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THE IMPACT OF GROUND-BASED GPS SLANT-PATH WET DELAY MEASUREMENTS ON SHORT-RANGE PREDICTION OF A PREFRONTAL SQUALL LINE

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1. INTRODUCTION

Spatial distribution and temporal variation of moisture field in the low-level atmosphere play an important role on convective initiation. However, with conventional upper-air observing systems and surface station data, it has been difficult to obtain accurate low-level moisture observations at high temporal and spatial resolution. Recent advances in ground-based Global Positioning System (GPS) atmospheric sensing technique allow measurement of integrated water vapor with good precision and can potentially fulfill this need. At present, a near real-time analysis of GPS precipitable water (PW) observations is available from the NOAA/FSL network and the SuomiNet (Ware et al. 2000), which consists of approximately 125 sites over the United States. Although the retrieval and applications of GPS PW has reached a high level of maturity, the retrieval technique of GPS slant-path water vapor estimate and its application for numerical weather prediction are only in the beginning stage.

Slant-path wet delay (SWD) represents a propagation delay in microwave signal transmitted from GPS satellites due to atmospheric water vapor only. By retrieving this quantity accurately, we can estimate the moisture distribution in the troposphere. As a ground-based receiver can track up to 12 satellites simultaneously at any given time with typically 30 sec sampling, the collection of hundreds of slant wet delay measurements along each ray path can capture meso-scale variation of water vapor distribution (see Fig.1).

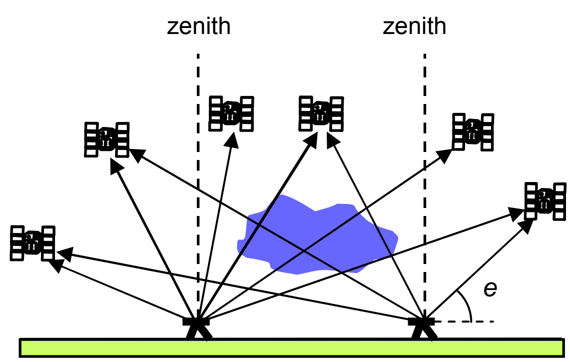

Fig. 1. GPS meteorology. Slant wet delay data represents total phase delay due to tropospheric water vapor only along each ray path (from a ground receiver site to each GPS satellite). Each slant wet delay measurement can be expressed as its own azimuth and elevation angles (e).

To understand the impact of GPS slant wet delay data on the prediction of a squall line, we conduct a set of observing system simulation experiments (OSSEs)

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using PSU/NCAR MM5 model (Version 3.0) and its four-dimensional variational data assimilation (4DVAR) system. We also assess the importance of slant wet delay relative to the other conventional observations in terms of rainfall prediction.

2. METHODOLOGY AND EXPERIMENT DESIGN

2.1 *Assimilation of Slant Wet Delay*

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:

$$N = N_{dry} + N_{wet} = 77.6\frac{P}{T} + 3.73\times10^{5}\frac{e}{T^{2}} \quad (2.1)$$

$$SWD^{m}(t_{r_2}) = 10^{-6}\int_{receiver}^{moodeltop} N_{wet}\,ds \quad (2.2)$$

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.

$$J(x_o) = \sum_{r_1} W_x[x^{m}(t_{r_1}) - x^{obs}(t_{r_1})]^{2} + \sum_{r_2}\gamma[SWD^{m}(t_{r_2}) - SWD^{obs}(t_{r_2})]^{2} \quad (2.3)$$

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 γ are weighting coefficients.

The weighting coefficients for the measurements (W_x *and* γ) are defined as a diagonal matrix with a constant element, which is the inverse of the measurement error. In this paper, 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).

2.2 *Experiment design*

In this OSSE study, we selected a prefrontal squall line which occurred in southeastern Kansas – northwestern Oklahoma and produced 24-hr rainfall amount of 89.8 mm around Lamont, OK on 30 October, 1999. To simulate the prefrontal squall line, the nature run was performed with 3km grid mesh and 50 vertical layers and was integrated for 18 hours from 1200UTC 29 October. The computational domain (see Fig. 3) 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 no 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 based on (2.1) and (2.2). 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 carried out at 27km grid 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 runs. 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 at 2100UTC.

