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IMPROVED GOES WATER VAPOR PRODUCTS OVER CONUS – PLANNING FOR GOES-R

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1. INTRODUCTION

The investigation of the Geostationary Operational Environmental Satellite (GOES)-12 total precipitable water (TPW) product data and the coinciding Global Positioning System (GPS) TPW record for the past year and a half has revealed that the moist bias in GOES-12 sounder-derived products remains similar to that from other GOES satellites and is consistent over time. Despite joint efforts with the Cooperative Institute for Meteorological Satellite Studies (CIMSS) and National Environmental Satellite Data and Information Service (NESDIS) to modify the sounding retrieval algorithm, bias error characteristics (as compared to GPS TPW) are very close to data sets garnered during the 2002 International H2O Project (IHOP) from GOES-8 and GOES-11. So the compelling question for us at Earth System Research Laboratory (ESRL) is just how can we best use the GPS asynoptic data to improve the satellite operational products? If we improve the current GOES product data, will we be able to produce a better GOES-R product? The result is work summarized by this paper in which we established a means to characterize the current GOES error based on past data and apply the correction in real time to new product data; furthermore, we examined the characteristics of proxy GOES-R advanced baseline imager (ABI) data derived from current moderate resolution imaging spectroradiometer (MODIS) polar orbiter data and assessed its performance.

2. THE GOES AND GPS DATASETS

GOES-12 data were acquired from NESDIS Center for Satellite Applications and Research (STAR) and the development and testing group that prepared the product prior to releasing it to NESDIS operations to support National Weather Service activities. Typically, the data were gathered from the second of a three-step process to get the data products to the field. The first step was to develop an algorithm. This was done at the University of Wisconsin (CIMSS). The second step was to test the initial product on a routine basis at NESDIS (the data used in this study); and the third was to produce the actual data. We chose to assess the data in the second level of development since it was one step ahead of operational status (somewhat improved) and perhaps not as frequently modified as the development dataset. Furthermore, it could potentially be modified if we discovered some kind of issue that could be corrected. For the most part, the data used here were fairly close to what was operationally produced by NESDIS. Typically, GOES sounder radiance data is the main ingredient in solving a retrieval of thermal and moisture profiles. The moisture profiles are then integrated to compute total precipitable water fields.

GPS-TPW data were produced at ESRL using techniques for production that have become routine after about a decade of development. The system is scheduled to be transferred to the National Weather Service for operational management. The acquisition of water vapor from GPS satellites is tantamount to discerning the change in the speed of light through the atmosphere due to the presence of water vapor (Wolf and Gutman 2000). The determination of water vapor-induced "signal delay" is used to derive a value for the zenith "equivalent" integrated water. Unlike satellite sounder retrievals, the distribution or profile of the water vapor in the vertical is

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not derived; only the sum total can be computed.

Even though the satellite and GPS are totally different systems, and use different techniques to compute TPW, the end result is the same. The GPS system is known to be more accurate, comparable to ground-based passive microwave measurements and much better than traditional radiosonde data. In fact, GPS measurements have been used to identify bad batches of radiosonde instruments. The typical precision of GPS water measurements is on the order of 0.2 to 0.3 mm liquid water equivalent. What GPS lacks is the ability to reveal the vertical distribution of moisture. Also GPS measurements are essentially point data collected from working groundstations. Conversely, GOES data offer the potential for vertical moisture detail, have fairly continuous horizontal measurements (for clear regions, cloudy areas cannot be sensed in the full atmospheric column in the infrared), and are available on an hourly basis.

The GOES-12 data used in this statistical assessment were archived coinciding with GPS-TPW data (Birkenheuer and Gutman, 2005) over the course of about two years. Pairs of data were identified satisfying the criteria that the distance between the GPS and satellite locations were within 10km and both data samples were collected within 20 minutes. We did not discriminate whether the GPS or GOES data were obtained first or second. This was similar to the same criteria used in the IHOP data comparison effort.

No attempt was made to quality control the analyzed data. Both GOES- and GPS-TPW were essentially in their rawest form that one would use operationally. It became evident after assessment that some GPS data suffered from poor orbital predictions and bad data values. Accurate GPS satellite orbit information is an essential requirement for good GPS water vapor derivation. However, these processing breakdowns were few, and given the size of the overall dataset (nearly 1.8 million pairs) were deemed insignificant.

