Assimilation of Ground-based GPS Slant-Path Water Vapor Measurements and Its Impact on Short-Range Prediction of a Pre-frontal Squall Line: An OSSE Study

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1. Introduction

Water vapor is one of the most significant constituents of the atmosphere because its phase changes are responsible for cloud and precipitation and their interaction with radiation is a crucial factor in climate variation. Despite of its importance to atmospheric processes over a wide range of spatial and temporal scales, water vapor is one of the least understood and poorly described components of the atmosphere.

With the recent advance in Global Positioning System (GPS) Meteorology, ground-based GPS receivers have become an important instrument that can potentially provide high resolution water vapor measurements at low cost. The raw measurements from the receiver are phase-delays of the microwave signals transmitted from GPS satellites due to the atmosphere, which can be used to derive water vapor accurately with independent measurements of surface pressure and mean air temperature. The integrated water vapor along each ray path between a GPS satellite in view to a ground-based receiver is called slant water vapor. After projecting each slant water vapor to the zenith and averaging them over a certain period of time, precipitable water (PW) is obtained, which is the integrated water vapor in the vertical air column. One advantage of slant water vapor measurement over the precipitable water measurement is that slant water vapor contains information on the distribution of water vapor around a ground-based GPS receiver, while precipitable water contains the information only directly above the receiver site. However, the slant water vapor measurement can be affected by noise due to instabilities of the receiver, site multipath, etc. Current GPS techniques can retrieve the integrated water vapor along the line of sight with an accuracy of a few mm (Braun et al. 2001).

There have been several precedent studies on the assimilation of precipitable water into weather prediction models and their impacts on short-term forecasting of convective weather. In the study of a case in Severe Environmental Storms and Mesoscale Experiment (SESAME) 1979, Kuo et al. (1996) showed that the assimilation of precipitable water (PW) and surface humidity data could lead to significant improvement in short-range precipitation forecasts of a strong convective event, when such data are used together with wind and temperature data. Guo et al. (2000) showed, through a case study of the Department of Energy (DOE) Atmospheric Radiation Measurements (ARM) Program's Water Vapor Intensive Observation Period (WVIOP) of 1996, that four-dimensional variational data assimilation (4DVAR) of GPS precipitable water vapor measurement has a significant impact on the rainfall prediction. But, it has relatively small influence on the recovery of the vertical structure of moisture. One shortcoming of the Guo et al. (2000) study was the limited number of ground-based GPS receiver sites. With a total of 14 GPS sites clustered over a relatively small area, it was hard to demonstrate a strong impact on weather prediction over a much broader region. McDonald et al. (2001) performed an observing system simulation study and demonstrated successful recovery of three-dimensional water vapor distribution from a hypothetical high-density network of GPS site using the three-dimensional variational data assimilation (3DVAR) technique.

At present, near real-time analysis of GPS water vapor observations is available from NOAA/FSL network and SuomiNet (Ware et al. 2000), which consists of 115 sites over the United States. However, this network is not sufficient to properly capture the mesoscale variation of the atmospheric moisture. Therefore, in this study, we perform an observing system simulation experiment to simulate GPS observation from a hypothetical network and to assess its impact on short-range prediction of a prefrontal squall line. The OSSE study will allow us to assess the impact of station density, measurement frequency, cut-off elevation angles and other parameters on the results of data assimilation. It would also allow us to evaluate the importance of the slant-path water vapor measurement relative to the precipitable water measurement.

2. Methodology and experiment design

a) Assimilation of slant wet delay

To transform the delay unit of the GPS raw measurements into the water vapor unit, conversion parameter needs to be used with the assumption that the atmosphere is azimuthally isotropic. As the water vapor field in the real atmosphere has strong nonisotropic component, this can introduce errors. In this study we choose to directly assimilate slant wet delay to avoid errors associated with this assumption.

