THE VALIDATION OF GOES-LI AND AIRS TOTAL PRECIPITABLE WATER RETRIEVALS USING GROUND-BASED MEASUREMENTS

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Abstract

The Cooperative Instittute for Meteorological Satellite Studies (CIMSS) Geostationary Operational Environmental Satellites (GOES) NearCasting System is designed to monitor and predict pre-storm environments in which severe convection is likely to occur over the next 1-9 hours. The hourly-updated system is exceptionally data-driven and is highly dependent on accurate measurements of atmospheric moisture content. The NearCasting System uses three deep-layers of Precipitable Water (3LPW) provided by the retrievals determined from GOES Sounder observations, using the Li et al. (2008) version of a physical algorithm for retrieval of vertical atmospheric profiles. The three individual layer measurements can also be added to determine the Total Precipitable Water (TPW) in each retrieval. Experiments with the NearCasting System, however, have pointed to a number of potential issues with the GOES-Li moisture retrievals, most notably diurnally varying biases (systematic error) and an apparent annual cycle in random errors.

In order to determine the characteristics of and correct these errors throughout the day and from season to season across the Contiguous United States (CONUS), GOES-Li retrievals from all hours of the day during 2011 have been compared to a variety of high-quality ground-based asynoptic observations available throughout the day, including TPW from a network of surface Global Positioning System (GPS) Receivers found across the CONUS, as well as 3LPW observations derived from the Southern Great Plains Atmospheric Radiation Measurement (SGP-ARM) Microwave Radiometer (MWR) and Raman-Lidar (RL) systems. Background 03-09 hour NOAA Global Forecast System (GFS) model forecast fields used in the GOES-Li retrieval processing were also compared against the retrievals themselves at ground based sites using the same validation experiments to help determine the source of the bias errors and whether the GOES data reduce random errors in other forecast products. The validation methods were partitioned by month, diurnal cycle, and cloud amount. Validation of the GFS forecast provide useful information on model bias, with differences discovered between GOES sectors (East and West). Retrievals over the CONUS from the Advanced InfraRed Sounder (AIRS) retrievals onboard the NASA polar orbiting AQUA satellite were also compared against the ground based GPS and SGP-ARM data, when available, to determine their utility in subjective forecaster applications and to provide independent measurements of cloudiness.

Results showed that the strong diurnal variations in bias were highly correlated with similar biases in the GFS first guess fields in the TPW fields. The quality of the GFS background TPW fields also varied from one forecast cycle to another, with substantially larger biases and random errors in the runs started at 1200 and 1800 UTC. The largest reduction in random errors (i.e., correct information is added) from the satellite observations used in the GOES-Li retrievals occurred during the warm months. Substantial vertical differences in the biases (both GFS and GOES retrieval) were also observed in the 3LPW data, with the moisture in the lowest 100 hPa having the largest positive bias. Finally, although the monthly biases in the GOES-Li retrievals of TPW show a substantial annual cycle, the relative biases (calculated as the monthly bias divided by the month mean TPW value) show little annual variability and therefore should be useful as a means of removing cycle-to-cycle bias changes observed in NearCast evaluations.

INTRODUCTION

Geostationary sounders provide important information about the current state of the vertical structure of the atmosphere, especially moisture. The focus of this paper will be the vertical structure of moisture in the atmosphere, specifically the 3LPW derived from the existing GOES sounders. Although the geostationary sounder information is under utilized in current National Weather Prediction (NWP) models, it is being utilized to provide an initialized pre-convective environment in the University of Wisconsin CIMSS NearCast model. The NearCast model assimilates the GOES sounder PW observations from 2 layers: 900->700 and 700->300 hPa. The NearCast model utilizes temperature and moisture retrievals to forecast stability parameters in pre-convective environments.

To diagnose the quality of satellite sounding retrieved PW, comparisons are made to an array of Global Positioning System (GPS) PW measurements across the United States (Fig 1). We also compared the PW to the Raman Lidar (RL) at the SGP-ARM site in Lamont, OK to get a better understanding of the PW errors within the 3LPW. This study will illustrate diurnal and seasonal biases discovered in the GOES-Li product that are related to the biases observed in the GFS model that is used as the first guess. Both the eastern (<100˚ W) and western (≥100˚ W) CONUS sectors are compared to the GPS data, with differences between sectors observed. An inter-comparison of GOES-13 (East) with GOES-11/15 (West) is also done. Furthermore, PW data from the official operational version 5 of the AIRS retrieval algorithm is also validated against the GPS to determine if they could be used to improve upon GOES-Li moisture retrievals. AIRS cloud fractions are used to investigate how cloud amount affects the quality of the moisture retrieval of both AIRS-v5 and GOES-Li. The results from this study will assist in making bias corrections to the sounder PWs when assimilated into the NearCast model.