Of course, one motivation for this work was to not only characterize the GOES bias (differences between GOES and GPS), but also to see if applying a correction based on this characterization would be useful on real-time data acquired after this sample was evaluated. Furthermore, another point of interest was a comparison of this evaluation to that of GOES-10 data with GPS. GOES-10 data were acquired at roughly the same time as the GOES-12 data set, but the GOES-10 acquisition was begun at a later date, resulting in a smaller sample. Also, there were not as many matches between GPS sites and GOES-10 because there are fewer GPS sites in the western conterminous United States (CONUS).

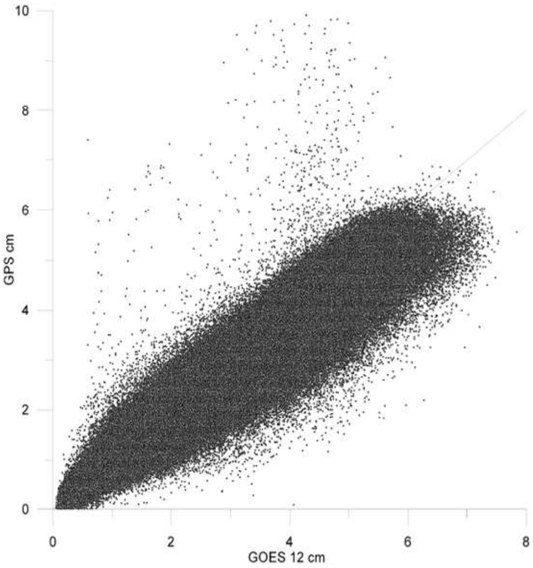

Fig. 1 above shows the scatter plot of roughly 1.8 million GPS-GOES-12-derived total moisture comparisons for approximately 1.5 years, ending January 2007. A 1:1 line is plotted from 0.0 to 8.0 cm. This exhibits a GOES moist bias similar to what we observed during IHOP 2002; as moisture amount increases, the GOES bias increases. We refer to this as the rooster tail effect since the moist bias appears to curve toward a greater bias at higher moisture levels. The above plot is for all times of day and is a sum total of all observations. Even with these remaining in the data set; they are still dwarfed in number by the huge volume of points plotted near the 1:1 diagonal.

Hourly bias (focusing on asynoptic times) was examined similar to what was done for the IHOP data analysis, Birkenheuer and Gutman 2005. This reveals a strikingly similar pattern (Fig. 2) in which minima are seen near 00 UTC and 12 UTC while intervening times have the bias figures climbing. The overall moist GOES bias is computed to be near 0.2 cm for the entire data set. The hourly values lay on either side of this value.

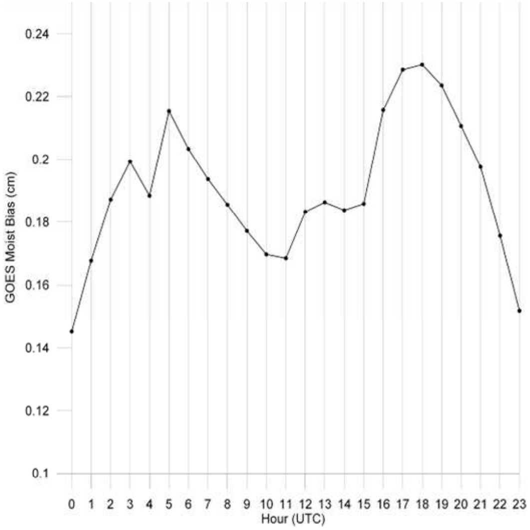

Fig. 2 Shows the hourly bias observed in the data set acquired for GOES-12 and GPS paired comparisons from June 2005 to January 2007. The essence of the bias characteristics for this data set emulates the observations made during IHOP 2002. Again the lowest bias is at 00UTC and a secondary minimum is at 11UTC, identical to the IHOP results.