At microwave wavelengths, refractivity in the troposphere is related to atmospheric pressure, temperature and water vapor pressure. And wet delay can be expressed as the following:

$$N = N_{dry} + N_{wet} = 77.6\frac{P}{T} + 3.73\times10^{5}\frac{e}{T^{2}}$$

$$SWD^{m}(t_{r_2}) = 10^{-6}\int_{receiver}^{moodeltop} N_{wet}\,ds$$

To include slant wet delay observations into the 4DVAR system, an additional term needs to be added to the cost function. As the slant wet delay (SWD) is not a model predictive variable, we need an observation operator which projects model-predicted pressure, temperature, and moisture onto the wet delay.

$$J(x_o) = \sum_{r_1} W_x[x^{m}(t_{r_1}) - x^{obs}(t_{r_1})]^2 + \sum_{r_2} g[SWD^{m}(t_{r_2}) - SWD^{obs}(t_{r_2})]^2,$$

,where $x^{m}(t_{r_1})$ are the model variables at time t_{r_1}, $x^{obs}(t_{r_1})$ are the direct observations at time t_{r_1}, W_x and g are weighting coefficients.

The weighting coefficients for PW and SWD (W_x *and* g) are defined as a diagonal matrix with a constant element, which is the inverse of the measurement error. In this paper, PW measurement error is 1.5 mm and SWD observation error is a function of elevation angle of each ray path assuming an isotropic atmosphere. The measurement error for the slant wet delay is derived based on Table 1 of Braun et al. (2001).

b) Mesoscale model and experiment design

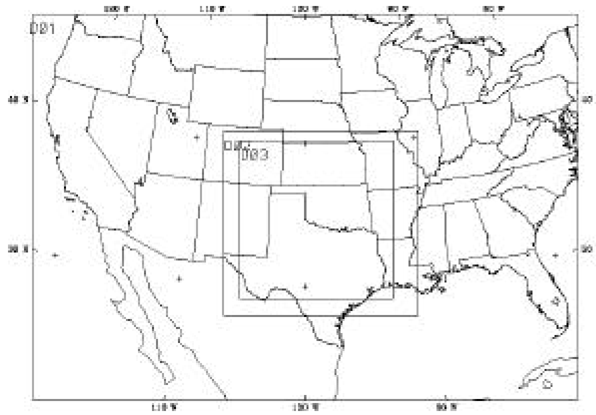

Fig. 1. Domains of observing system simulation experiments. Domain 3 is used for both the natural run (at 3-km resolution) and the 4DVAR experiment (at 27-km resolution). Domain 2 (9-km resolution) is used to provide lateral boundary condition for Domain 3 in a one-way nested mode.

The PSU/NCAR mesoscale model MM5 version 3 and its 4DVAR system were used in this study. We upgraded the MM5 4DVAR system, which was originally coded based on MM5 version 1, to be consistent with the I/O structure of MM5 version 3. To simulate the prefrontal squall line which was formed over the Kansas-Oklahoma panhandle at 0100 UTC 30 October 1999, the natural run was performed with 3km grid mesh and 50 vertical layers and was integrated for 18 hours from 1200UTC 29 October. The computational domain (Domain 3 in Fig. 1) contained an array of 403 x 388 grid points. In this run, the explicit moisture scheme and MRF planetary boundary layer (PBL) scheme were employed; but cumulus parameterization was used. The results from the natural run were used to simulate slant wet delay measurements from a hypothetical network of GPS sites. This was done by integrating the wet refractivity along the ray path which was assumed to be a straight line from the stations to each GPS satellite. For the satellite positions, actual orbit data at the observation time were used.

We conducted four data assimilation experiments. To obtain improved simulations from the experiments, all forward runs were performed at 9km horizontal resolution with 23 vertical layers. However, due to computation cost, all 4DVAR experiments were done at 27km resolution. In this study, as the vertical resolution is considered to be more important than the horizontal resolution in the calculation of slant wet delay, vertical resolution was maintained at 23 layers in 4DVAR experiments. Because of differences in horizontal resolution, we should take into account some errors from linear interpolation between forward and 4DVAR run. In the MM5 4DVAR system, Grell cumulus parameterization, Bulk PBL, and explicit moisture scheme were used, while Kain and Fritsch cumulus scheme and Reisner 1 mixed-phase microphysics scheme and Blackadar PBL scheme were used in the forward run.