Exp 3. Optimal IC1 Run is the slant wet delay assimilation experiment. The optimal initial condition was obtained at 2100UTC through 4DVAR assimilation of slant wet delay over a 3-h time window from 2100 UTC to 0000UTC 30 October. The slant wet delay observations were simulated from the “nature run” at every 10 min time intervals. As the cutoff elevation angle for each ray path is 5 degrees, we ignored the bending effect and treated the ray path as a straight line in this study. The hypothetical network consists a total of 64 GPS receiver sites regularly distributed over the Oklahoma - Kansas region with 90-km spacing (as shown as black dots in Fig. 5c).

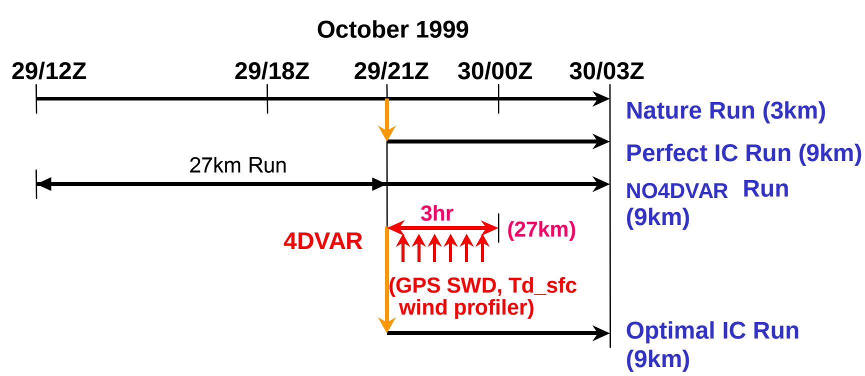

Fig. 2. Schematic diagram of the OSSE experiment design.

Exp 4. Optimal IC2 Run is the assimilation of wind profilers and surface dew point station data. In this experiment, we used real observation network which is composed of 15 wind profilers and 203 National Weather Service (NWS) surface stations in Southern Great Plain region (as shown as black dots and red asterisks in Fig. 5d). Wind profiler data was averaged every hour while surface station data was taken every 5 min as an instantaneous value. However, no GPS SWD were assimilated in this experiment.

To more realistically simulate those measurements, we generated random errors which are of uniform distribution with a random number generator and then add these errors to the "perfect" observations. The magnitude of random errors is similar to that of the real measurement errors. Figure 2 provides an illustration of this experiment design.

3. RESULTS

To examine how the 4DVAR assimilation of slant wet delay changes the atmospheric state in the minimization process, we examine the changes of model control variables with iterations. Figure 3 shows the water vapor mixing ratio at the lowest sigma level (σ = 0.985) before and after 40 iterations. With increased iterations, the low-level moisture is increased near the border of Kansas-Oklahoma where the squall line forms in a few hours. Comparing the moisture distribution "before minimization" (Fig. 3a) and "after minimization (40 iterations)" (Fig. 3b), we note that the contour of 11 g kg^{-1} is expanded to southeastern Kansas. As a result, specific humidity in this area is increased by 1.0 g kg^{-1}.

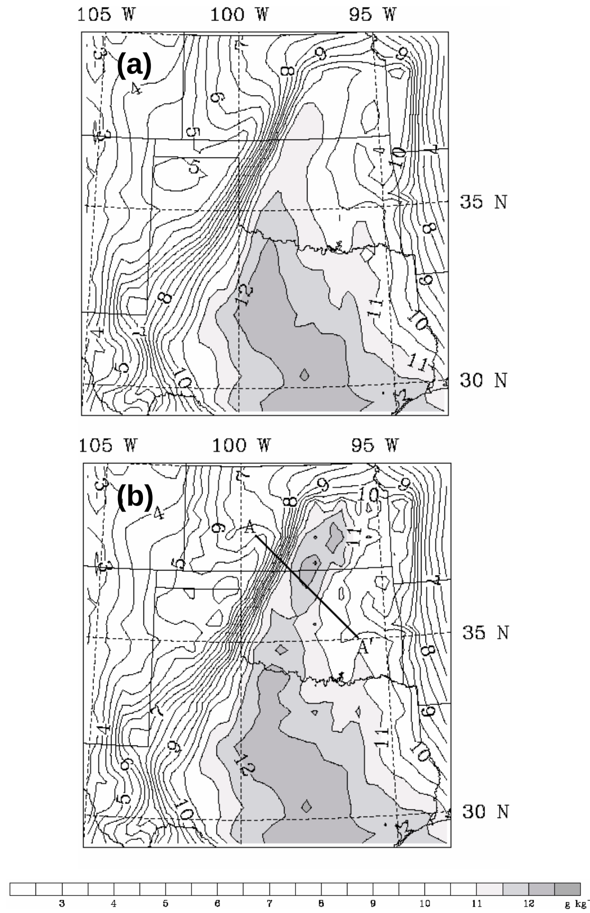

Fig.3. Water vapor mixing ratio at the lowest sigma level (σ = .985) at the initial time valid at 2100UTC 29 October during the minimization process at (a) iteration 0 (b) iteration 40. The area greater than 11 g kg^{-1} was shaded. Contour interval is 0.5 g kg^{-1}.