2.1 *GOES-R ABI Data*

GOES-R ABI data was synthesized by CIMSS and the National Aeronautics and Space Administration (NASA) for the use of this and other testing (Schmit et al. 2005). Near real-time ABI-synthesized TPW product data were devised for testing using MODIS data for a basis. A subset of MODIS channel data were used to generate synthetic ABI products for preliminary GOES-R testing.

The ABI data were acquired via FTP download and added to our GPS real-time database infrastructure in the same way that we treat conventional GOES. Therefore, all of the tools that were developed for assessing and characterizing GOES data could readily apply to GOES-R ABI. Similar to traditional GOES, difference (bias) statistics were derived from these data. Figure 3 shows the primary statistics from the ABI synthetic data acquired and measured against GPS data since roughly mid-July 2007.

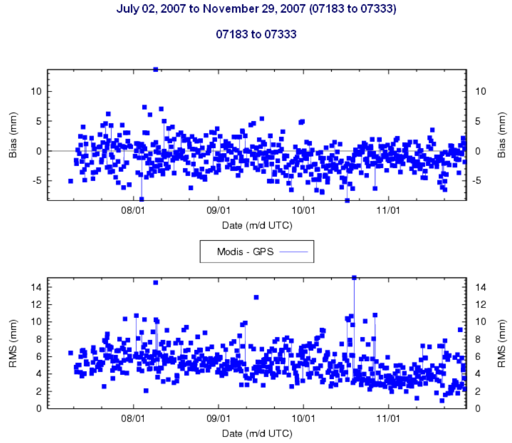

Fig. 3 Plots bias (ABI-GPS) mm above and root mean square (RMS) of the difference data below. What is labeled as MODIS is in fact proxy ABI data. The trend seen in the ABI data was initially near zero bias but as we moved into a drier season, the ABI product appears to become dry biased. Overall RMS statistics decrease as the seasonmoves to the dry time of year. No removal of outliers was performed on these plots. The handful of high RMS values (greater than 10 mm) can likely be ignored.

Even though the ABI data appear to be dry biased, the fundamental differences compared to current GOES data appear to be lower. RMS values are certainly better with mean values in the 0.5-cm range falling with time as the atmosphere dries. The most worthwhile test period will be next spring when the CONUS moistens up and a higher moisture signal is available.

Figures 4a and 4b contrast the current GOES CONUS with ABI simulations for roughly the same day.

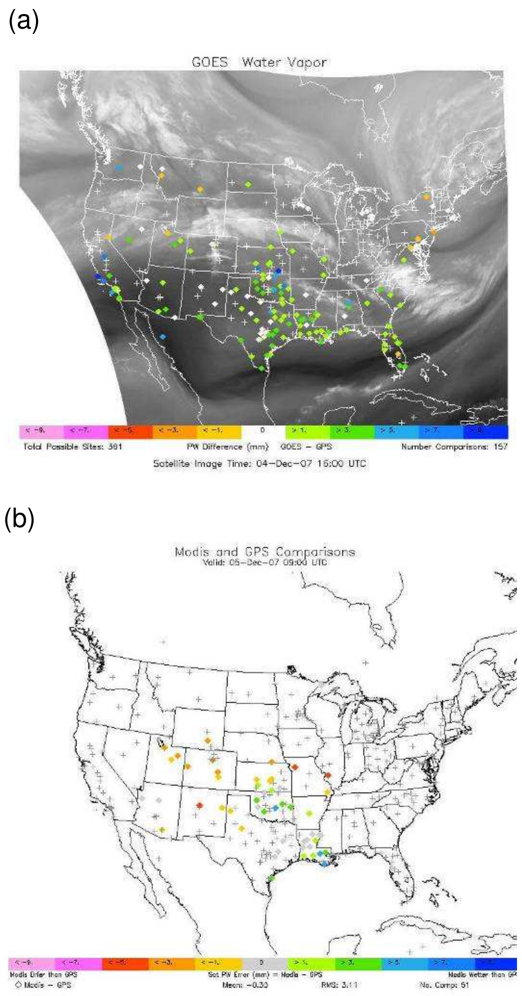

Fig. 4 Contrasts CONUS images of current GOES-(both 12 [east] and 11 [west] 16UTC 7 December 2007 in 4(a) above, and synthetic ABI data at 09UTC 7 December 2007 in 4(b), below. In 4a the GOES imagery channel 3 (6.7 micron) data is displayed beneath the plotted information. In both images, white 4(a) or gray 4(b) diamonds are most favorable as they show minimal differences between GPS data and the satellite-computed TPW.

