Final Report

Assessing and Improving the Accuracy of Passive Operational Sounders Using GPS

Work done under JPL Contract # 1203314

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FINAL REPORT ON

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Summary

This final report describes the work undertaken to compare the total water vapor amount computed from wet delay measurements from a dozen sites in the National Geodetic Network with the precipitable water vapor computed from GOES Sounder data operationally at the University of Wisconsin-Madison. The purpose of this study was to compare precipitable water values measured remotely from GPS sensors (at the bottom of the atmosphere) and GOES sensors (at the top of the atmosphere). Both sensors yield estimates of precipitable water. How do they compare? What could improve the agreemtent? Could the GPS derived water vapor be used to arrive at a correction term for the GOES? These are some of the issues that can be explored by a careful comparsison of collocated and contemporaneous data.

A summary of these comparisons has revealed no appreciable bias (aggregate) in either data set with one exception. Data from one station reflects a high bias in the wet delay measurements compared with the GOES data. Since the wet delay was re-computed at JPL from routine data with the added information of the station pressure and temperature, any bias due to local atmospheric condition is not the reason for the bias. Instead, topographic effects may be a source of the anomaly.

Although the original objective was to examine the day-night differences in the GPS and GOES water vapor retrievals, the GPS data sample is not extensive enough to enable any conclusive statements about day-night differences. Additional processed GPS data and analysis are required for this purpose and are the main focus of this proposal, however these additional data were not received from JPL but were needed to do the required processing. Additionally, it is apparent that it will be beneficial to obtain a local reference for the GPS data that can be similarly processed and compared with the GOES retrievals of total water vapor. The early results were presented at the AGU 2000 Fall conference (Lindstrom et al., 2000).

A detailed report was communicated to Dr. Rob Kursinski (now at U of Arizona) and is online at: http://www.ssec.wisc.edu/~scottl/calval/commonformat/report.html as part of a proposal to JPL to continue the work under a new contract after Dr. Kursinski left JPL for University of Arizona. The feeling is that this work ended prematurely before some definitive conclusions could be drawn from the comparisons as the amount of processed GPS data received from JPL was not sufficient. The contract ended before this could be accomplished and additional efforts to continue the work under a separate contract were not successful. What follows is a report on the work done till the contract termination.

1. Introduction

GPS Precipitable Water (PW) is determined from the signals received from the GPS spacecraft at the receiver by determining the atmospheric delay as a combination of the "dry" and "wet" delay. The determination requires knowledge of the thermal structure and the surface pressure at the GPS receiver site. Generally the reduction of the GPS data uses a climatic mean for the receiver site to generate the PW, but it is limited by departures in the atmospheric structure and hence the purpose of the study was to see how specially processed PW retrievals from selected GPS receivers for which station data were available compared to the operational water vapor product derived from the GOES-E and GGOES-W satellites by NOAA/NESDIS at the University of Wisconsin-Madison. The specially processed GPS data were provided by Yoaz Bar-Sever at the Jet Propulsion Laboratory. PW data were generated at 5-minute intervals for every sixth day from August 1999 through August 2000. Processing was done using GIPSY software; full details are available in Bar-Sever et al., 1998. The data were provided at 13 stations scattered across the United States.

These data are compared to the closest (in time and space) PW value computed from sounder data. Sounder data at a point is available at most hourly, but less frequently in cloudy conditions. (The hourly sampling rate reflects the 40-minute scan time required for the satellite to sense the continental US). Thus the GPS data is much more temporally dense: hundreds of values per day at a point. Sounder PW data can be very spatially dense: thousands of points over the United States are possible in clear conditions 24 times daily.

The sounder PW point was required to be within a 1-degree latitude/longitude box centered on the GPS receiver. The closest such point was selected. Both Sounder and GPS PW values were required to be climatologically valid. The GPS data more often had invalid values; such values were related to erroneous pressure or temperature readings at the GPS site, i.e., things that were easily caught by gross error checking. On average for this time period and these stations, 95% of the data were good. There is station-to-station variability, of course: DHLG and SIO3 had good data >99.9% of the time; PLTC (81.7%) and MDO1 (89.1%), the two least reliable stations for this study, had good data somewhat more intermittently.

The GOES sounder instrument determines PW from multispectral data in the infrared. (A description of the sounder instrument and processing methods is at http://cimss.ssec.wisc.edu/goes/goes.html). The important points of the online documents are repeated below. See also Ma et al. (1999).

2. GOES Operational Processing that yields precipitable water:

At the GOES subsatellite point (at the [0N, 75W] for GOES-8 and at [0N, 135W] for GOES-10) each satellite data point (i.e., the footprint) is 8 kilometers (roughly circular) and the points are spaced 10 km apart. The subsatellite point is not where the GOES-GPS comparisons are made, however; as the comparison points move poleward and laterally away from the subsatellite point, the footprint enlarges and can become more elliptical. For example, at Madison, the GOES-8 footprint it 11 km in the E-W and 16 km in the N-S; Over the CART site in Oklahoma, it is 12 km in the E-W and 15 km in the N-S. Precipitable water with the sounder is computed using 9 points (a 3x3 box). That means the precipitable water is a point representative of a 33x49 km box in WI and a 36x45 km box over the CART site. Precipitable water measurements from the GOES sounder are valid for an area larger than precipitable water measurements from the GPS data (GPS precipitable water is a measurement for a cylindrical volume with a circular diameter of about 30 km). Scenarios where the characteristics of the two measurements could introduce errors into the analyses done here are easy to envisage (For example, if there is a very tight gradient).

Sounder data used here are from within a 1-degree latitude/longitude box centered on the GPS receiver. In other words, sounder data within about 50-100 km of the GPS receiver are used for the comparison. The latitude and longitude of those sounder points are the centroid of the (up to) nine non-cloudy GOES footprints from which data are used to compute the precipitable water. If the footprints are represented by the letters below:

```
A B C D E F

G H I J K L

M N O P Q R
```

and the sky is cloudy at A, G, and M, the centroid latitude/longitude will obviously be a little different than if C, I, and O are cloudy. Precipitable water values are computed using 9 points (ABCGHIMNO), then the algorithm steps over 3 columns and uses the 9 points to the right of row CIO (DEFJKLPQR). Each GOES footprint is used only once to compute precipitable water. Any of the nine footprints will be rejected if it is cloudy, and at least four must be "clear" to produce good data. The algorithm uses nine points to reduce noise -- i.e., for smoothing.

2.1 Natural Variability of GOES Sounder observations

Scatter plots of precipitable water data from adjacent points are presented here to show the natural variability of GOES precipitable water observations. Understanding this variability is vital if the differences between GOES precipitable water and GPS measurements are to be understood. Figures 1 and 2 show the variability for all points (GOES-8 and GOES-10) for points separated by at most 25 km (Fig. 1) or 40 km (Fig. 2).

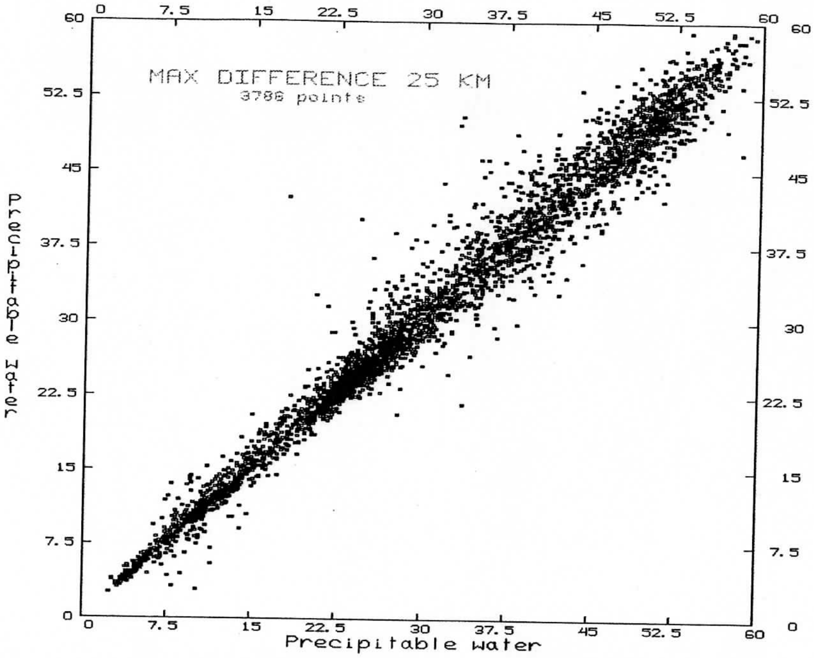

Figure 1: Scatterplot of precipitation water [mm] for adjacent points from GOES-8 and GOES-10 data. The maximum distance between the adjacent points is 25 km.

