Comparison of GPS slant wet delay measurements with model simulations during the passage of a squall line

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[1] Slant wet delay (SWD) measurements from a ground-based GPS observation network provide accurate, high-resolution moisture information for mesoscale analysis. In this study, we compared SWD simulated from a 9-km MM5 model in a prefrontal squall line event against actual GPS SWD observations by NOAA's GPS network. We found that the model simulation did not capture abrupt moisture changes and small-scale variations observed in the nonisotropic component of slant wet delays associated with the squall line. This result suggests that SWD measurements can be very useful in improving model moisture analysis. *INDEX TERMS:* 1894 Hydrology: Instruments and techniques; 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; *KEYWORDS:* GPS, Precipitable water, Slant wet delay (slant water vapor), MM5, Squall line. **Citation:** Ha, S.-Y., Y.-H. Kuo, Y.-R. Guo, C. Rocken, and T. Van Hove, Comparison of GPS slant wet delay measurements with model simulations during the passage of a squall line, *Geophys. Res. Lett.*, *29*(23), 2113, doi:10.1029/2002GL015891, 2002.

1. Introduction

[2] Ground-based GPS sensing technology can now accurately estimate the propagation delay due to the neutral atmosphere in GPS microwave signals. By isolating the phase delay caused by the atmospheric water vapor alone, we obtain the line-of-sight slant wet delay (SWD) [*Ware et al.*, 1997], which represents the amount of integrated water vapor along each ray path. As the individual SWD, however, can be strongly affected by noise in the GPS phase measurements, it has been difficult to obtain accurate SWD observations. Alternatively, all available SWD measurements were mapped to zenith and averaged over a certain period of time to obtain zenith wet delay (ZWD), which can be used to derive precipitable water (PW) with a conversion parameter. Ground-based GPS PW can be obtained with accuracy better than 2 mm [*Rocken et al.*, 1995], but it also loses valuable information on the spatial distribution of moisture and the benefit of the high temporal resolution of SWD measurements. A ground-based receiver can track 5 to 12 satellites simultaneously at any given time with typically 30 sec sampling. *Braun et al.* [2001] validated GPS slant-path measurements against a water vapor radiometer, and showed that GPS slant wet delays can be obtained with an accuracy of a few mm.

[3] In this study, we compare the SWD measurements over four ground stations in the central part of the NOAA Forecast Systems Laboratory (FSL) GPS observation network with those simulated from a mesoscale model in a pre-frontal squall line case. Such a comparison can be used to evaluate the performance of the model, and provide insights on the utility of SWD in improving model moisture analysis.

2. A Squall Line Case in the Central United States on 30 Oct. 1999

[4] A pre-frontal squall line formed over the western Kansas-Oklahoma area on 2100UTC 29 October 1999. It then moved across the NOAA ground-based GPS network in the central United States. This squall line system produced a maximum precipitation amount of 89.8 mm over a 24-hr period near Lamont, OK (Figure 1). The NOAA GPS network provided high-quality GPS observations that were processed to obtain SWD values before, during and after the passage of the squall line.

[5] We used the PSU/NCAR mesoscale model MM5 Version 3 (http://www.mmm.ucar.edu/mm5/mm5v3.html) to simulate the squall line over the domain as in Figure 1 and compared the forecast results with GPS water vapor measurements. The model was configured with 9 km horizontal grid spacing, 157 $\times$ 166 grid mesh, 50 σ levels and a combination of physics packages (Dudhia simple ice moisture scheme, Grell cumulus parameterization, Medium-Range Forecast model PBL scheme). The initial condition at 1200UTC 29 October was obtained from the NCEP/NCAR Reanalysis data.

[6] The 9-km MM5 model with parameterized convection was able to simulate the development of the squall line. However, the formation and the movement of the squall line were slower than those in the observed system based on radar echoes. Also, the hourly precipitation was weaker than the observation for 24 hours from the initial time (not shown).