As can be seen in Fig. 4, the ABI data appear to be drier than conventional GOES and for the most part closer to GPS measurements over this central CONUS comparison. When the comparison initially began in July 2007, a superior agreement between ABI and GPS was observed over conventional GOES since current GOES was routinely observed as moist biased (resulting in the correction algorithm discussed below). The initial reaction was that ABI product data was superior. However, as we now have had some opportunity to study more ABI data, we see that there might be a systematic dry bias that is now becoming more evident as we head into the normal dry climate season over CONUS. This tendency is most evident in Fig. 3, and requires further study.

2.2 *GOES Correction Algorithm*

The basic formulation of the bias correction was decided to be a power law relationship that would guarantee zero change for zero moisture (no imposed linear bias). Note in Fig. 1 that bias does tend to 1:1 as we near the zero point on the plot. Therefore, the overall correction strategy is:

$$G_c = aG^b \qquad (1)$$

where G_c are the corrected GOES moisture values, G are the initial product values as received from NESDIS, a is a scaling term and b is a power term, both dimensionless. The b term removes curvature from the paired measurements, while the scaling term helps to move the linear agreement to the 1:1 line. The selection of this fitting equation was made such that no absolute bias offset was defined.

The method of solution for (1) was variational analysis. This was chosen because it has an advantage over traditional linear least squares determination of coefficients a and b. In traditional least squares fitting of (1), the corrected GOES measurement G_c would be replaced with the corresponding set of GPS measurements. The log of the equation would be first taken rendering a linear equation. The log of the GOES moisture and log of GPS data would be terms used in computation of coefficients. The absolute values of very small (near zero) numbers would be very large, as well as numbers that were naturally large; however, the upper limit to the moisture values would typically be near 7 to 8 cm. For example, the log of 8 is 0.9 while the log of 0.003 is -2.522. Thus, very small and very large values drive the solution for the least squares since the absolute value of the log terms are largest at both extremes. Only focusing on very tiny and very large numbers results in a potentially unrepresentative correction.

Instead, the variational method was used as the following simple functional:

$$J = \sum_{i=1}^{N} (G_{ci} - GPS_i)^2 \tag{2}$$

where J was minimized via iteration using the Powell method (Powell, 1962) by modifying coefficients a and b from (1) and summed over all of the data (N points) consisting of paired (i) GOES and GPS data. The best fit (and lowest J value) therefore forced all of the corrected GOES measurements to be as close as possible in magnitude to GPS. The variational method puts direct linear weight on the water amount differences. Thus, small differences (less than one, even if they described large amounts of water) would likely carry almost insignificant weight in determining the result, while ever increasing values of moisture discrepancies would proportionally influence the correction terms.

Table 1 enumerates the tabulated statistical data for each hour and summarizes the plotted data in Fig. 1.

Table 1. Overall and Hourly Statistics of the GOES 12 compared with GPS TPW

Sample Size	**Difference mean (cm)**	**Difference sigma (cm)**
1846382	0.189(~0.2)	0.34

Hourly statistics:

			Hour
77149	0.145	0.327	0
79163	0.168	0.333	1
79677	0.187	0.341	2
79633	0.199	0.347	3
64712	0.188	0.354	4
55388	0.215	0.367	5
63340	0.203	0.364	6
78400	0.194	0.354	7
78478	0.185	0.356	8
79518	0.177	0.355	9
78712	0.170	0.360	10
78860	0.169	0.352	11
80721	0.183	0.350	12
83206	0.186	0.332	13
84387	0.183	0.320	14
81874	0.185	0.324	15
78148	0.216	0.325	16
74347	0.229	0.328	17
76359	0.230	0.330	18
76794	0.224	0.336	19
78273	0.211	0.331	20
80293	0.198	0.332	21
81052	0.176	0.325	22
77922	0.152	0.329	23

Referring to Table 1, we see that the hourly standard deviation (sigma) in many cases is less than the overall sigma for the entire population. It was not surprising to discover that the higher sigma values correlated with the hours containing the most curvature in the scatterplot (not shown).