Before the results are discussed in detail, the GOES-Li and AIRS-v5 sounder datasets are explained, as well as the GPS and SGP-ARM RL instruments. After the results are presented, a detailed summary will be provided with a synopsis of the major findings presented.

DATA

For the entire period (01 Jan – 31 Dec 2011), the GOES Sounder moisture retrieval used in this study is that of Li et al. 2008. The GOES Sounder has 18 infrared spectral bands (and one visible), with a nominal sub-satellite spatial resolution of 10 km. Each 3X3 Field of View (FOV) area is repeatedly used to determine the clear or cloudy conditions of each central pixel, with only clear profiles are permitted (Dostalek and Schmit 2001). Prior to 05 Dec 2011, the GOES-11 sounder was used as the primary instrument for moisture retrievals across the western CONUS (>100˚ W) sector. After the aforementioned date, the improved GOES-15 sounder was used in the West (Hillger and Schmit, 2011). Depending on location, a GOES Sounder takes measurements in either a period from hr plus 46 min to hr plus 16 min in the east, or from hr plus 01 min to hr plus 20 min in the west.

AIRS, flying on board the low earth orbiting AQUA satellite, is a cross-track hyperspectral scanning instrument with a scan swath of 800 km, a spatial resolution of 13.5 km at nadir and a complement of 2378 spectral channels (***http://airs.jpl.nasa.gov/instrument/how_AIRS_works/***). The plethora of channels allows for higher and more precise (~1 km) vertical resolution than current GOES sounders that lack the vertical resolution due to fewer and broader weighting functions. At middle latitudes, the instrument makes two overpasses over the same location during a 24 hour period. Over the CONUS sector, these occur during the day between 18-20 UTC and at night between 06-08 UTC. The derived TPW from Level-2 version 5 standard products are used for the validation comparisons below. The AIRS retrievals are produced over a 3 X 3 FOV array, such that they fit into one FOV (40 km) of the Advanced Microwave Sounding Unit (AMSU), which is used in generating a cloud cleared profile regression first guess (Maddy et al. 2008).

A network of ground-based GPS receivers over the CONUS is used to validate the quality of GFS, GOES, and AIRS TPW values (Fig 1). A detailed review of the use, location and implementation of the GPS Meteorology (GPS-Met) array to determine TPW is given by Rama Varma Raja et al. (2007).

Though GPS is unable to provide vertical distributions of moisture, it is able to provide accurate TPW measurements (Leblanc et al. 2011) from the wet delay term (Wolfe and Gutman, 2000) throughout the day and night. The observation times of GPS TPW typically occur 15 min before and after the top of the hour.