[7] Figure 2 shows the comparison of the GPS precipitable water (PW) measurements with the model simulations at Vici (VCIO), Lamont (LMNO), Purcell (PRCO), and Haskell (HKLO) in Oklahoma following the sequence of squall line passage as shown in Figure 1. In general, we found that the observed PW increases rapidly before the

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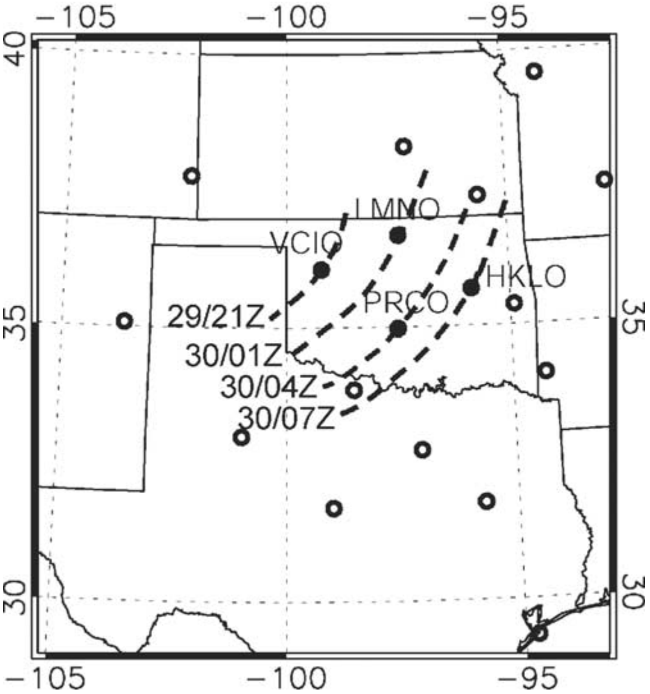

Figure 1. The NOAA GPS observation network. As of October 1999, a total of 18 stations were available in the Southern Great Plains region (open circles). Dashed lines show the passage of the squall line at four GPS stations (marked as ●)as a function of time.

approach of the squall line and decreases after its passage. However, the model simulated PW appears to have smoother variability in time. And when we compare the time of squall line passage at each station in GPS observations and MM5 model simulations (as marked as ▲ and Δ, respectively), the simulated squall line always has a time lag of a few hours. As a result, MM5 under-predicts PW before the arrival of the squall line and over-predicts PW after its passage at all four stations. Note that GPS data were missing at Lamont, OK due to the power outage before 1330UTC and for 2 hours from 2330UTC 29 October.

3. The Comparison of SWD Between GPS and MM5

[8] To examine the information content of SWD measurements before, during, and after the squall line passage, we compare the GPS SWD observations to the MM5 simulations at Lamont, OK at 5-min time intervals in Figure 3 and summarize the statistics in Table 1. GPS SWD was extracted from double difference processing and corrected for station dependent errors by using site-specific multipath correction maps [*Braun et al.*, 2001]. Since the atmospheric refractivity can be expressed as a function of pressure, temperature and specific humidity to a good approximation [*Boudouris*, 1963], we can estimate SWD in the numerical simulation by integrating wet refractivity (N_{wet}) from a ground-based receiver to each GPS satellite in view. As the lowest elevation angle in our GPS measurements was above 5°, we ignored signal bending and assumed each ray path as a straight-line. [We have evaluated the accuracy of straight-line approximation in the estimate of SWD (as compared with a ray-tracing method) and found the approximation is accurate above 5° elevation angles with less than 1% rms error.]

$$SWD_i^m = 10^{-6} \int_{receiver}^{satellite} N_{wet}\, ds \quad , where\ N_{wet} = 3.73 \times 10^5 \frac{e}{T^2}$$

where water vapor pressure is e [mb], temperature is T [K], ds has unit of length along the GPS ray path, m stands for satellite number and i receiver site.