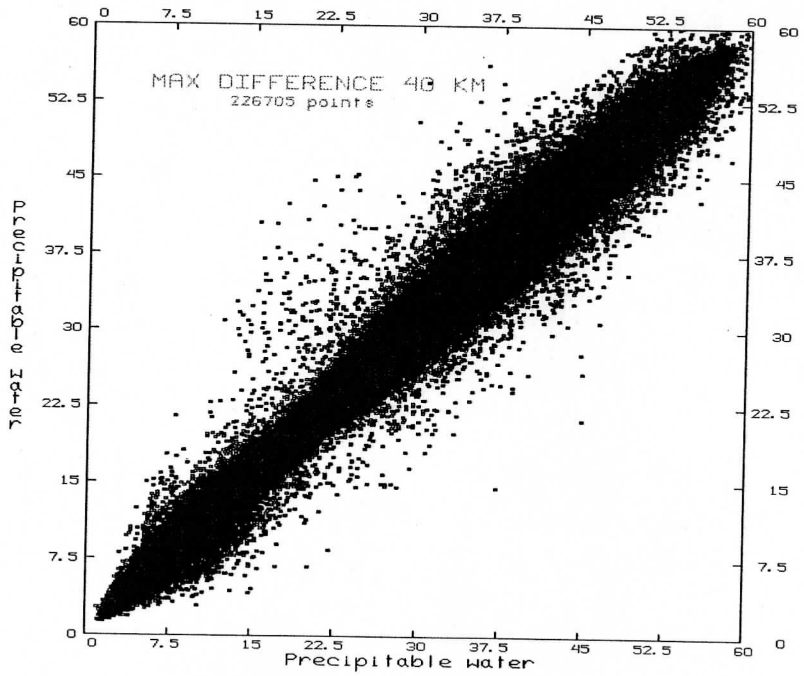

Figure 2: As in Figure 1, but for a maximum distance between points of 40 km.

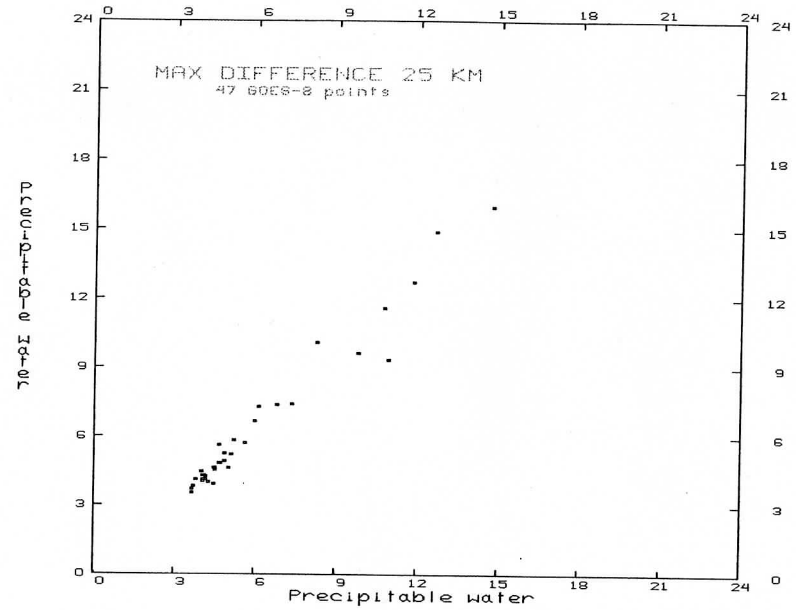

Figure 3: As in Figure 1, but for GOES-8 land points over the Continental United States only.

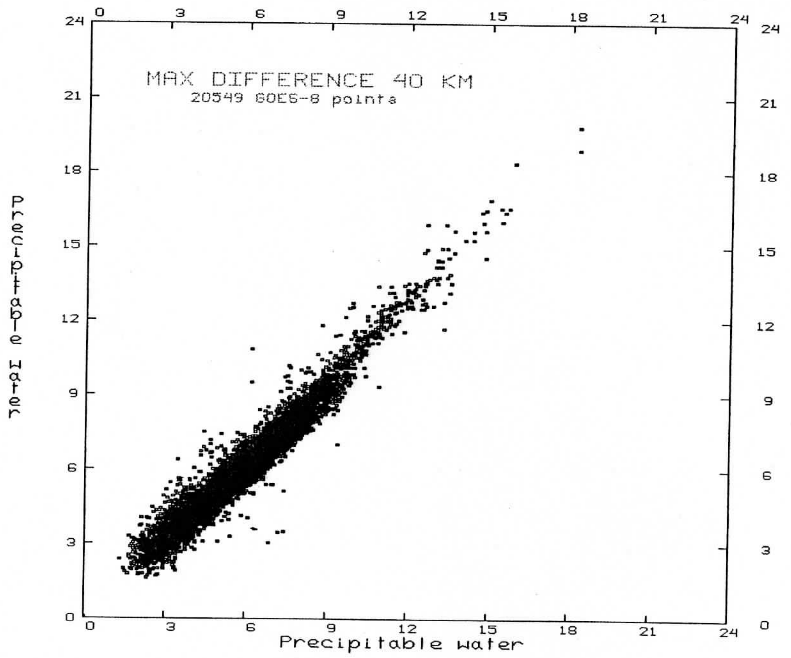

Figure 4: As in Figure 2, but for GOES-8 land points over the Continental United States only.

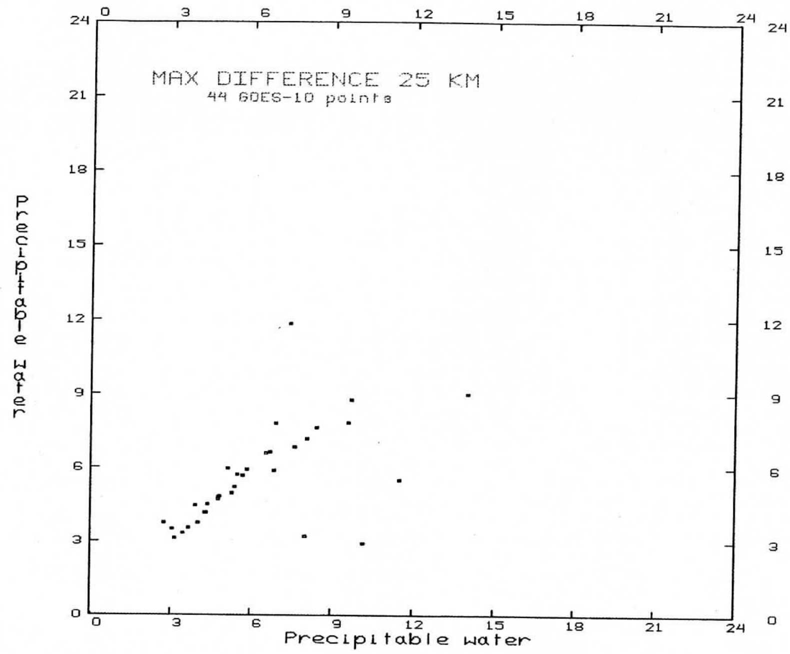

Figure 5: As in Figure 3, but for GOES-10.