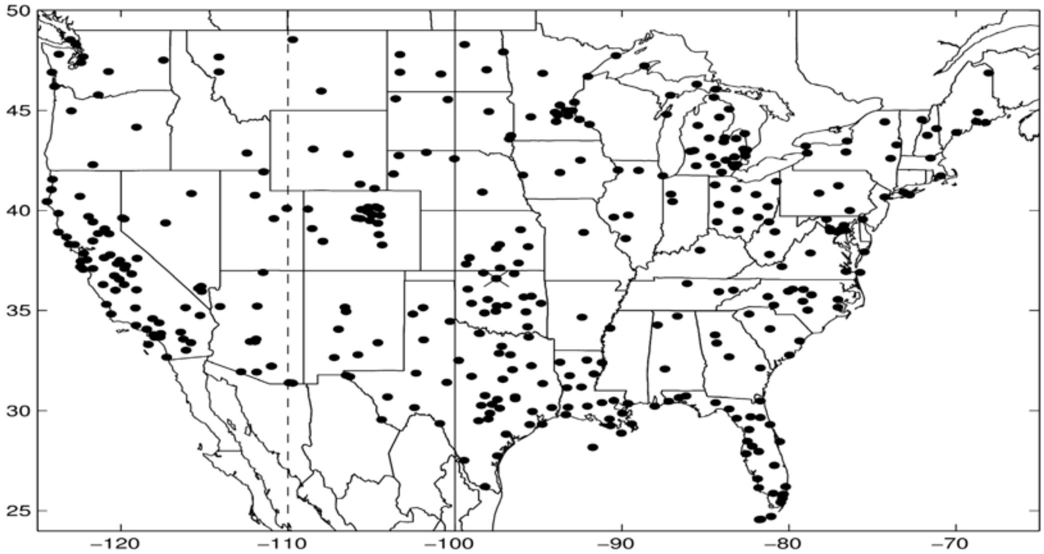

Figure 1: **TPW inter-comparison sites. Denoted are the locations of GPS receivers (dots) and the SGP-ARM site in north-central Oklahoma (X). The black line at 100˚ W is a boundary delineating GOES-13 (East) from GOES-11/15 (West) sector retrievals that are used in comparisons. The dashed line at 110˚ W is a boundary to delineate two sectors across the western domain.**

For further validation of GOES-Li, GFS and AIRS-v5 retrievals, and to provide information about the TPW and vertical distribution of PW, the Raman Lidar (RL) is used at the SGP-ARM site near Lamont, OK (36.61˚ N, 97.49˚ W). The purpose of SGP-ARM is to improve scientific understanding of radiative feedback processes in the atmosphere, and to provide continuous field measurements that promote the advancement of forecast and climate models (Mather and Voyles, 2013). All datasets provided are final best-state results, with observations taken every 10 minutes. The provided RL mixing ratios allow for PWs to be calculated, with quality checks (i.e., sanity check with co-located MWR data) to provide assurance that only the best quality RL moisture values are used in the validation.

RESULTS

GOES-Li and GFS TPW are compared to GPS-Met when the distance between GPS and GOES clear-sky retrieval is 0 km or when multiple clear-sky retrievals within 25 km are present surrounding the GPS receiver, so that a bi-linear interpolation of both the GOES-Li and GFS TPW to the location of the GPS can be acheived. It is observed in the monthly statistics (Standard Deviation, and Bias) of such collocation comparisons (Fig 2) that they are close to one another, with GOES-Li predominantly wetter than the GFS. However, the Standard Deviation Error (SDE) of GOES-Li is noticeably improving upon the GFS during the CONUS convective warm season (May-Sep). This period is also associated with poor performance observed in precipitation forecasts in the short-term forecasts of operational models (Romine et al. 2013;Fritsch and Carbourne 2004).

	June		**July**		**August**	
	GOES-Li	**GFS**	**GOES-Li**	**GFS**	**GOES-Li**	**GFS**
00 UTC	-0.44	-0.49	-0.38	-0.81	+0.20	-0.78
06 UTC	-0.65	-0.30	-0.09	-1.40	+0.21	-0.80
12 UTC	+0.64	0	+1.25	-0.28	+1.21	-0.17
18 UTC	+0.49	+0.75	+0.97	+0.43	+1.01	+0.20

Table 1: **Comparison of the GOES-Li and GFS at GPS sites, with results broken down by model runtimes 00z (04-09 UTC), 06z (10-15 UTC),12z (16-21 UTC) and 18z (22-03 UTC). The values provided are the bias (mm).**