[9] For better visualization in Figure 3, we mapped both the modeled and the observed slant wet delays to the zenith using the *Niell* [1996] mapping function. And we stratify the 24-hr time period into four stages with 6-hr time intervals to investigate if $\Delta SWD = (SWD^{GPS} - SWD^{MM5})$ shows any significant changes related to the squall line passage. Each dot indicates the position of each satellite in view from the GPS receiver in terms of elevation and

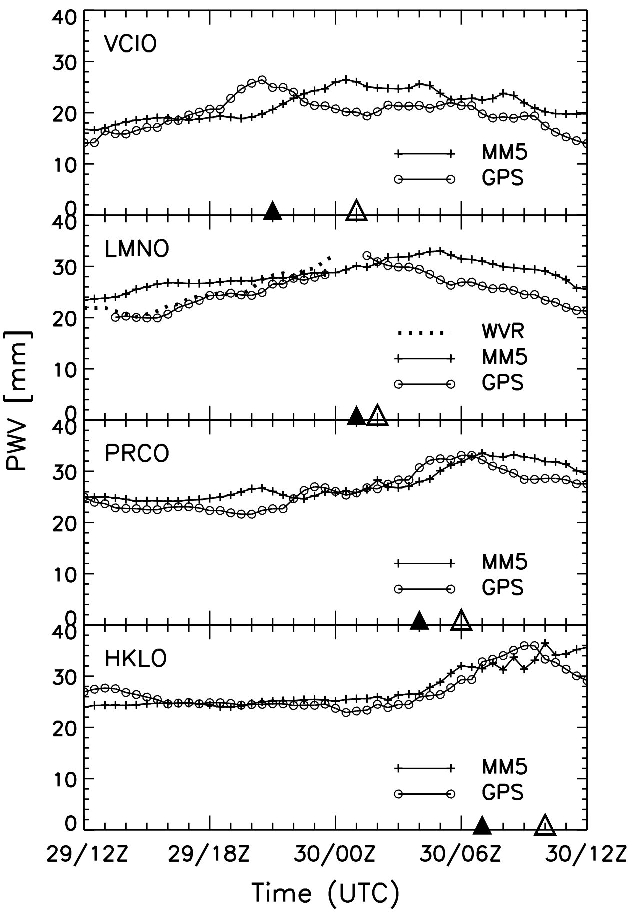

Figure 2. PW time series from GPS measurements (○) and MM5 model simulations (+) at Vici (VCIO), Lamont (LMNO), Purcell (PRCO), and Haskell (HKLO), OK in Figure 1. ▲ and Δ indicate the time of squall line passage at each station in radar echoes and MM5 model simulation, respectively. Dotted line at LMNO is PW from Water Vapor Radiometer. The rms error between GPS and WVR is 1.37 mm.

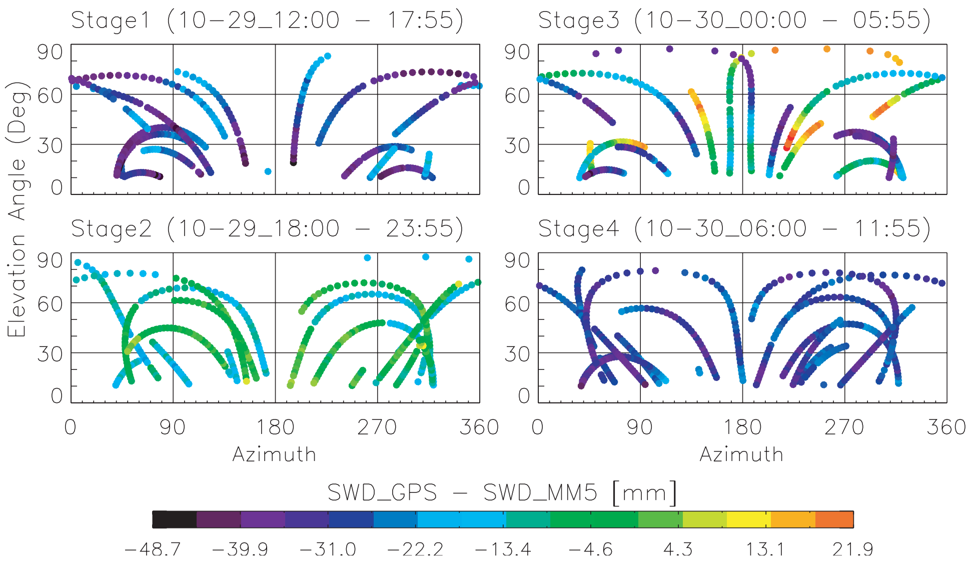

Figure 3. SWD comparison between GPS and MM5 (mapped to zenith) at Lamont from 1200UTC 29 to 1200UTC 30 October 1999.

azimuth angle. As marked in Figure 2, the time of squall line passage at Lamont, OK is 0100UTC and 0200UTC in the radar echoes and MM5 simulations, respectively, which corresponds to stage 3 (top right panel) in Figure 3.

