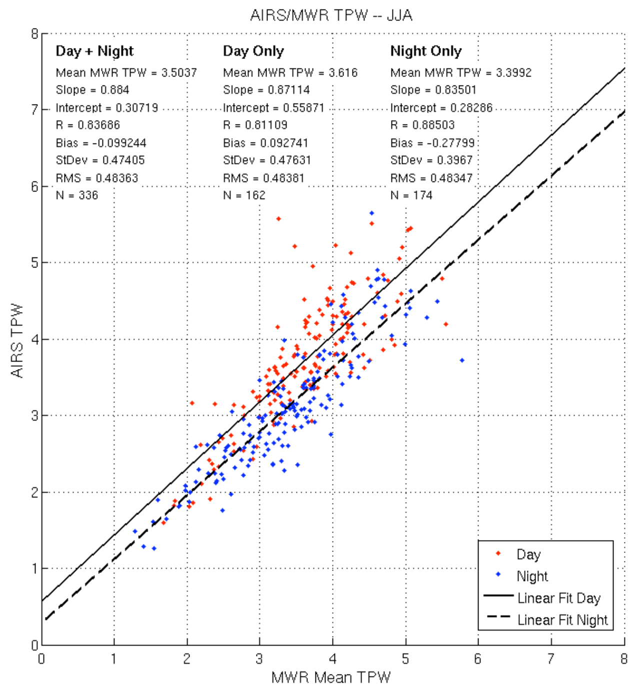

Figure 3. Scatter plot of the MWR mean TPW and AIRS TPW over SGP for daytime (red) and nighttime (blue) data over June, July, and August only. The solid (dashed) line is a linear fit of the daytime (nighttime) data.

5. DIURNAL TRENDS AT TWP

The ARM TWP site at Nauru provides a unique validation site for satellite retrievals of water vapor, since the ocean surface emissivity is well characterized and the seasonal variability of water vapor is low. Due to the limited availability of the improved MWR TPW product, this study considers co-located AIRS and MWR retrievals of TPW between September 2002 and December 2007 only. The same criteria that were used to constrain the AIRS and MWR matchups at the SGP site were also used for this site.

During the time period examined, a total of 776 AIRS overpasses of the TWP site met the given criteria. Of these, 414 were daytime observations and 362 were nighttime observations. Figure 4 shows scatter plots of daytime (red) and nighttime (blue) TPW data, all months of the year. The RMS and bias of both the daytime and nighttime data are slightly smaller than the values observed during the summer season over the SGP. However, the linear fits of both the daytime and nighttime observations exhibit a significant offset (around 0.88 for both daytime and nighttime) and slopes that are substantially different from 1 (0.80 for daytime and 0.83 for nighttime). The offset in the slope and intercept is most likely due to the smaller range of TPW values found at the Nauru site. Most of the MWR observations are clustered in a small range (between 4 and 6 cm), hence a linear fit is less useful for determining the accuracy of the satellite retrieval.

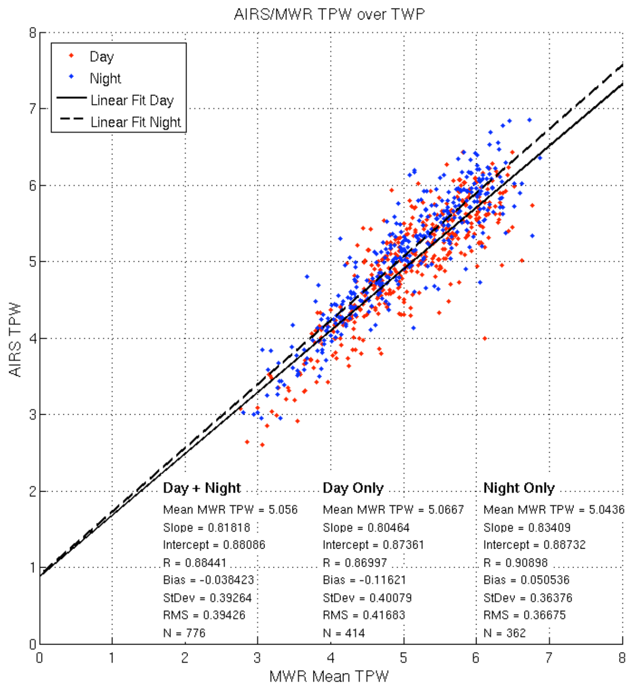

Figure 4. Scatter plot of the MWR mean TPW and AIRS TPW over TWP for daytime (red) and nighttime (blue) observations. The solid (dashed) line is a linear fit of the daytime (nighttime) data.