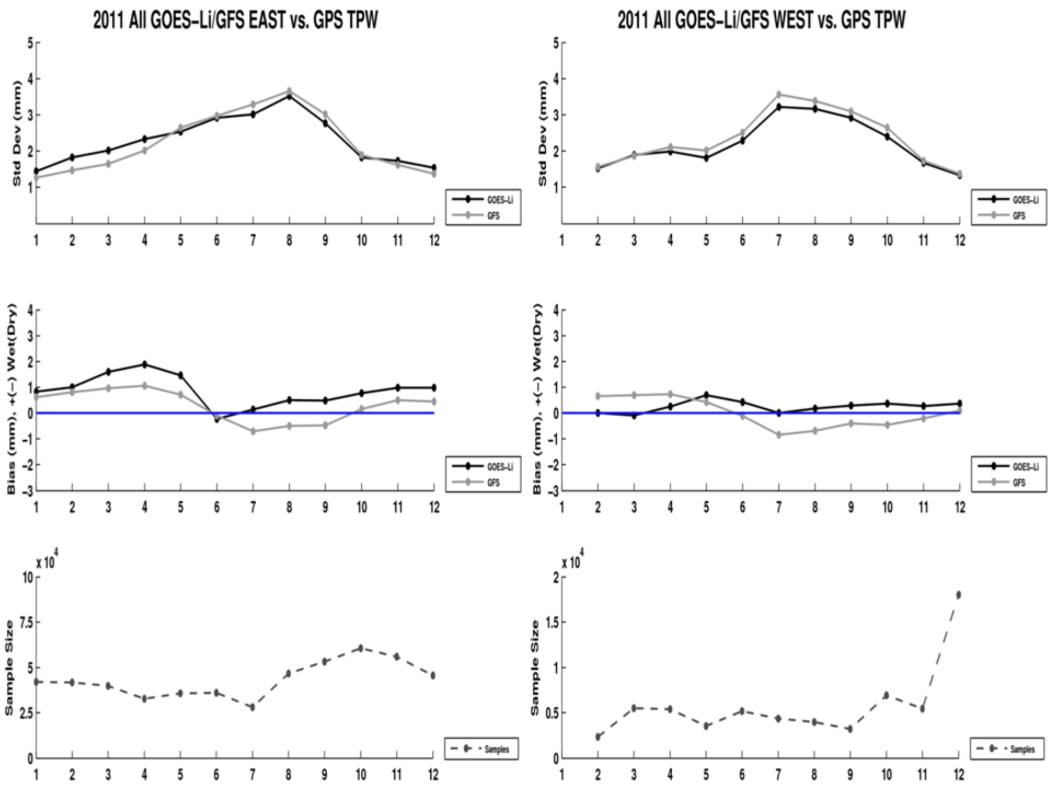

Figure 2: **2011 Standard deviation (top), bias (middle), and sample size (bottom) for TPW of 2011 bi-collocations, by month, of GOES--Li and GFS for the East (left) and West (right) domains at GPS sites across CONUS.**