Even though slant wet delay is an integrated value along each ray path, it is mostly contributed by the low-level moisture. Therefore, we expect the impact of slant wet delay assimilation to reach the entire boundary layer rather than just being confined to the lowest sigma level. Crook (1996) examined the sensitivity of moist convection to boundary layer thermodynamic parameters and found that convective initiation is most sensitive to surface temperature and moisture perturbations. To examine if the assimilation of slant wet delay can improve the atmospheric structure in the boundary layer, we show, in Fig. 4, the differences in water vapor mixing ratio, temperature, and 3-dimensional circulation vectors before and after minimization in the vertical cross section along the line AA' in Fig. 3b. Figure 4 indicates that the assimilation of slant wet delay moistens the entire atmosphere, especially the boundary layer, by as much as 1.5 g kg^{-1} where the squall line will be initiated. The region of moistening (the shaded area) is also overlapped by the region of positive temperature changes (solid line). As a result, the cross-frontal temperature and moisture gradients associated with the differential warming and moistening of the boundary layer aid to strengthen the surface cold front and to initiate the convection at the correct location. The strong rising motion immediately behind the moistened boundary layer, induced by the assimilation of slant wet delay, results in the strong moisture convergence just ahead of the surface cold front and triggers the release of the convective instability. These changes in the initial state significantly improve the model's skill in forecasting the onset time and the location of the squall line.

Next, to examine the impact of slant wet delay relative to other conventional observations on the short-term rainfall prediction, we compared the 3-hr accumulated rainfall ending at 0300 UTC from the four experiments – Perfect IC Run, NO4DVAR Run, Optimal IC1 and Optimal IC2 Run (see Fig. 5). The heavy rainfall area extending from northeastern Kansas to southwestern Oklahoma, seen in the Perfect IC Run, is not simulated in NO4DVAR. Instead, erroneous precipitation is generated over the northwestern Texas region (Fig. 5b). With the assimilation of SWD only, the forecast of the squall line and its associated heavy precipitation is greatly improved, especially over southern Kansas (Fig. 5c). In Optimal IC2 Run, however, the assimilation of wind profilers and surface dew point temperature fails to produce heavy rainfall and the maximum 3-hr accumulated rainfall is only 6 mm in the squall line area. Moreover, the squall line is not well-aligned in southeastern Kansas – northwestern Oklahoma even though surface station data concentrated in this area was assimilated at 5 min time intervals.

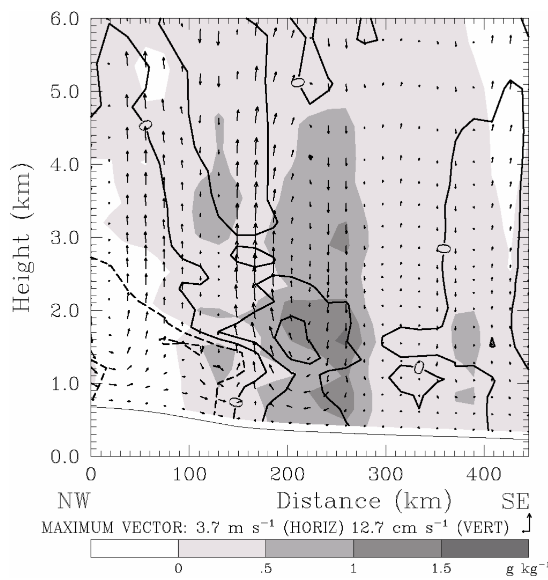

Fig. 4. Differences between "before" and "after" minimization in the vertical cross section along AA' in Fig. 3b. Positive Δq_v (=q_v_after – q_v_before) is shaded and ΔT (=T_after – T_before) is shown by solid line (warm anomaly) and dash line (cold anomaly), respectively. Contour interval is 0.5 °C. Three-dimensional wind differences between "before" and "after" minimization are also shown as wind vectors.