6. COMPARISONS FROM BOTH SGP AND TWP

Given the small range of TPW values present in the TWP data set, it makes sense to consider these data in conjunction with, rather than independent of, the SGP data. Figure 5 shows a scatter plot and linear fit for all of the data from both SGP and TWP. By examining data from both sites, a broader range of TPW values is included, and thus a linear fit is appropriate. From both sites combined, there are a total of 948 daytime and 896 nighttime observations that meet the given criteria. The linear fit of the daytime data has an intercept of 0.21, and a slope of 0.93. The linear fit of the nighttime data has an intercept of 0.10, and a slope of 0.95. However, this combined analysis mixes together the errors due to algorithms and MWR instruments that may be different at the two sites. Figure 6 shows the percent difference between AIRS and MWR TPW versus the MWR TPW for both day and night separately. In order to quantify the accuracy of the AIRS TPW product we choose to separate the results by MWR instrument (SGP and Nauru), by day and night, and by TPW amount. Table 1 contains the mean, standard deviation, number of points, and uncertainty in the mean for 1 cm TPW bins from 0 to 7 cm. Figure 7 shows the percent difference between AIRS and MWR TPW grouped into 1 cm bins, plotted against the mean MWR TPW within each bin. Shown separately are the daytime + nighttime data (top), daytime data only (middle), and nighttime data only (bottom). Results from SGP (TWP) are plotted in red (blue). Error bars are the uncertainty in the mean % difference for a given bin. The largest error bars in this case indicate a very small number of data points within a given bin (for instance, in the 5-6 cm bin, there are only 4 data points from SGP during the daytime). Considering both daytime and nighttime data, the bias error is very close to the AIRS science team suggested error of +/- 5% for bins between 1 and 5 cm for SGP, and 3 to 7 cm for TWP. This plot clearly shows a significant moist bias in the AIRS data for very low TPW cases (less than 2 cm). This bias is particularly apparent in the nighttime data. Additionally, the nighttime data at SGP exhibit a dry bias when the TPW exceeds 2 cm, a trend that is not seen in the daytime data over this site. Conversely, the differences between the daytime and nighttime bias error over TWP are slight, which indicates that there may be a site-specific nighttime retrieval issue.

		0-1	1-2	2-3	3-4	4-5	5-6	6-7
SGP Day	Mean Std Dev # Pts Uncert	0.1106 0.1102 114 1.0318	0.0646 0.1550 147 1.2786	0.0295 0.3465 84 3.7809	0.1328 0.4486 127 3.9805	-0.0420 0.4707 58 6.1812	-0.3248 0.8662 4 43.3124	0
SGP Night	Mean Std Dev # Pts Uncert	0.1833 0.1858 75 2.1453	0.1172 0.2349 170 1.8014	-0.1625 0.2945 126 2.6237	-0.3723 0.3465 121 3.1499	-0.2551 0.4679 35 7.9090	-0.9056 0.5449 7 20.595	0
TWP Day	Mean Std Dev # Pts Uncert	0	0	0.0620 0.2660 3 15.359	0.0021 0.2878 41 4.4941	0.0478 0.3384 140 2.8601	-0.1427 0.3594 177 2.7011	-0.5624 0.4191 53 5.7561
TWP Night	Mean Std Dev # Pts Uncert	0	0	0.1050 0.0972 3 5.6128	0.1886 0.3105 45 4.6291	0.1825 0.2686 121 2.4414	0.0192 0.3535 132 3.0770	-0.2479 0.4071 61 5.2119

Table 1. AIRS minus ARM SGP TPW Differences (cm)

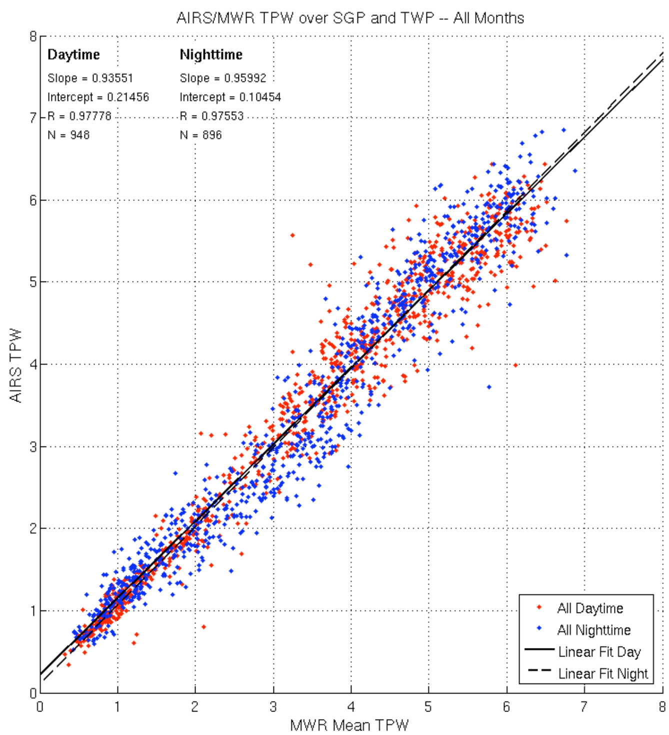

Figure 5. Scatter plot of the MWR mean TPW and AIRS TPW over both SGP and TWP for daytime (red) and nighttime (blue) observations. The solid (dashed) line is a linear fit of the daytime (nighttime) data.