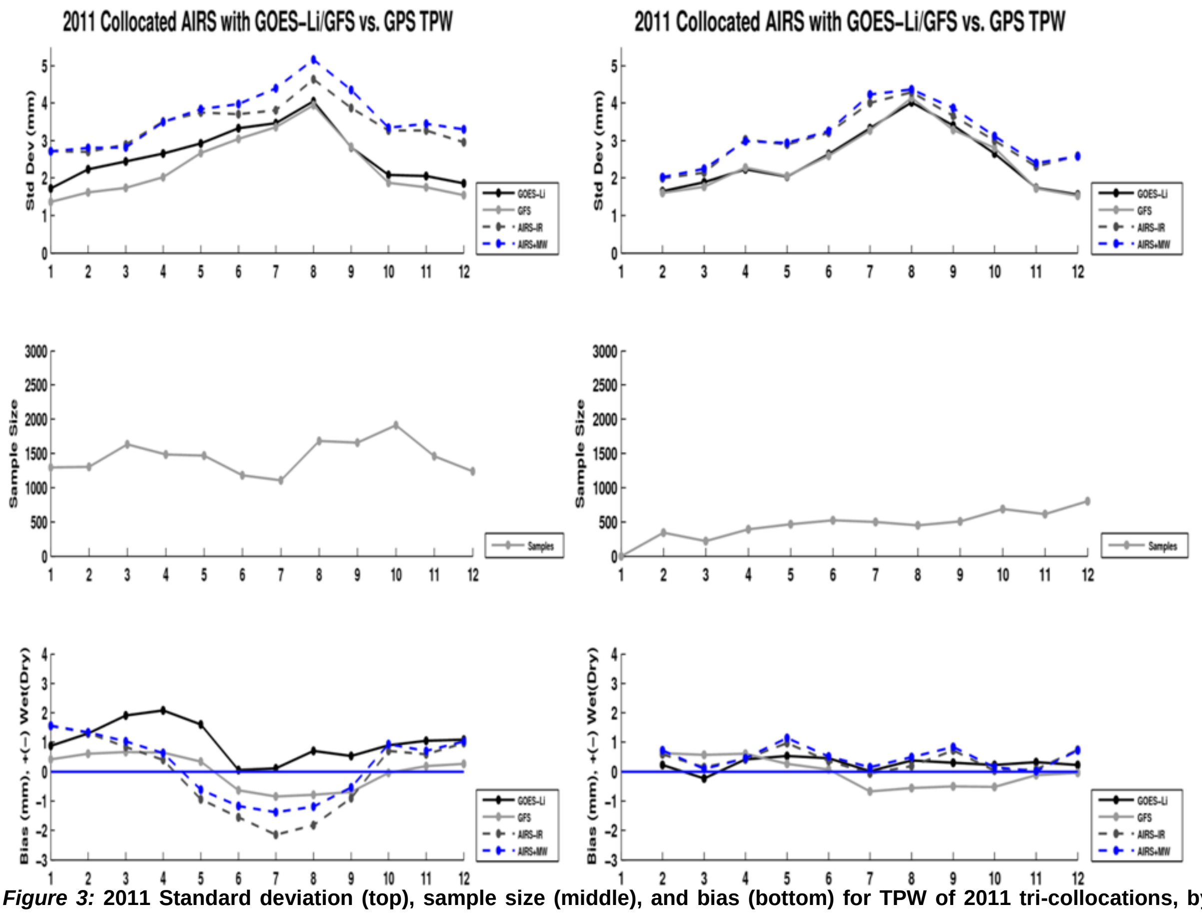

Figure 3: **2011 Standard deviation (top), sample size (middle), and bias (bottom) for TPW of 2011 tri-collocations, by month, of GOES-Li, GFS, and AIRS for the East (left) and West (right) domains at GPS sites across CONUS.**

A strong diurnal or model run dependent cycle in the comparison statistics is observed during the summer with the GOES-East retrievals (Table 1). The GOES retrievals are noticeably moister than the GPS when the 12 and 18 UTC model run times are used as background (16 to 03 UTC GOES sounder retrieval times). Also of note is the dry bias associated with the GFS 00 and 06 UTC model run times (04-15 UTC GOES sounder retrieval times) during the summer.

When a three-way (tri-collocation of retrievals within 25 km of GPS) comparison of GOES-Li/GFS and AIRS-v5 is made with GPS (Fig 3), it is confirmed quantitatively that maximum (minimum) random errors occur late in the summer (mid-winter), with winter and spring biases for GOES-Li and GFS being obviously wet over the eastern domain. A dry bias is observed for GFS during the summer, while the GOES-Li bias is closer to neutral during the Jun-Jul period over the eastern domain (Fig 3). Late in the summer and continuing into autumn, the bias in GOES-Li becomes positive. The GFS bias over the same period is dry during Aug-Sep and closer to neutral during Oct-Dec. In addition, it becomes apparent that the GOES-Li has smaller SDE than AIRS-v5, indicating that even with superior vertical resolution, the AIRS-v5 products exhibit deficiencies in their retrieval processing. These issues may include over-zealous channel filling (Manning and Lee 2007), land emissivity uncertainties (Hulley, 2009), coarse horizontal resolution resulting in fine scale wet features inside the AIRS sounding FOV being averaged out by broader dry regions (McMillin et al 2005), missing determination of background errors in the H20 band (Joiner et al. 2007) and sub-pixel clouds in larger FOVs that can all lead to spurious TPW that adversely affects the output statistics.