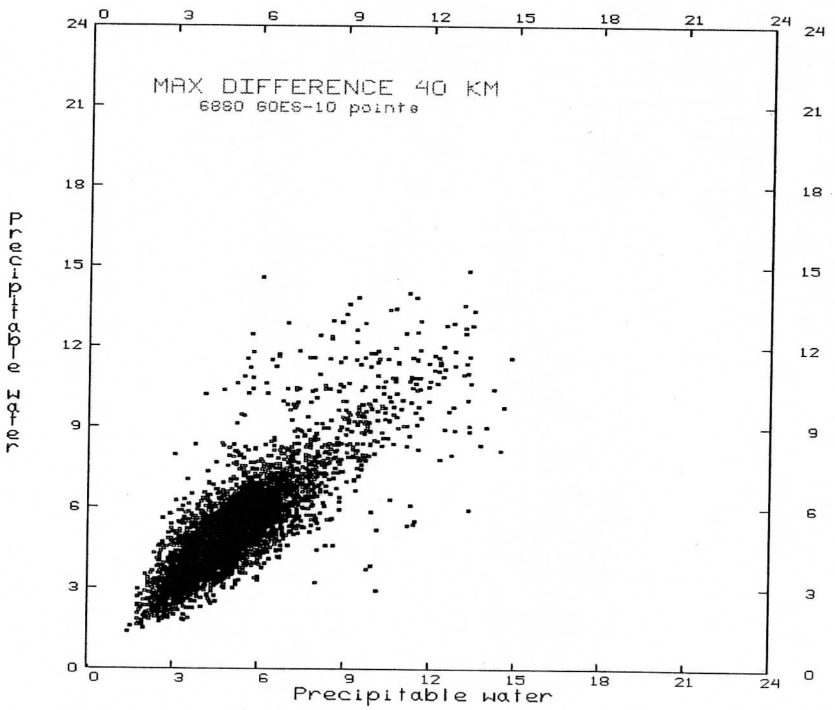

Figure 6: As in Figure 4, but for GOES-10.

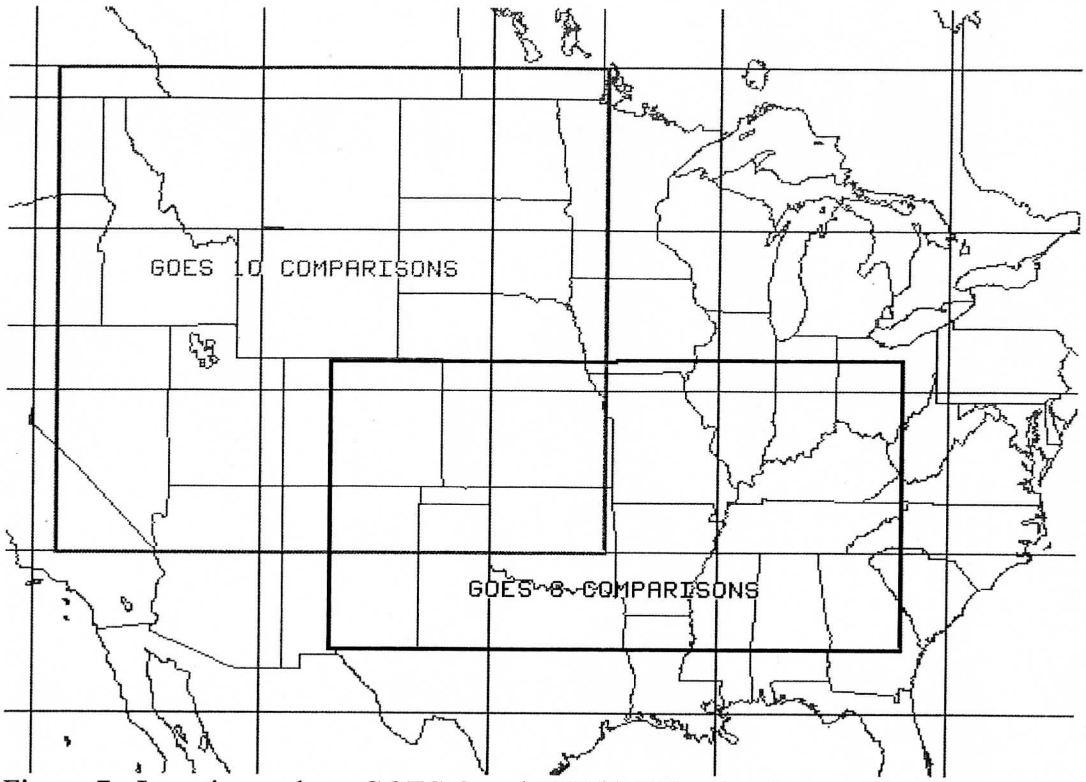

Figure 7: Locations where GOES-8 and GOES-10 land-only precipitable water values used for Figures 1-6.

Figures 3 and 4 show the same comparisons for GOES-8 points over land only, and Figures 5 and 6 show the same comparisons for GOES-10 over land only. Figure 7 shows the locations of the land-only points. Adjacent points agree fairly well in the two datasets. Note that GOES-10 shows more scatter than GOES-8, even though GOES-10 is a cleaner instrument. The chief cause behind the scatter in the GOES-10 plots is related to the terrain variability. Surface pressure is an important parameter when the precipitable water is computed. This surface pressure is derived from numerical model output. Figures 8 and Figure 9 show the differences stratified as a function of surface pressure for GOES 8 and GOES 10, respectively. Note how the magnitude of the difference decreases as the surface pressure increases. A possible conclusion is that the GOES precipitable water has less point-to-point variability over flat land. Part of this variability is, of course, natural. As the surface pressure drops, the amount of atmosphere holding water vapor is reduced, so the precipitable water will of course decrease. So if the comparison between two adjacent points includes a big height/surface pressure difference, then of course there should be a big difference in the GOES measurement of precipitable water. How these differences relate to the actual location of the GPS data will impact the GOES-GPS comparison. Finally, Figure 10 shows the relationship between the magnitude of the precipitable water difference between adjacent points (maximum separation distance: 40 km). Again, the relationship between pressure

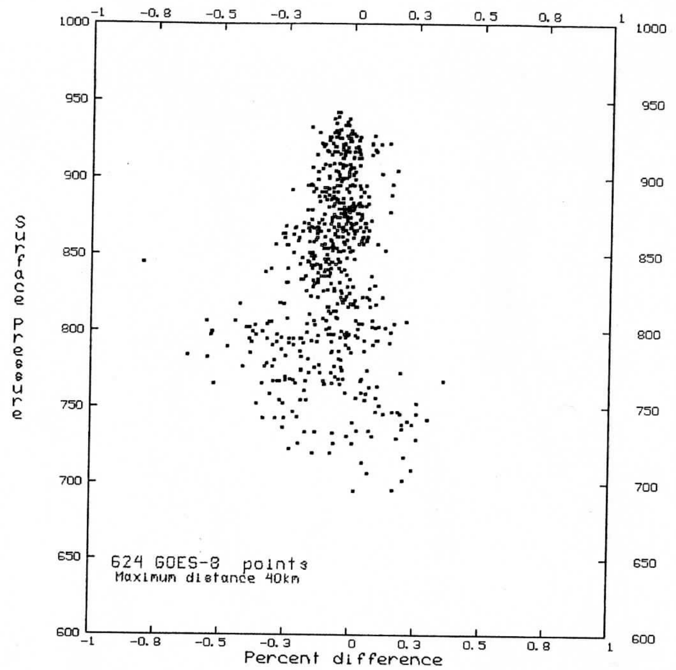

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Figure 8: Percent difference between adjacent GOES-8 precipitable water values (maximum distance: 40 km) as a function of surface pressure.

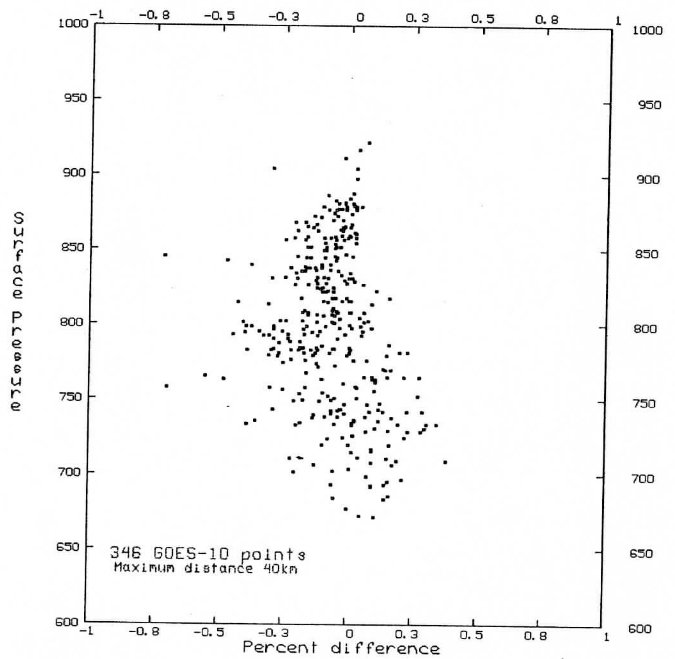

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Figure 9: As in Figure 8, but for GOES-10.