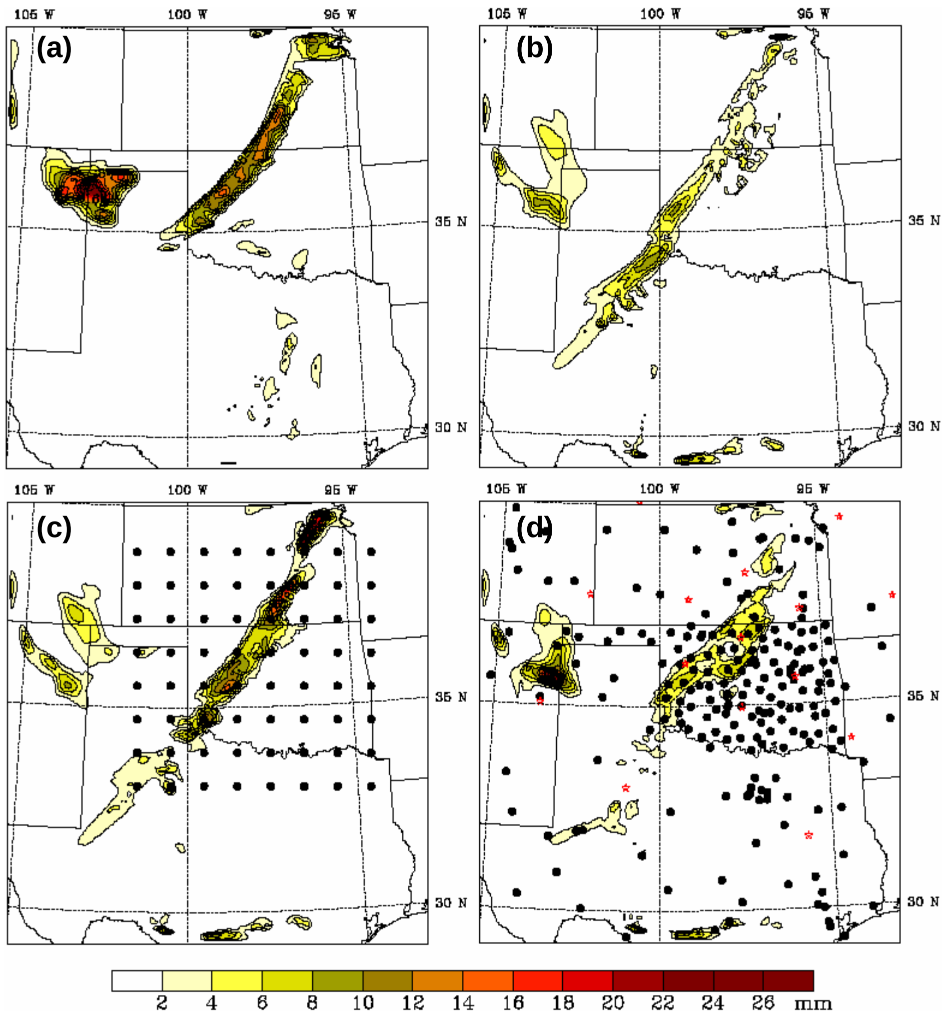

Fig. 5. The 3-hr rainfall ending at 6-h forecast valid at 0300 UTC 30 October for (a) Perfect IC Run (b) NO4DVAR Run (c) Optimal IC1 Run (d) Optimal IC2 Run. Contour interval is 2 mm. Black dots indicate (c) a hypothetical observation network for GPS slant wet delay data and (d) the actual NWS surface stations. Red asterisks in (d) represent the actual location of wind profilers.

4. CONCLUSION

In this OSSE study, we simulated ground-based GPS slant wet delays from a hypothetical dense network over the Kansas-Oklahoma region and demonstrated that the variational assimilation of slant wet delays effectively improved the short-term numerical forecast by changing moisture, temperature and wind fields in the low-level atmosphere. These changes, in turn, leaded to better forecast of precipitation in the squall line area.

In contrast to slant wet delay assimilation, the assimilation of wind profiler data and surface dew point temperature from the current observation network could not produce heavy rainfall in the squall line even though measurements with high resolution in time and space were available for surface station data.

These results suggest that slant path water vapor measurements from the ground-based GPS receivers can complement other moisture observation sources, and can be used to substantially improve mesoscale moisture analysis and precipitation forecasts.

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