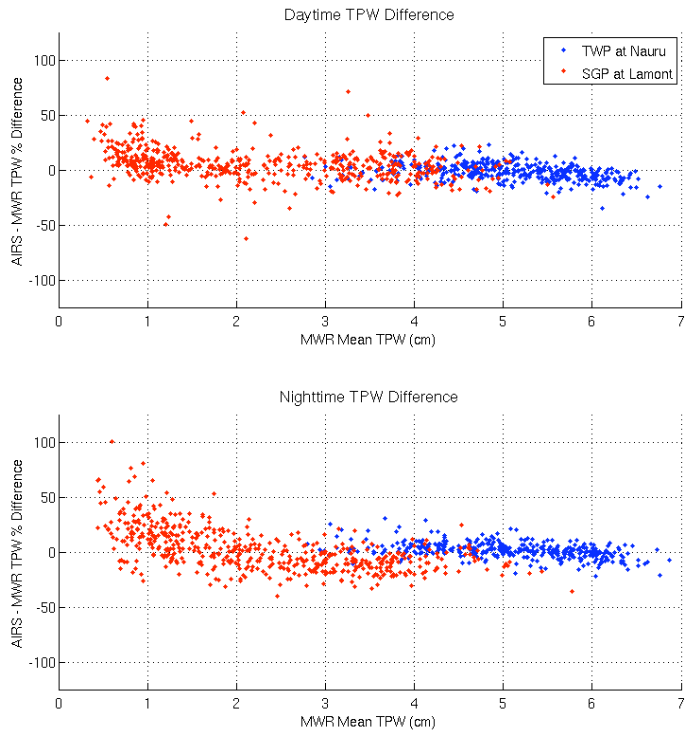

Figure 6. Percent difference between AIRS and MWR TPW at TWP (blue) and SGP (red).

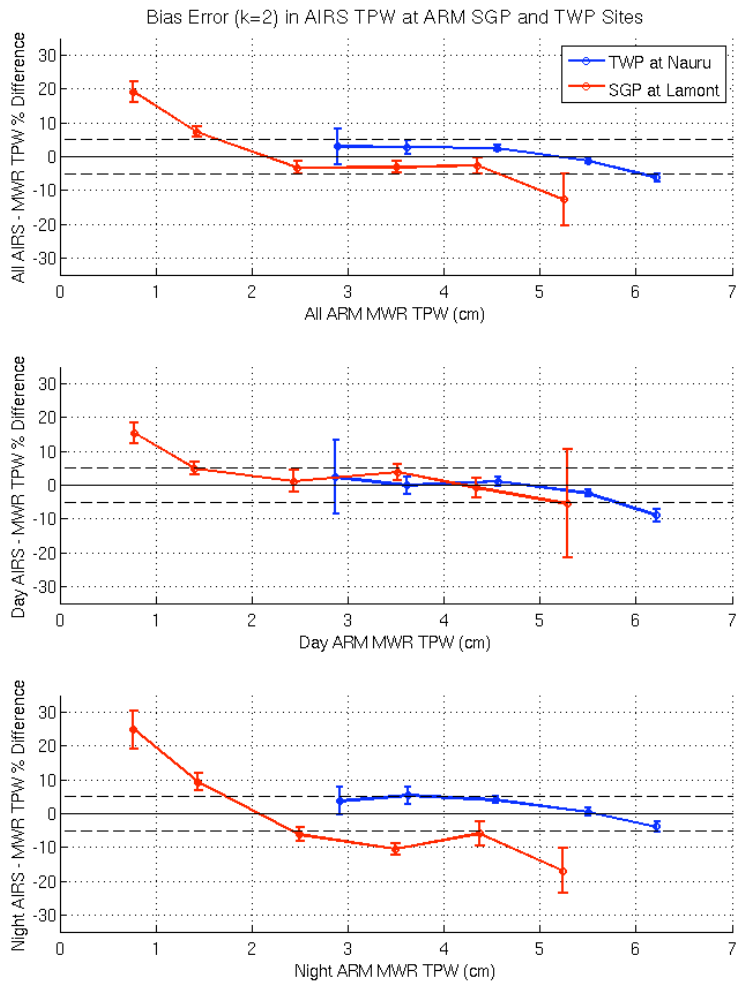

Figure 7. Percent difference between AIRS and MWR TPW for 1 cm bins, for all daytime + nighttime data (top), daytime data only (middle), and nighttime data only (bottom). Data from TWP (SGP) are plotted in blue (red). Error bars are the uncertainty in the mean % difference for a given bin (k=1).

7. FUTURE WORK

AIRS TPW is within about 5% of the MWR for total water amounts greater than 2 cm but nearly 20% for amounts less than 1 cm. Additionally, the AIRS retrievals have a significant dry bias with respect to the MWR during the nighttime summer over SGP. Future work will seek to examine the potential correlation of this bias with surface emissivity characterization at this site. Also, accuracies of the retrieval at lower water amounts will be addressed by including comparisons at the ARM North Slope of Alaska (NSA) site. The ability of AIRS to detect diurnal changes in TPW will be documented using data from all three ARM sites, and the nighttime (and/or site specific) retrieval biases will be further examined.

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