[10] An interesting result is that significant positive ΔSWD values show up only in stage 3 while negative ΔSWDs dominate in all the other stages. As summarized in Table 1, this results in the highest standard deviation at stage 3. A possible reason for negative mean bias even in stage 3 is that data was missing for ~2 hours during the squall line passage. To better understand how the differences (ΔSWD) evolve with time, we plot all available ΔSWDs together as a time series in Figure 4. We obtain results that are fairly consistent with Figure 3 for the other three Oklahoma stations. The highest positive peak of ΔSWD appears during the squall line passage, while MM5 simulated SWDs are mostly larger than GPS observations in all the other stages. This implies that the smooth temporal and spatial variability of the water vapor field in the forecast model could not capture the increase of moisture associated with the approach of the squall line. This result is in agreement with the study by *Yang et al.* [1999] in which shows that the error in the water vapor field of a numerical forecast model increases as humidity increases.

[11] Another interesting result is that the positive ΔSWD at Vici is much higher than the other stations and the time difference of the squall line passage is also greatest at Vici. As indicated in Figure 1, the squall line formed near Vici at 2100UTC 29 and moved over Lamont at 0100UTC, Purcell at 0400UTC, and Haskell at 0700UTC 30. By the time the squall line moved over Purcell and Haskell, it was already well developed. However, when it was near Vici, the squall line was just at its incipient stage. This indicates that the moisture field predicted by the 9-km MM5 simulations had the greatest deficiency in the initial stage of the squall line development.

Table 1. Statistics (mm) for ΔSWD (=SWD^{GPS} – SWD^{MM5}) at Lamont in Figure 4, mapped to zenith

	Stage 1	Stage 2	Stage 3	Stage 4
Max	−14.15	8.73	21.91	−21.93
Min	−48.69	−25.11	−46.42	−44.07
Mean bias error	−28.47	−11.25	−11.83	−31.37
Standard deviation	7.60	7.28	17.62	3.97

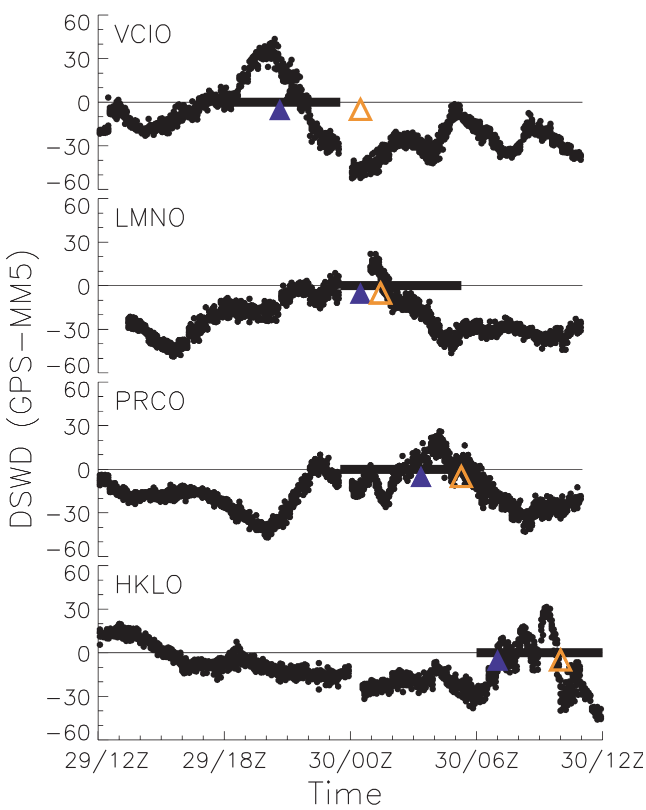

Figure 4. The same as Figure 2 but for ΔSWD (mapped to zenith). The stage at which the squall line passed through the station is marked with a thick solid line.