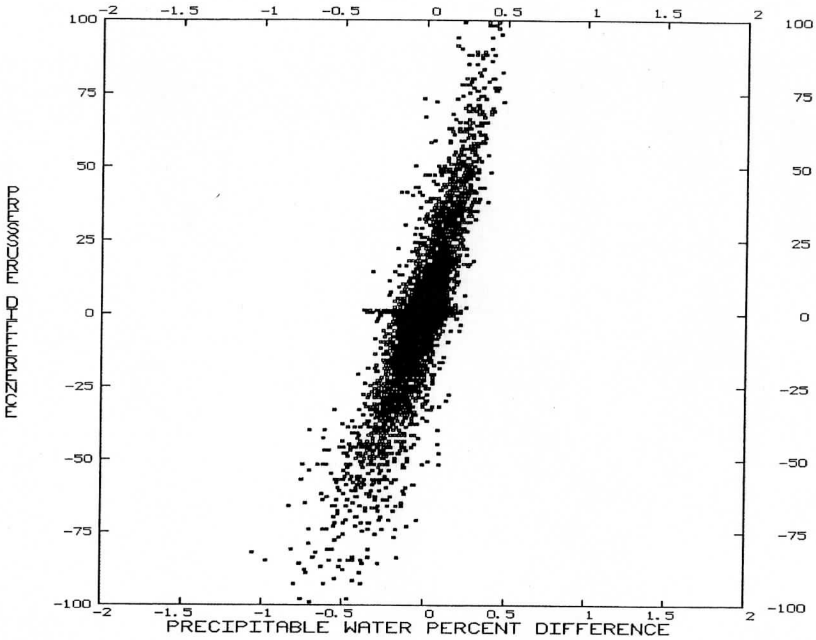

Figure 10: Magnitude of difference between adjacent GOES (8 and 10) measurements of precipitable water (maximum separation distance: 40km) as a function of pressure difference between the adjacent points.

Differences between adjacent points and scatter in the precipitable water difference are obvious, and it should be clear that comparisons between GOES and GPS over higher terrain might have somewhat higher errors as a result.

3. GPS Precipitable Water Data Used in the Study

GPS data (for this study, the delays -- which are used to compute the precipitable water) were received from two different sources: from Yoaz Bar-Sever at JPL and from Prof. Chuck Demets at the University of Wisconsin-Madison. The two data sources showed the differences between the routine processing (Demets) using climate data and the impact of the station data on the wet delay retrieval. It is worth noting that the routinely processed data used different software than the data received from Bar-Sever (JPL), so it is possible that some of the differences are due to software processing and not difference between the atmospheric model and the actual station data at the GPS receiver site.

GPS data were examined at 10 different stations located within the US that had station sensors (temperature, pressure) and for which processed wet delays were available were used in this study. The station locations are described in Table 1 below.

Table 1: List of stations considered in study

Abbreviation	Common Name	Latitude/Longitude	Elevation above geoid
AOML	University of Miami, Miami, FL	25.73 N 80.16 W	1m
DHLG	Durmid Hill, CA	33.39 N 115.79 W	-83 m
HKLO	Haskell, OK	35.68 N 95.86 W	191 m
JPLM	JPL Mesa, Pasadena CA	34.20 N 118.17 W	424m
LMNO	Lamont, OK	36.69 N 97.48 W	280 m
MDO1	McDonald at Ft. Davis, TX	30.68 N 104.02 W	2005 m
PLTC	Platteville, CO	40.36 N 104.73 W	1503 m
SCIP	San Clemente Is, CA	32.91 N 118.49 W	453 m
SIO3	Scripps, La Jolla, CA	32.86 N 117.25W	35 m
SOL1	Solomons Is., MD	38.32 N 76.45 W	-18 m
USNO	US Naval Observatory, DC	38.92 N 77.07W	49m
VNDP	Vandenberg AFB, CA	34.56 N 120.62 W	-12 m
WSMN	White Sands, NM	32.41 N 106.35 W	1204 m

Recall that GPS precipitable water is an average for a cylindrical volume with circular diameter of approximately 30 kilometers -- this resolution is a bit finer (meaning it covers a smaller area) than the resolution for the GOES precipitable water.

There are many ways to process the data as well; for this study, precipitable water that was computed (by Yoaz Bar-Sever) using GPS data processed by GiPSY (GPS Inferred Positioning SYstem) software developed at JPL. In addition, Wayne Feltz at SSEC provided a snippet of precipitable water computed using GaMIT software (where GaMIT means GPS at MIT). Figure 11 shows the wet delay from GPS data processed by GiPSY at JPL (source: Yoaz Bar-Sever at JPL, YB-S in the figure) vs. GPS wet delay processed using GaMIT (source: Chuck Demets, University of Wisconsin, CD in the figure). It is difficult to see a consistent difference between the two, although GiPSY data do show somewhat larger peaks. Figures 12-15 are comparisons of GiPSY and GAMIT precipitable water at stations in Oklahoma. One thing that is evident in the Figs. 12-15 below: the GiPSY precipitable water is usually a bit smaller (i.e., it shows less water vapor in the air) than the GaMIT precipitable water. There are times when the reverse is true, but in general, GiPSY is slightly drier.

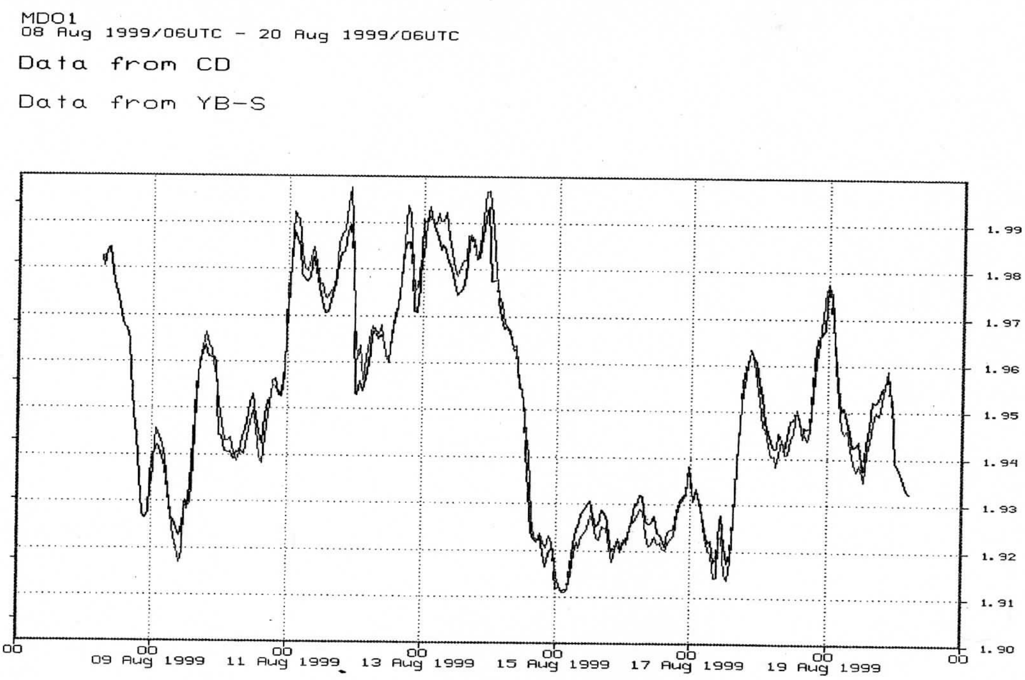

Figure 11: Wet Delay in GPS data from Yoaz Bar-Sever (YB-S in figure, processed with GiPSY) vs. Wet Delay in GPS data from Chuck Demets (CD in figure, processed with GaMIT) at Ft. Davis, TX in mid-August, 1999.