In order to provide an upper-bound benchmark in terms of forecast accuracy for the data assimilation experiments we conducted Exp. 1 -- "Perfect IC Run". The initial condition for this experiment was obtained by taking the atmospheric state at every third grid point of the nature run at 2100UTC 29 October. This experiment represents a case where best possible initial condition is available for a forecast model at 9-km resolution. The difference between this run and the natural run is caused primarily by model errors (difference between 3-km and 9-km grid, and their associated physical parameterization schemes).

The second experiment is a "no data assimilation run" -- Exp 2. NO4DVAR. This experiment represents a lower-bound benchmark, reflecting the accuracy of a forecast model initialized by a global analysis. We first conducted a 27-km MM5 experiment using the National Centers for Environmental Prediction (NCEP) global analysis at 1200UTC 29 October as the initial condition. The 9-h forecast from this 27-km run was then interpolated to the 9-km grid and used as the initial condition for Exp 2. NO4DVAR at 2100UTC.

Exp 3. Optimal IC1 Run is the PW-only assimilation experiment. The optimal initial condition was obtained at 2100UTC through 4DVAR assimilation of precipitable water over a 3-h time window from 2100 UTC to 0000UTC 30 October. The precipitable water observations were obtained from the "nature run" under the hydrostatic assumption. The actual PW measurement from a ground-based GPS receiver is an averaged value over 30 min while the PW simulated from the natural run is an instantaneous value. Therefore, in the real data assimilation, we should include the temporal projection operator in the cost function for PW. But in OSSEs, observations and model simulated variables are both instantaneous fields, and the temporal projection operator is not necessary. The hypothetical network consisted a total of 64 GPS receiver sites regularly distributed over the Oklahoma - Kansas region with 90-km spacing. Measurements are assumed to be available at 30-min intervals.

Exp 4. Optimal IC2 Run is the assimilation of both PW and SWD measurements from the same network over the same 3-h time window. Cutoff elevation angle for each ray path is 5 degrees for this study.

All forward runs were conducted at 9-km horizontal resolution from the four different sets of initial conditions to investigate the impact of slant wet delay on short-term precipitation forecast. Figure 2 provides an illustration of this experiment design.

3. Results

Although Exp. 1 was initialized from the "perfect" initial condition, because of "model error" due to the differences in model resolution and physical parameterization from the "true atmosphere" (natural run), it still exhibited a sizeable forecast error. While precipitation in "nature run" was simulated by the explicit microphysical parameterization on the 3km grid, rainfall in all four experiments including perfect initial case was produced by cumulus parameterization. Therefore, we should bear in mind these systematic errors between the nature run and all other experiments when interpreting the results. Also note the numerical model in 4DVAR used 27 km grid mesh while all forward runs had 9-km resolution. The errors from interpolation between grids with different resolutions can generate dynamic imbalance at the initial time.

Figure 3 shows the 3-hr accumulated rainfall after 6 hour forecast valid at 0300UTC 30 October. Keep in mind the assimilation time window is 3 hours from 2100UTC to 0000UTC, which is part of the forecast period. As explained in section 2, Exp 2 did not have the benefits of GPS data assimilation. The high rainfall area extended from northeastern Kansas to southwestern Oklahoma, seen in Exp 1, was not simulated. Instead, erroneous precipitation was