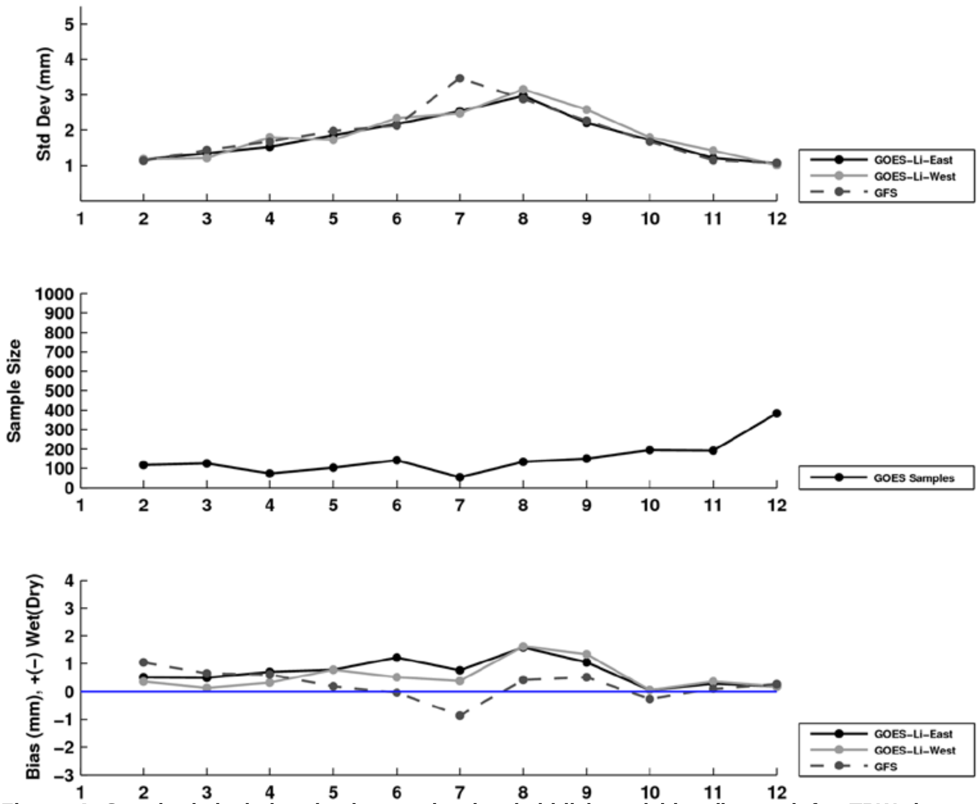

Figure 4: **Standard deviation (top), sample size (middle), and bias (bottom) for TPW, by month of 2011, of direct comparison of GOES-Li East (13) versus West (11/15) at GPS sites in the overlap region of 100˚ to 110˚ W.**

When the GOES-Li East and West are compared directly at GPS sites across the 100-110˚ W overlap region in Fig 4, it is seen over the first six months of the year that the GFS, GOES-East and GOES-West retrievals have similar SDE, with GOES-West having slightly higher (lower) SDE in Apr (Mar) and Jun (May). In July, the GFS has a 1 mm higher SDE than both GOES-East and West; however, the sample size for that month is only 53. As the sample sizes rebound for Aug onward, the GOES-West has higher SDE, with GOES-East having a SDE closer to the GFS. By the time the superior GOES-15 sounder replaces GOES-11 over the west in Dec, both GOES-15 and GOES-13 obtain SDE similar to GFS. When broken up into two sectors (>110˚ and 100-110˚ W), it is was found that GFS moisture profiles have a dry bias over the far west; however, eastward of 100˚ W the bias is reduced.

When the bias is broken down by cloud fractions provided from AIRS-v5 (Fig 5), the GOES-Li relationship acts like a step function with a +0.5 mm jump observed in the bias as the cloud fraction approaches 0.1, but remaining fairly steady for higher cloud amounts. For AIRS the relationship to cloud fraction is observed to be of reverse sign (dry) and more linear. Overall in the eastern domain it is apparent that the retrievals (especially AIRS-v5) do better when the scene is mainly clear, and that in partly cloudy conditions moisture profiles should be used with caution.

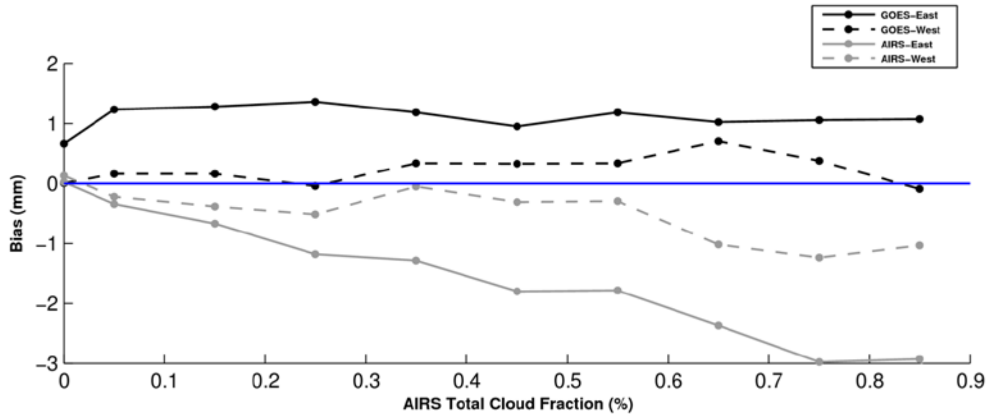

Figure 5: **The relationship between AIRS Total Cloud Fraction (x-axis) and TPW bias (y-axis) for both GOES-Li and AIRS TPW values in 2011, distinguished by location (west or east domain across CONUS).**