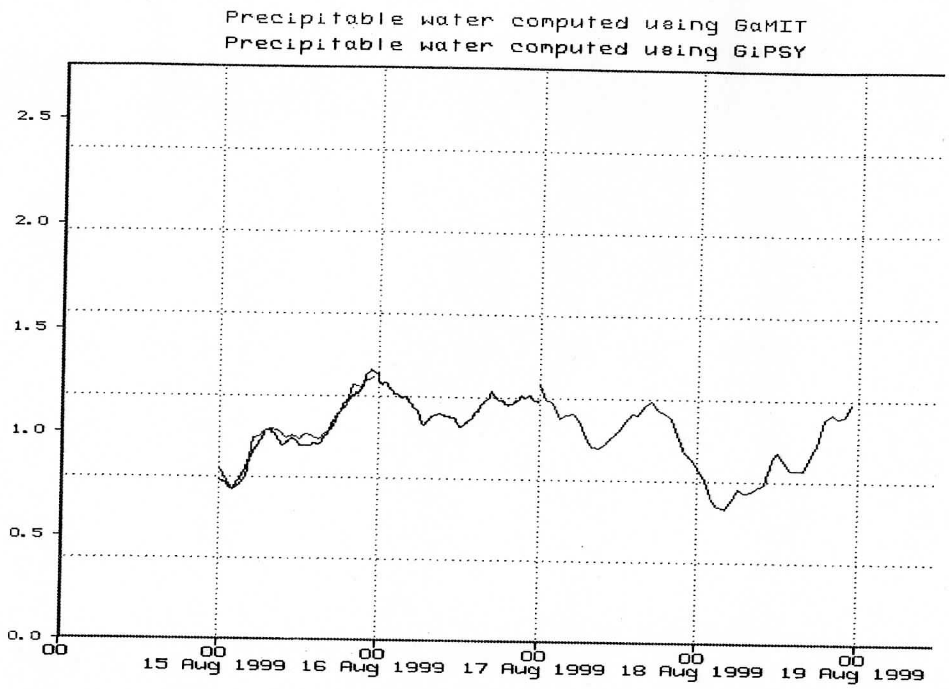

Figure 12: Comparison between precipitable water [inches] computed by GaMIT (red) and GiPSY (black) in mid-August at Lamont, OK (36.7 N, 97.6 W).

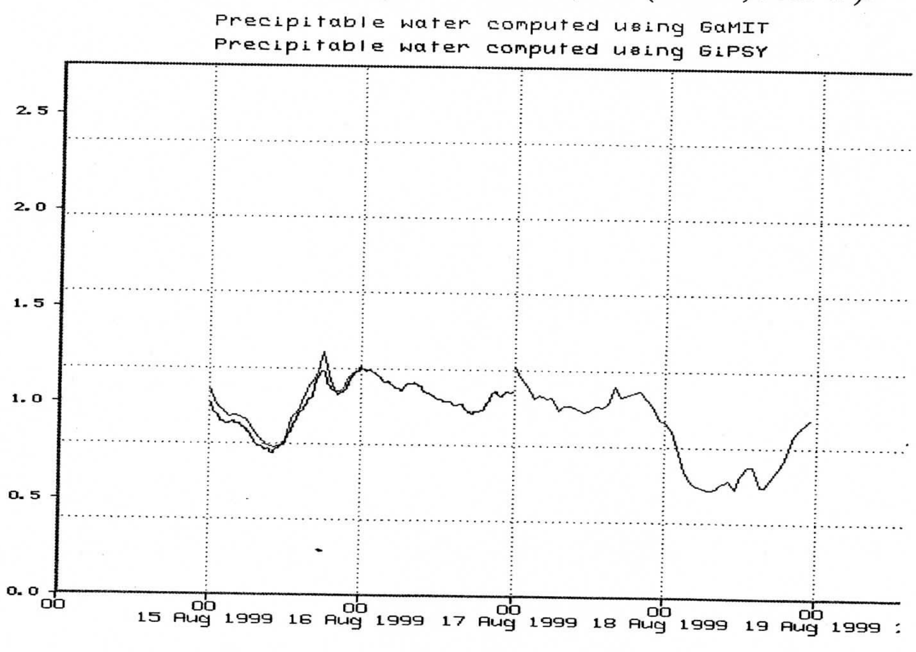

Figure 13: As in Figure 11, but for Vici, OK (36.1 N, 99.3 W)

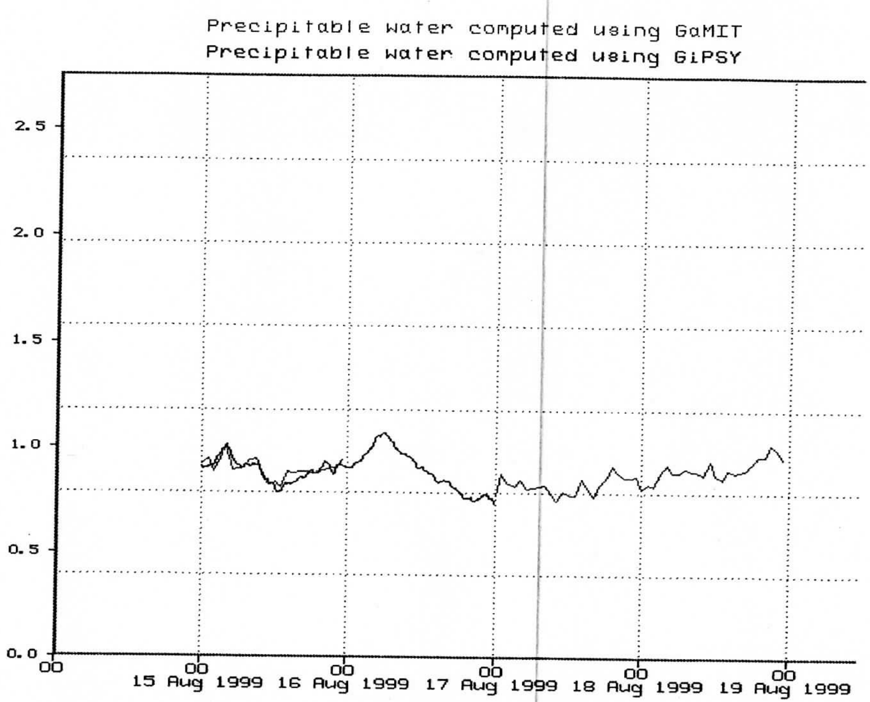

Figure 14: As in Figure 11, but for White Sands, New Mexico (32.3 N, 106.5 W)

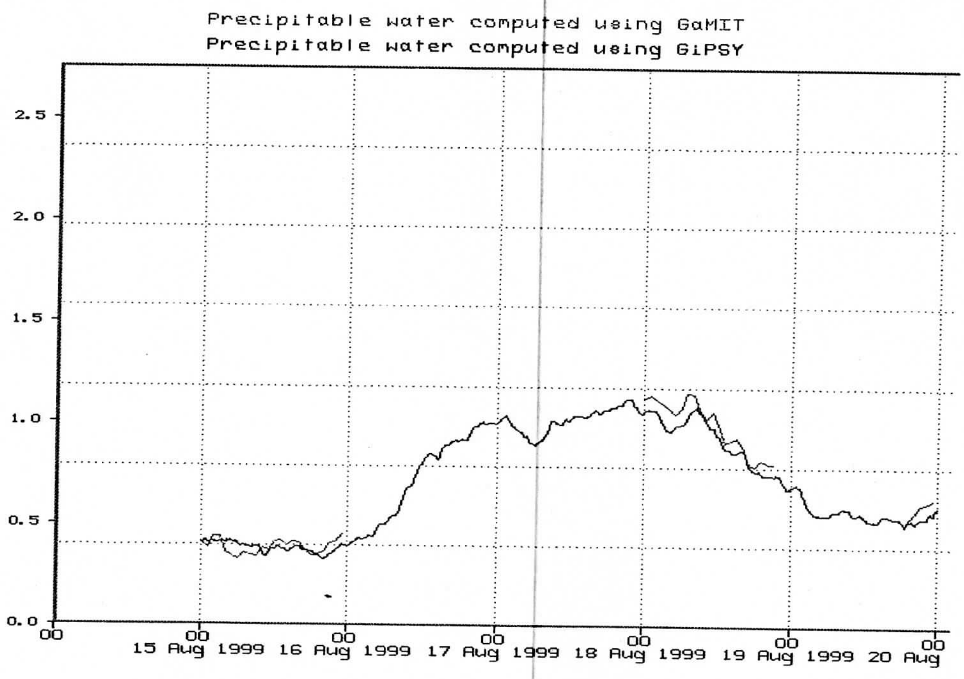

Figure 15: As in Figure 11, but for Scripps Institute of Oceanography in La Jolla, CA (32.8 N, 117.25 W).