Table 2 summarizes the terms *a* and *b* for each hour followed and Table 3 enumerates GOES-GPS differences and sigma on an hourly basis. There are many interesting highlights that can be gleaned from this information. The simple algorithm appears to work well providing a robust correction algorithm that is a function of hour. The hourly corrections after 16 UTC are interesting in that the *b* term, or power term, is near unity, which indicates that at these times there was minimal curvature in the bias, and the bias correction was more of a simple linear scaling function. On the other hand, hours 0 and 11 required more curvature and less bias correction.

Table 2: Hourly Correction Coefficients for GOES 12

a	***b***	**Hour**
0.979470611	0.952045858	0
0.96386236	0.958807886	1
0.951016307	0.962379932	2
0.932851493	0.974993765	3
0.938412488	0.973992229	4
0.928518832	0.971161544	5
0.932472348	0.975237787	6
0.936737478	0.97503674	7
0.943030536	0.971995413	8
0.945574582	0.972088754	9
0.953864217	0.967487574	10
0.952823639	0.967738211	11
0.944226384	0.970142543	12
0.934683204	0.977410853	13
0.928368866	0.98369354	14
0.923411667	0.988313854	15
0.90421778	0.997356713	16
0.896550059	1.00138319	17

0.896099865	1.00216639	18
0.900296807	1.00008261	19
0.905209124	1.00010216	20
0.923843801	0.986412048	21
0.942986071	0.975428104	22
0.970267594	0.958948851	23

The following shows a summary similar to the first table after applying the GOES correction algorithms. Bias results are near zero at all hours and we see a reduction in the GOES variance overall.

Table 3: Statistics after Applying Bias Corrections

Num	Bias (cm)	Sigma (cm)	Hour
77149	0.001	0.292	0
79163	0.002	0.297	1
79677	0.001	0.302	2
79633	-0.001	0.311	3
64712	0.000	0.320	4
55388	-0.000	0.323	5
63340	-0.001	0.325	6
78400	-1.90 E-05	0.320	7
78478	9.42 E-05	0.321	8
79518	-0.000	0.322	9
78712	0.000	0.330	10
78860	-0.000	0.320	11
80721	-0.000	0.314	12
83206	-0.001	0.296	13
84387	-0.002	0.284	14
81874	-0.003	0.290	15
78148	-0.005	0.286	16
74347	-0.005	0.290	17
76359	-0.004	0.293	18
76794	-0.004	0.300	19
78273	-0.005	0.298	20
80293	-0.003	0.298	21
81052	-0.002	0.291	22
77922	0.000	0.296	23

Overall Bias (cm)	Overall Sigma (cm)
-0.001	0.305

The hourly corrections were applied to all data and then the overall statistics recomputed at the end of Table 3. The results show very little bias and an overall reduction in sigma by 0.0362 cm.

Figure 5 shows the GOES corrected data when broken down by hour, similar to Fig. 2.

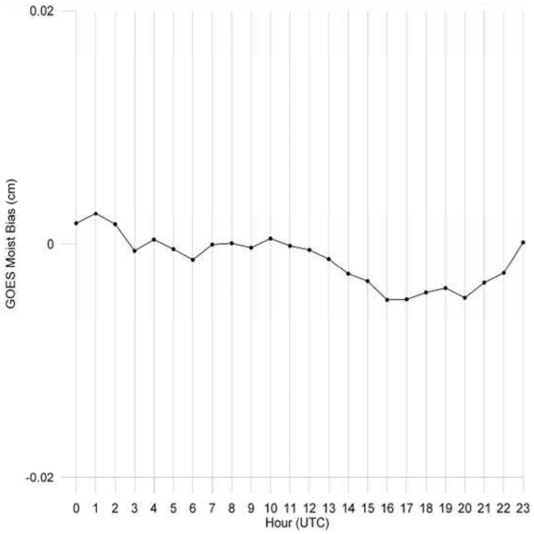

Fig 5. Hourly bias (GOES-GPS differences) modified by one of 24 unique algorithms. Bias values are all near zero cm.