Comparisons with RL at the SGP-ARM site is broken down into the 3LPW (Table 2) to help asses vertical information content in the satellite retrievals. Overall, a significant wet-bias in GFS and GOES-Li is relegated to the near surface (>900 hPa) layer; above this a dry bias is observed. The dry bias is strongest in the 700-900 hPa PW layer, where the GFS and GOES-Li have SDE between 5-10% of the RL TPW. In the 300-700 hPa PW layer, the GOES-Li has consistently higher accuracy than the GFS while maintaining a slight (< 5%) dry bias (Feb being the exception). In the >900 hPa layer, at this single location the GOES-Li and GFS maintain a SDE between 4-8% of the Lidar TPW. The GOES-Li moisture retrievals tend to slightly reduce (< 2%) the significant wet bias in the first guess, however they show a slightly larger SDE for the majority of year, with an improvement in precision over the GFS especially occurring in Jan-Feb and Sep-Oct.

Noticeable differences in bias from night to day are evident when looking at the diurnal (04-09 versus 16-21 UTC) statistics (Table 2). The dry bias above the near surface layer is strongest at night and weakest during the day. In the 300-700 hPa layer, the bias is more persistent at night, while remaining weak to non-existent during the day. In the 700-900 hPa layer, the dry bias remains strong in both periods, even with noticeable weakening of the bias during the day with Feb, Jun and Aug being the exceptions. A strong moist bias is consistently observed in both day and night in the > 900 hPa layer, with a slight increase in the moist bias observed during the day versus night. The greatest precision occurs especially in the 300-700 hPa layer for the nighttime period, with the GOES-Li showing the better precision over GFS throughout the year. Below 700 hPa, the quality is worse with more inconsistencies between the GFS and GOES-Li. The accuracy for GOES-Li and GFS is mainly better during the day versus night in the 700-900 hPa layer. In the near surface layer during the day, the precision for GOES-Li is especially better (worse) than GFS during the Sep-Oct (Mar-May) periods.

	GOES-Li 12Z (Day)	**GFS 12Z (Day)**	**GOES-Li 00Z (Night)**	**GFS 00Z (Night)**
300<-700 hPa	-0. 56 (0.89)	-0. 77 (1.08)	-2.22 (0.87)	-1.86 (1.08)
700<-900 hPa	-3.99 (2.26)	-3.18 (2.01)	-5.53 (2.37)	-5.67 (2.17)
>900 hPa	+8.20 (1.29)	+9.32 (1.27)	+6.71 (1.27)	+6.61 (1.29)

Table 2: **Comparison of the GOES-Li and GFS 3LPW (far left column) at the SGP-ARM Raman Lidar site, with results broken down by model runtimes 12z daytime sounder retrievals (16-21 UTC) and 00z nighttime sounder retrievals (04-09 UTC). The values provided are the relative bias (%) compared to RL monthly mean and SDE (mm) within paranthesis .**

The AIRS-v5 retrievals were also compared to the SGP-ARM RL (Table 3). Due to a limited number of collocations with 315 in total for 2011, only absolute biases are shown. A similar pattern emerges with the AIRS-v5 having a wet bias in the >900 hPa near surface layer, and dry bias in both the 900->700 hPa and 700->300 hPa layers. Radiosondes have been observed to be drier (wetter) than AIRS in the lower (upper) atmosphere (McMillin et al. 2007), and discernible dry bias has been noted by Jones and Stensrud (2012) in the AIRS 700-500 hPa mixing ratios when compared to radiosondes. Comparatively, the biases when compared to RL for the two layers >900 hPa and 900->700 hPa for GOES-Li were similar to AIRS-v5, with GFS having a larger wet bias than both GOES-Li and AIRS-v5 in the >900 hPa layer and a smaller dry bias than both in the >700-900 hPa layer. The statistics indicate that the AIRS-v5 retrievals have a significant dry bias above 700 hPa, and a dry bias similar in magnitude to GOES-Li in the 900-700 hPa layer, while having a wet bias that is 0.43 mm less than the GOES-Li in the >900 hPa layer. Furthermore, this reinforces the influence that the first guess (GFS) has on the final GOES retrieval product.