In this study, GiPSY-derived precipitable water was used. The above plots suggest little difference in results occurred because of the choice of the GPS data processing algorithm.

Time series plots of GOES sounder precipitable water and wet delay from the GPS were produced to get a feel for how well those two variables tracked. The wet delay data were received from Chuck Demets at the University of Wisconsin (CD data in the plots) and that data are plotted against sounder precipitable water. This was actually done for 10 stations, but only Lamont, OK, which shows patterns similar to the other stations, is shown here. Figure 16 (below) shows that the two data values track closely. The gaps in the GOES sounder data are a result of cloudiness. If more than 3 of 9 pixels are considered cloudy, a sounder value of precipitable water cannot be generated.

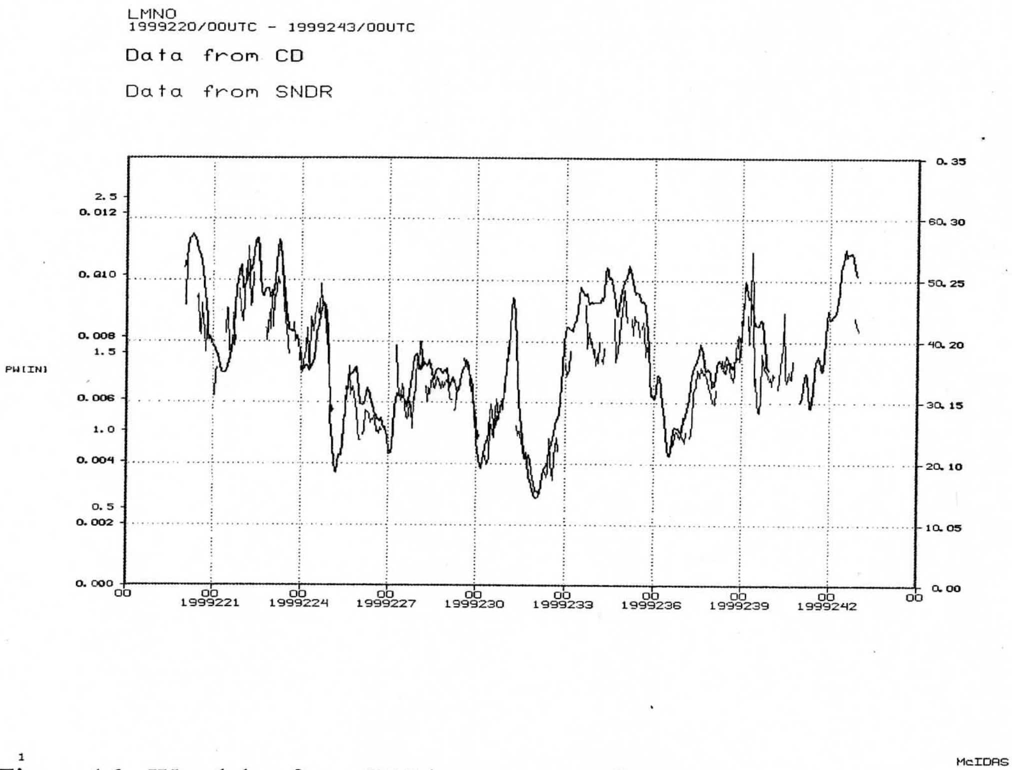

Figure 16: Wet delay from GPS instrument and GOES Sounder precipitable water for 20 days in 1999.

4. GPS / GOES Precipitable water Comparisons

None of the figures above suggest a great bias in the comparisons between precipitable water from the sounder and precipitable water from GPS. Care should be taken when comparisons are done over highly variable terrain because of uncertainties that may be introduced into the sounder data by the surface pressure, which pressure is a vital component of the retrieval algorithm that is used to compute thermodynamic variables from the sounder data.

Comparisons in this study are done only for Sounder data and GPS data that are recorded within 5 minutes of each other. This time accounts for the 42 minutes required to produce sounder data over the entire United States. GPS data are valid for a pencil volume that extends from the surface to the satellite. GOES data are valid for a cylinder in the line of sight from the satellite. Note also that the response function used by the GOES sounder can miss some of the moisture in the boundary layer. GOES data are restricted by cloudiness and are available only in clear and partly cloudy regions. Figures 17-20 show scatterplots of GOES precipitable water versus the difference between GOES and GPS estimates of precipitable water. Variability is present between stations, but in general little bias is present. There can, however, be significant spread in the difference.

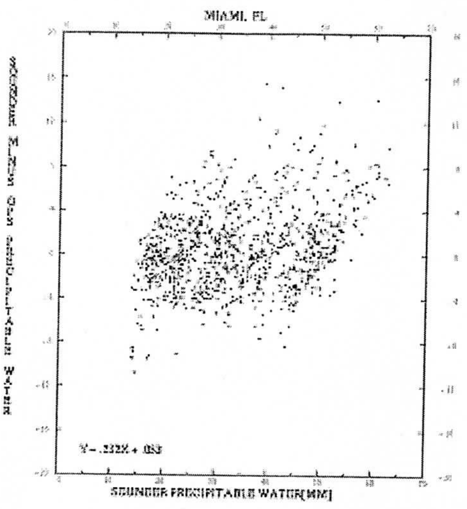

Figure 17: Sounder Precipitable water vs. (Sounder-GPS) precipitable water at Miami FL for the case when at least 4 of 9 pixels surrounding the GPS site are not cloudy. Data are for 1999/2000.

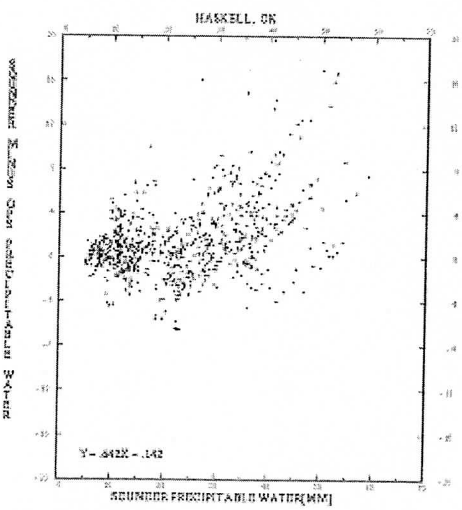

Figure 18: As in Figure 17, but for Haskell, OK.

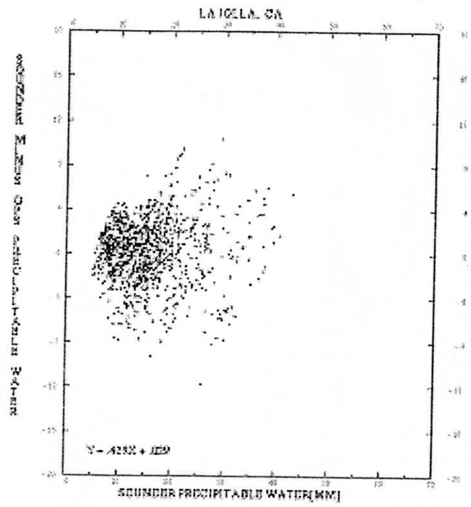

Figure 19: As in Figure 17, but for La Jolla, CA.