Figure 6 is the recomputed scatterplot similar to Fig. 1 that shows the comparison of GPS and GOES-TPW data after the correction has been applied to each data point.

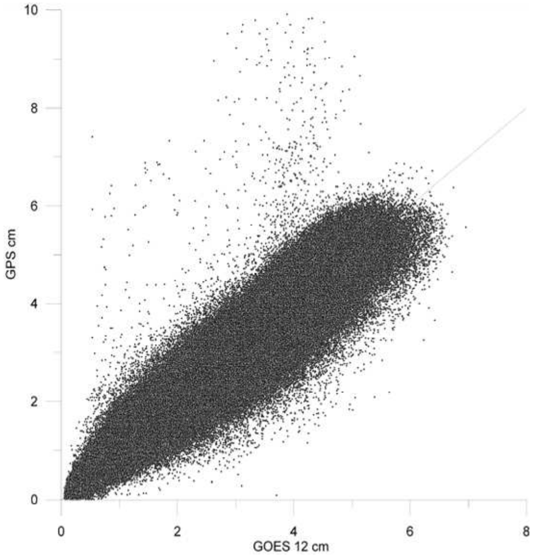

Fig 6. Scatterplot of corrected GOES data compared with GPS values.

It is worthwhile to note that the data now line up with the diagonal 1:1 line and the spread in the data appears to be improved near 2 cm and at the high moist end of the plot.

3. GOES-10 EVALUATION

GOES-10 was paired with GPS-TPW data in a similar fashion as just described for GOES-12 data, but fewer data pairs were studied since roughly a half year (June 2006-January 2007) were archived. GOES-10 was scanning the western CONUS and generally measured differences were less than what was seen for GOES-12. On the other hand, the moisture amounts in the western US are much lower than studied in the GOES-12 data. The lower differences did not surprise us given that GOES-12 scatterplots showed better agreement at low vapor totals. Somewhat surprising was the bias-corrected result that we performed on the data using the same correction relationship (1). Applying the same variational scheme as used for GOES -12, the correction coefficients were worked out for GOES-10 and shown in Table 4.

Table 4: Bias Correction Coefficients for GOES-10

a	*b*	Hour (UTC)
n/a*	n/a	0
0.996533394	0.95236516	1
0.996538579	0.946112096	2
0.989015937	0.951574981	3
0.983487904	0.952166796	4
0.988218307	0.950105309	5
0.986881852	0.944489419	6
0.987462819	0.942130029	7
0.982085943	0.954229712	8
0.977829933	0.967253745	9
0.977529407	0.956604183	10
0.982349575	0.9490183	11
0.981856227	0.955889702	12
0.975823998	0.963789642	13
0.982822776	0.962480724	14
0.988664567	0.972649038	15
0.985295117	0.980493426	16
0.975872576	0.987788618	17
0.964276195	0.994780362	18
0.963219404	0.993331313	19
0.959865749	1.00000048	20
0.952994823	0.996276438	21
0.970916569	0.983162522	22
0.973964751	0.969606757	23

**Coefficients are not available at 00UTC in the western US due to the lack of continuous surface data for GPS computations. As the stations in the western CONUS mature, 00UTC data will eventually become routine as they are with the eastern CONUS.*

As can be seen in Table 4, the nature of the correction terms is similar to GOES-12. This was surprising since the initial bias values did not appear to be that great, but as mentioned, the water vapor levels out west are typically lower than measured by GOES-12. However, these results indicate that the nature of the bias for GOES-10 is strikingly similar to GOES-12. We note the very similar *b* term result near 20 UTC when it is very near unity. This indicates, as in the case of GOES-12, that in the local afternoon time frame, the bias lacks curvature and needs simple scaling to remove the bias. Whereas at other times, especially near synoptic times, the bias correction requires more of a curvature correction. Though the magnitude of the coefficients for GOES-12 and GOES-10 are not identical, they are similar enough to suggest a fundamental commonality.