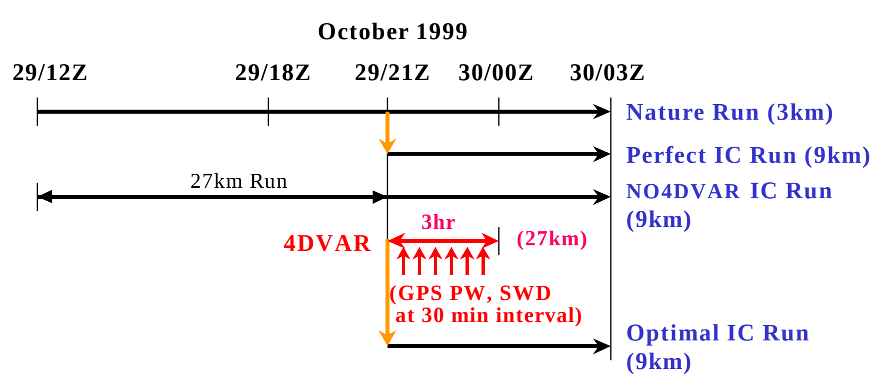

Fig. 2. Schematic diagram of the OSSE experiment design.

generated over northwestern Texas region. With the assimilation of precipitable water measurements from a dense network of GPS receivers over the pre-frontal squall line region, Exp 3 simulated the rainfall area over Oklahoma fairly well, though with weaker intensity. When both PW and SWD were assimilated, the forecast of the squall line and its associated heavy precipitation was much improved, especially over southern Kansas (Exp 4).

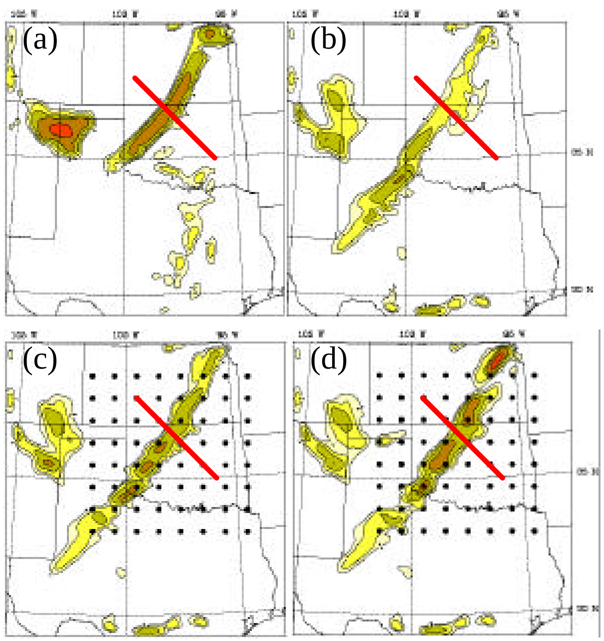

Fig 3. The 3-h accumulated rainfall at 6-h forecast valid at 0300UTC 30 October for (a) Exp 1 – perfect IC case (b) Exp 2 – NO4DVAR case (c) Exp3 – PW assimilation (d) Exp4 – PW+SWD assimilation. Contours are 1, 2, 4, 8, 16, and 32mm. In (c) and (d), dots indicate loci of the simulate GPS receiver sites.

Figure 4 shows the equivalent potential temperature and the two-dimensional circulation in the cross section along the red line in Figure 3. The results indicate that the assimilation of slant wet delay gave a better prediction of the vertical distribution of the warm moist air than the assimilation of PW alone. In Exps. 2 and 3 (panels b and c), high-θ_e air did not reach the 700-mb level. Since the bulk PBL scheme was used in the 4DVAR experiment, moisture structure in the low-level was not well retrieved even with the assimilation of slant wet delay. This was attributed to the limited capability of the bulk PBL in simulating the turbulent transport within the convective boundary layer. Therefore, we will need to improve the physical realism of an assimilation model in the future in order to obtain better results.