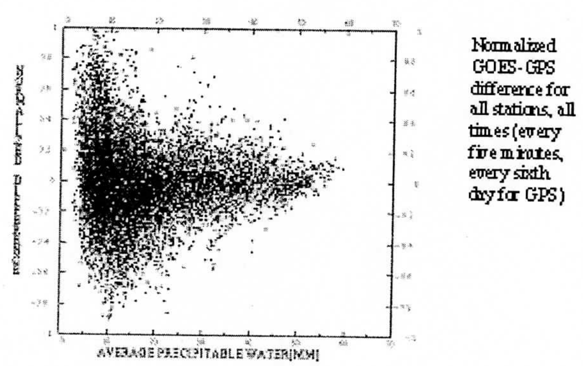

Figure 20: As in Figure 17, but for all stations considered.

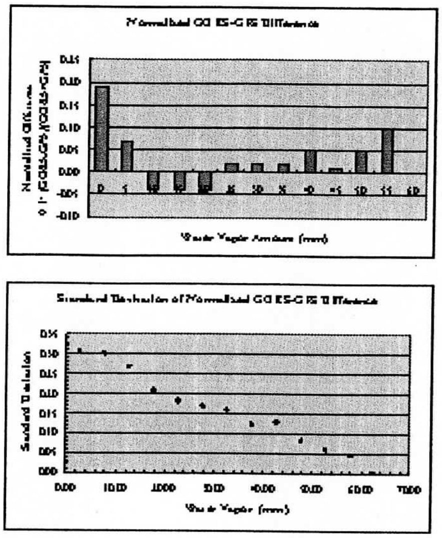

Figure 21: Normalized precipitable water differences (GOES-GPS) as a function of GOES precipitable water (top); standard deviation of the normalized difference.

Figure 21 (above) shows binned values of mean differences as a function of precipitable water. For low precipitable water amounts (< 10 mm), GOES derived estimates are larger by as much as 20% than GPS values. For moderate amounts of precipitable water (10-25 mm), GOES derived precipitable water is lower than the GPS value by about 4%. For amounts in excess of 25 mm, the GOES estimate is higher than the GPS derived estimate, increasing from about 2% (at 25 mm) to 10 % (at 60 mm) for the stations considered.

Some differences between the two values can be explained. Consider the figure below that shows precipitable water at San Clemente Island, in the Channel Islands, off the coast of southern California. Note that GPS precipitable water is available only every 7th day. At this station, GPS values are consistently less than the GOES value.

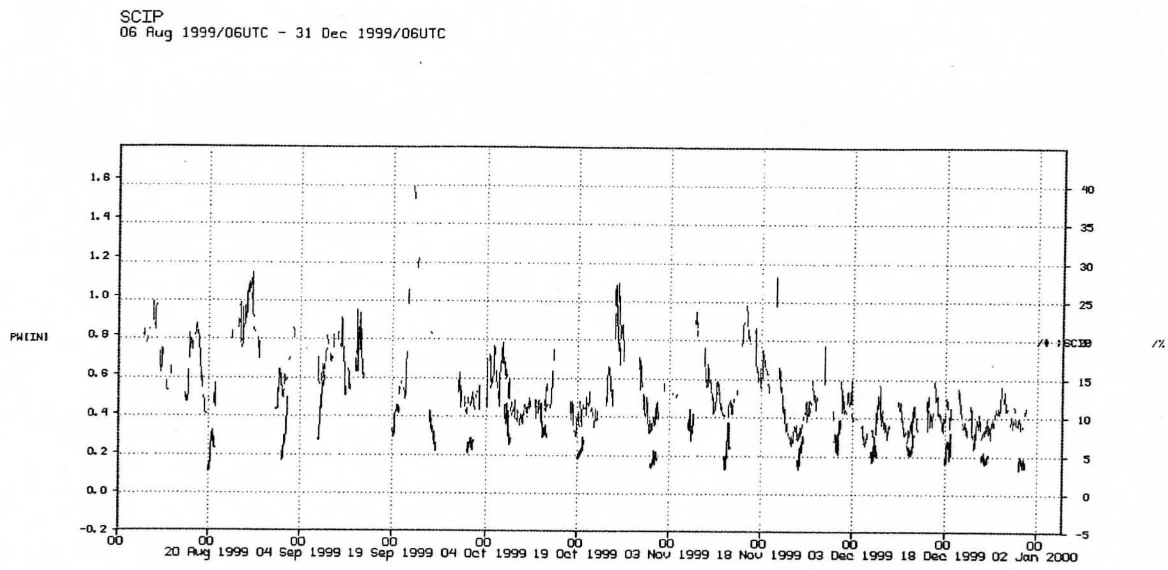

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Figure 22: GOES precipitable water (red) and GPS precipitable water (black) at SCIP for the dates indicated.

The GPS sensor on the mountain peak at San Clemente Island, CA yields a measurement of water vapor *above* the sensor. The GOES instrument, in contrast, will include measurements of water vapor at heights between the mountain peak and surrounding lower regions. Thus, GPS and GOES instruments may give different answers that are consistent with the atmospheric structure. Consider the atmosphere sounding in Fig. 23 that shows a strong marine inversion at San Diego. A GPS receiver at 453 meters (about 950 mb) on Catalina Island will not be influenced by the water vapor at levels below the receiver. Water vapor below the GPS receiver will influence the GOES sounder signal, however, and the two signals will reflect measurements that do or do not include water vapor below the GPS receiver. Both measurements are valid, and both reflect true measurements of the portions of the atmosphere sampled. Table 2, for example, shows that the atmosphere below 950 mb contains 20-40% of the precipitable water. It is not surprising, then, that GPS precipitable water consistently under-reports values compared to GOES at this station. Similar errors occur at the GPS sensor at Ft. Davis in Texas (MDO1) (not shown).

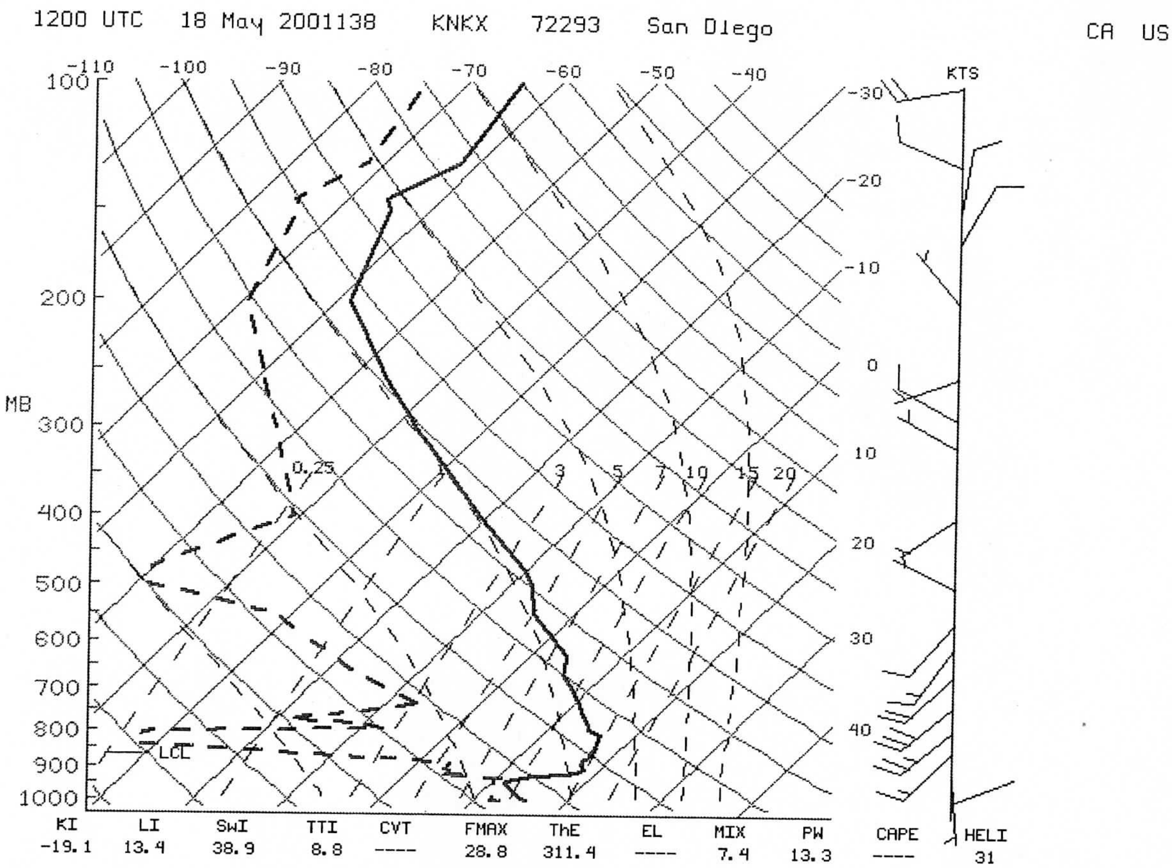

Figure 23: Skew-T log-p vertical profile of atmospheric variables (thick solid line: Temperature; thick dashed line: Dewpoint temperature) at San Diego, CA on 18 May 2001