	AIRS-v5	GOES-Li	GFS
300<-700 hPa	-1.40	-0.16	-0.29
700<-900 hPa	-1.31	-1.19	-1.11
>900 hPa	+1.29	+1.72	+1.87

Table 3: **Comparison of the GOES-Li, GFS and AIRS-v5 at the SGP-ARM Raman Lidar, with results broken down into 3 LPW. The values provided are the absolute bias (mm).**

CONCLUSIONS

Knowing the vertical structure of moisture in the atmosphere is vital for convective forecasting, such as in the UW NearCast System. Knowing the quality of derived soundings from geostationary such as GOES and polar orbiters such as AQUA AIRS are essential to determine TPW. These PW values for the latest GOES-Li and AIRS-v5 algorithms are validated against an array of GPS units across CONUS that provide accurate measurements of TPW. Furthermore, at the SGP-ARM site the GOES-Li TPW and AIRS-v5 3LPWs are compared to Raman Lidar.

Comparisons of GOES-Li to GPS indicate a distinct warm-season (Jun-Aug) diurnal cycle to bias that is related to GFS model runtime, with daytime (nighttime) retrievals when 12 and 18 (00 and 06) UTC GFS are used as first guess, a wet (dry) bias is observed, with the GOES-Li consistently wetter than the GFS first guess. The AIRS-v5 bias over the eastern CONUS is shown to be consistently dry during the warm season, while the AIRS-v5 SDE is consistently larger than the GOES-Li and GFS. The SDE for GOES-Li is larger than GFS in the cold season and similar to and slightly lower than GFS during the warm season. This is especially evident over the GOES-West domain (≥100˚ W). A reduced SDE that the GOES-Li retrievals have over GFS in the warm season points to the problems that forecast models have in resolving vertical and horizontal moisture structures in warm and potentially convective environments. It is shown that both the GOES-Li and AIRS-v5 do better in clear FOVs; however, problems arise when the moisture retrievals in non-clear FOVs are evaluated. The AIRS-v5 experiences an increasing dry bias with increased cloud fraction, while GOES-Li has a stepwise wet bias that is sensitive to small cloud amounts wih a flattening above cloud fractions of 0.1. Interestingly, the sensitivity to cloud fraction for both GOES-Li and AIRS-v5 over the western CONUS is noticeably less distinct.

Comparison at western CONUS GPS stations, in particular, shows a more pronounced period of lower SDE for the GOES-Li compared to GFS. When the west is separated into two sectors, it was found that the greatest reduction of SDE seen in GOES-Li versus GFS is originating west of 110˚ W. It was also found that over the far west the GFS has pronounced dry bias from Jul through Oct. When the bias and SDE of GOES-East and GOES-West are compared directly in the overlap region, it is observed that the biases are similar with GOES-East having lower SDE than GOES-West, which is to be expected, because the GOES-11 sounder has been shown to have more noise and coarser resolution than the GOES-13.

To get a better understanding of the GOES-Li and AIRS-v5 PW retrieval quality among the 3LPW (>900 hPa, 900->700 and 700->300), RL moisture retrievals at the SGP-ARM site in north-central OK are used. The GOES-Li shows the best quality in the 700->300 hPa layer, with minimal daytime bias and random error that is consistently lower than the GFS. Even though random error remains low in the GOES-Li at night, a more persistent dry bias is observed. On the other hand, AIRS-v5 has much larger relative dry bias than both GOES-Li and GFS in the 700->300 hPa layer. In the 900->700 hPa layer, a persistent dry bias is observed in all retrievals, with the relative magnitude of the bias being larger at night for GOES-Li and GFS. Apparent is the significant moist bias observed in all retrievals in the the near surface layer. This is most likely a product of the GFS being used as a first guess. The AIRS-v5 tends to have the smallest bias in the near surface layer, which is possibly the result of the AIRS having many more sounding channels which are better than the few available on the GOES Sounder for resolving the near surface layer.

The results from this study can potentially be used to improve upon current satellite-based moisture retrievals by better accounting for biases, especially related to cloud cover. Furthermore, these results could also be used to develop bias corrections for the satellite retrieval moisture data assimilated into the GOES NearCasting System, thereby improving its results and reducing forecast error.

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