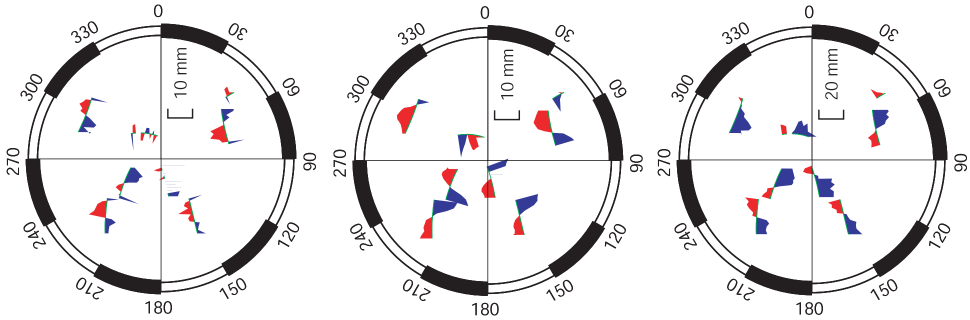

Figure 5. Sky plots of (a) GPS SWR (b) MM5 SWR and (c) ΔSWD (=SWD^{GPS} – SWD^{MM5}) at LMNO from 0200UTC to 0300UTC 30 October. Plot center is the zenith and the circumference is the 0° horizon. Red (positive) and blue (negative) residuals are plotted relative to satellite ground tracks (green).

[12] *Braun et al.* [2001] pointed out that GPS SWD is composed of an isotropic and the nonisotropic part. In general, the isotropic component dominates the SWD measurements and its temporal variation closely follows the changes in PW. Now, we discuss if the nonisotropic component of the SWD contains useful information for weather models. Figure 5a shows the zenith-mapped slant wet delay residual (SWR) for the GPS measurements at Lamont from 0200 UTC to 0300 UTC 30 October 1999. SWR is obtained by averaging all available zenith-mapped SWDs for one hour and subtracting this hourly mean from each SWD. Therefore, the SWR of each ray path represents the nonisotropic component of the SWD. The corresponding result from the 9-km MM5 simulation is shown in Figure 5b. The difference in total zenith-mapped SWD (including both the isotropic and nonisotropic components) between GPS observation and MM5 simulation is shown in Figure 5c. In the comparison of (a) and (b), we note that GPS data shows higher fluctuation than MM5 simulations along 8 satellite sky tracks at the same sampling frequency of 5-minute intervals. There are significant differences in the SWR between MM5 and GPS observation for individual ray paths. Very often when the GPS SWR shows a positive residual, the MM5 SWR gives a negative residual, and vice versa. This reflects the fact that the small-scale variation of the atmospheric moisture in the vicinity of the GPS receiver is not well captured by a 9-km MM5 model. During this time period, the zenith wet delay is quite similar between GPS (200.3 mm) and MM5 (204.1 mm). Thus, ΔSWD in (c) is mostly caused by the difference in the nonistropic components of SWD (e.g., SWR), not by the mean bias between GPS and MM5 ZWD. The difficulty of a mesoscale model in properly simulating these small scale variations of moisture observation indicates that such measurements can have a significant positive impact on improving the model moisture analysis when the GPS slant wet delay data are assimilated into the model [*Ha et al.*, 2002].

4. Summary and Conclusions

[13] In the comparison of slant wet delays, the model simulations showed smooth variation and could not capture the abrupt change of the moisture field associated with the approach of the squall line. Moreover, the quality of the moisture simulation was particularly poor a few hours prior to the initiation of the squall line. In the comparison of the nonisotropic component of slant wet delays, we demonstrated that the small-scale variation in the atmospheric moisture structure cannot be resolved by a 9-km MM5 forecast model. From a forecasting perspective, these results are very encouraging and illustrate the great potential for ground-based GPS slant wet delay observations to significantly improve moisture analysis and the subsequent prediction of severe weather such as squall lines.

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