Radiosonde at San Diego 00 UTC 7 June 2001				GOES Sounding 00 UTC 7 June 2001			
32:51:52 N 117:07:51 W				33:07:37 N 120:36:52 W			
Pressure (hPa)	Temperature (K)	Dewpoint (K)	Precipitable Water (mm)	Pressure (hPa)	Temperature (K)	Dewpoint (K)	Precipitable Water (mm)
747	288.75	268.75	5.89	780	290.93	264.43	4.96
850	294.95	276.95	11.16	850	294.08	269.31	7.08
925	294.15	277.15	15.80	920	294.40	270.63	9.51
947	289.15	285.35	17.51	950	294.11	271.94	10.60
990	293.15	285.15	21.55	1000	289.36	284.33	13.68
997	295.35	287.35	22.24	1014	289.36	284.33	14.86

Table 2: GOES and radiosonde precipitable water values for lowest pressure level as indicated

At stations characterized by more uniform topography, the comparisons are more straightforward. Consider Figure 24, which shows the comparison at USNO -- United States Naval Observatory in Maryland. Again, only every 7th GPS day is shown. Nevertheless, good tracking between the two measurement systems is indicated. When one increases, generally the other does as well. Trends are replicated very well between the two systems, regardless of any biases in the absolute values. In addition to the negative bias of the GPS data with respect to GOES at SCIP, there are positive biases at JPLM and DHLG. Figure 25 shows differences for each station as a function of precipitable water. The distributions are somewhat different than those distributions for 03-09 UTC (not shown). Future work will examine the diurnal variability of the GPS/GOES comparisons.

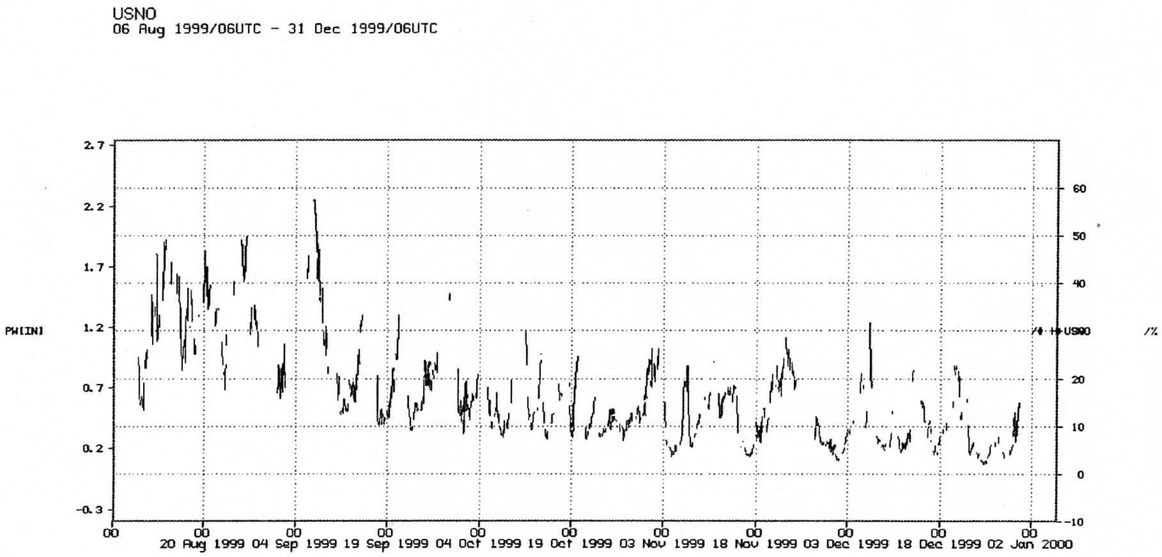

Figure 24: As in Figure 22, but for USNO.

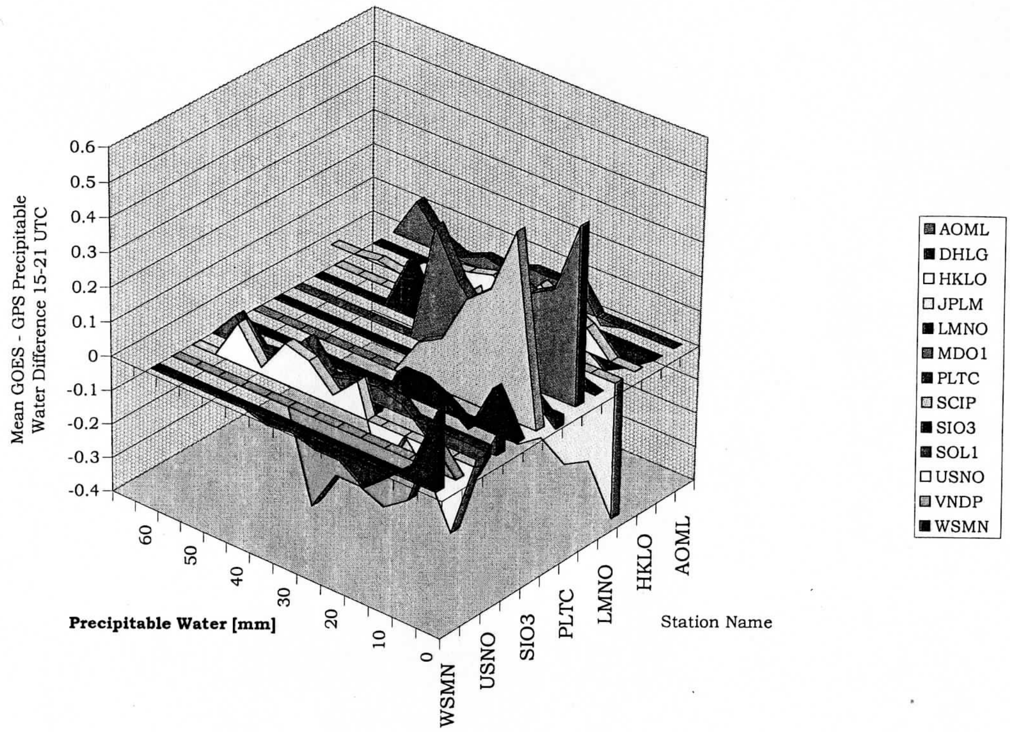

Figure 25: Mean GOES-GPS precipitable water difference as a function of GOES Precipitable water. Data for each station as noted, only for daytime values (15-21 UTC).

5. Summary

GOES and GPS instruments both yield consistent estimates of precipitable water. GOES estimates of precipitable water vary only slowly between adjacent fields of view. Similarly, GPS estimates of precipitable water at two nearby stations are similar. Comparisons between the two instruments are made difficult by resolution differences, by GPS instrument sites that are on isolated mountain peaks and by variable topography in GOES footprints. However, measurements from the two instruments compare favorably, especially over flat topography. The comparison is negligibly affected by the choice of GPS processing algorithm. Biases for individual stations can exist, but overall the bias between GOES and GPS precipitable water is small. Physical reasons for a large bias between the two measurements are related primarily to topography. Even if a bias is present, however, the tendency of GPS measurements is mirrored by GOES measurement tendencies. Differences between the two systems change between day and night for reasons that deserve further exploration. That work awaits future study, however.

References

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