4. REAL-TIME APPLICATION OF CORRECTION COEFFICIENTS

During the summer months of 2007, the coefficients derived from earlier GOES-12 and GPS measurements were used to correct GOES- 12 real-time data, and compare these corrected results to simultaneous GPS measurements. The object was to discern whether the correction algorithm based on earlier data would effectively improve subsequent data. Various comparisons were made. Initially, single stations were examined and found to be vastly improved by the correction algorithm. We then examined specific geographic regions to see if there were any latitudinal differences in correction (Fig. 7) or possibly optical path preferences (i.e., would we see better results in the south where there were higher water vapor amounts?). Results indicate the correction algorithm is robust and applicable to a wide range of latitudes.

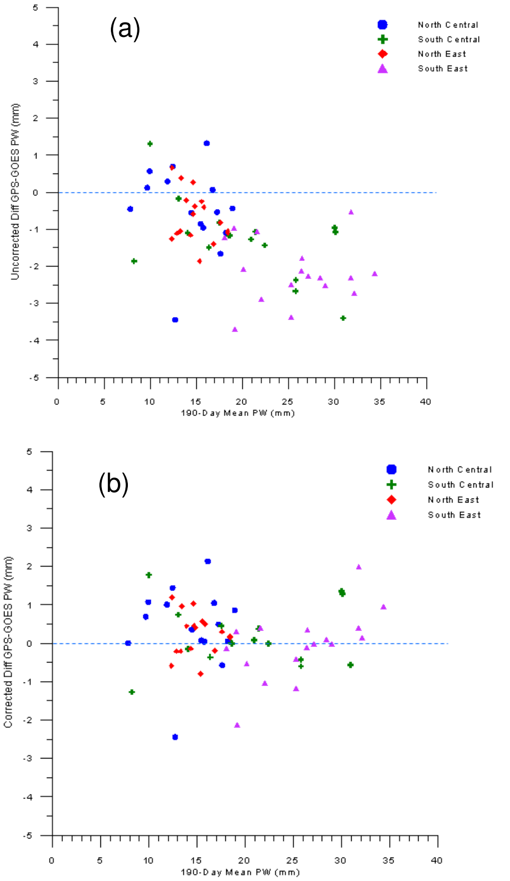

Fig. 7. Two scatterplots, contrasting regional changes to the 2007 GOES-12 data before and after applying the correction algorithm based on earlier data. Fig. 7(a) shows the uncorrected data identified by region, indicating the southeast CONUS (violet triangles) contained the greatest moist bias; Fig. 7(b) shows the same data after application of the bias correction algorithm. Data are clustered closer to the zero bias line with the most improvement seen in the southeast.

5. SUMMARY

The primary outcome of this study is a technique to correct satellite TPW product bias. Even more important, the study shows that the correction technique is valuable for real-time correction when based on prior data. The correction algorithm was devised using variational methods and has shown similar correction coefficients for both GOES-10 and -12. Individual station data were assessed both as a long-term and real-time trend (not shown here). We also showed that the previously derived coefficients were useful in different geographic regions (Fig. 7). These tests were only performed for GOES-12 for which there was the largest database for coefficient computation.

For GOES-R, the current indications are very promising. A comparison of GOES-R ABI proxy-derived product TPW with real-time GPS measurements indicates that the bias problems plaguing GOES-12 and 11 are far less substantial. Lower RMS error statistics obtained by using GPS as a standard measure also indicate that the algorithm for GOES-R shows potential to be a better product for round-the-clock application over the current GOES. However, the recent trend for ABI data in the dry season to drop to drier levels than GPS, points to the need for additional work to better understand this degradation in quality. In some sense, this appears to be opposite of the current GOES bias. Regardless, the current GOES correction algorithm should be fully applicable to ABI since the power term can be positive or negative.

We plan to continue to work on the ABI product generation with developers at NESDIS STAR and UW by providing GPS GOES comparison capability via the World Wide Web in real time. This will enable them to see immediate product changes with regard to algorithm modification made during ABI product development. The eventual goal is a seamless introduction of GOES-R-derived product data for TPW that will have few if any systematic problems. However, if problems are detected in the future product once GOES-R becomes operational, we now have a proven correction algorithm for the current GOES that can be easily adapted to GOES-R ABI.

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