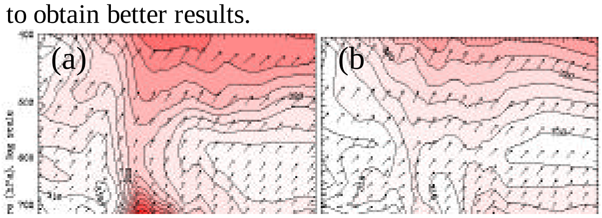

Fig 4. Equivalent potential temperature and two-dimensional circulation along the thick line in figure 3 at 6-h forecast. Contour interval for q_e is 1°K and shading area shows values greater than 320°K.

We also calculated the threat score for all three experiments as verified against Exp 1. The results for the precipitation thresholds of 1, 5, 10, 15, and 20 mm are presented in Fig. 5. Note that at 0000UTC 30 the squall line was not yet formed; while 0300UTC was the initial stage, and 0600UTC was the developing stage of the squall line over the Kansas-Oklahoma region. Even though the forecast of PW-only assimilation experiment is slightly better than the experiment with the assimilation of both PW and SWD at the threshold of 1 mm, the latter is superior to the former for all other thresholds at all times. And it is interesting that the difference in the threat scores between PW and PW+SWD assimilation increases as the threshold value is increased. This indicates that SWD assimilation improves short-term rainfall prediction both in terms of the rainfall distribution and intensity.

The improvement on the rainfall prediction through 4DVAR did not extend much beyond 12-h forecast in this study. As time proceeds, the superiority of SWD assimilation gradually diminishes. We attribute this result to the sweeping effects of the lateral boundary condition. Moreover, since moisture is a passive variable, its distribution will be increasingly governed by the dynamics of the weather systems in the later stage of the forecast. Therefore, the improvement in water vapor analysis cannot be sustained for an extended period of time.

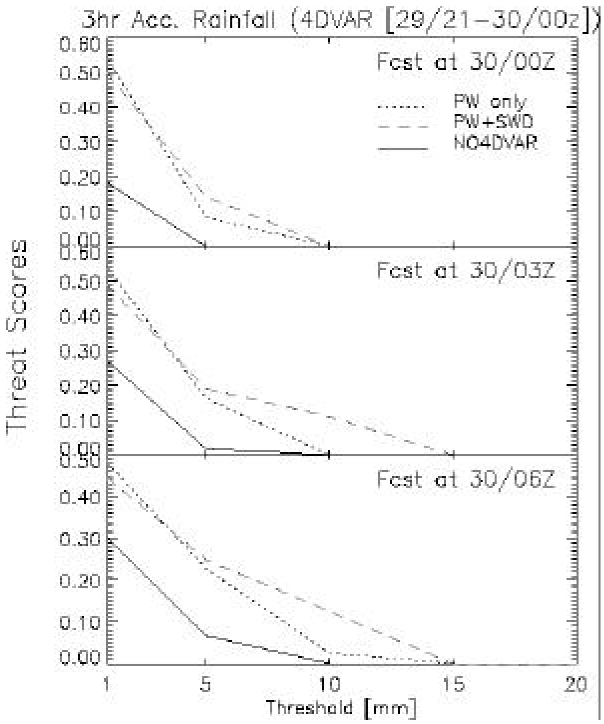

Fig 5. The threat score of 3-h precipitation at 3-h intervals from 0000UTC to 0600 UTC 30 October. NO4DVAR case is solid line, PW case dot, and PW+ SWD case dash.

4. Summary and conclusions

In this study, we performed a set of observing system simulation experiments to assess the impact of assimilating GPS slant wet delay on short-range prediction of a pre-frontal squall line. We showed that even without additional wind and temperature data, the assimilation of precipitable water measurements from a hypothetical network of GPS receiver improved the short-range forecast of precipitation. The addition of slant wet delay in 4DVAR assimilation further improved the model forecast, particularly in the prediction of large precipitation threshold and in simulating the three-dimensional distribute of moisture. The impact was particularly robust during the first 6-h of the forecast. These results suggest that slant path water vapor measurements from the ground-based GPS receivers are valuable data sets, and can be used to substantially improve mesoscale moisture analysis and quantitative precipitation forecasts.

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