# Impact of Ground-based GPS Retrievals on Moisture Field and Rainfall Forecast in WRF/3DVAR

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## 1. Introduction

The ground-based GPS network is relatively cheaper instruments which observe the integrated water vapor with high temporal resolution from 30 minutes to 5 minutes (depending on the analysis strategy), and with high accuracy of less than a few mm in precipitable water vapor (PWV). The GPS network has been deployed in many countries for the purpose of monitoring crustal deformations, navigation, and the surveying. The mean spacing of the GPS sites has been finer, and the networks have potential to retrieve the moisture field with finer resolution by analyzing the data with the meteorological purpose.

The 3DVAR experiment conducted by Guo et al. (2004) shows the positive impact of GPS PWV on rainfall forecast with the domain of 10-km grid distance in MM5/3DVAR system. We focus on 4-km grid distance WRF/3DVAR data assimilation system (Baker et al. (2004)), a successor of the MM5/3DVAR system, and also focus on the impact of moisture field by assimilating three kinds of GPS retrievals in the two different ground-based GPS networks in the U. S. and Japan.

## 2. Retrievals and Observation Operators in Ground-based GPS

The original retrieval including the moisture information in the GPS analysis is zenith total (or tropospheric) delay (ZTD). ZTD is separated into the two terms; zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD) which includes moisture information. Because ZHD which roughly accounts for 90% of the ZTD can be computed by in-situ pressure observation at the GPS site with very fine approximation, ZWD can be computed by subtracting ZHD from ZTD. PWV is computed from the ZWD with the empirical factors and some assumptions (e.g. Bevis et al. (1992)).

It is more preferable to assimilate ZTD or ZWD than PWV because they are or are closer to the original retrieval. We studied the difference of the impact on moisture field by assimilating the three GPS retrievals.

The observation operators used in the experiments is similar with Vedel and Huang (2004),

$$ZHD = 10^{-6} k_1 R_d \frac{P_s}{g_m}, \quad (1)$$

$$g_m = 9.784(1 - 0.0026 cos2\phi - 0.00028H), \quad (2)$$

where $P_s$ is surface pressure (hPa), $H$ is antenna altitude (km), $\phi$ is latitude of the site (degree).

$$ZWD = 10^{-6} \sum_{k=1}^{k=nk} [\frac{p_k q_k}{T_k \epsilon}(k_2 - \epsilon k_1 + \frac{k_3}{T_k})] dz_k, \quad (3)$$

where $p(Pa)$ is pressure, $q(kg \cdot kg^{-1})$ is specific humidity, $T(K)$ is temperature, $\epsilon = \frac{m_v}{m_d} = 0.622$ , $dz(m)$ is height of vertical grid $k$, $k_2$ and $k_3$ are $72$ and $3.75 \times 10^5$, respectively.

$$PWV = \sum_{k=1}^{k=nk} \rho_k q_k dz_k, \quad (4)$$

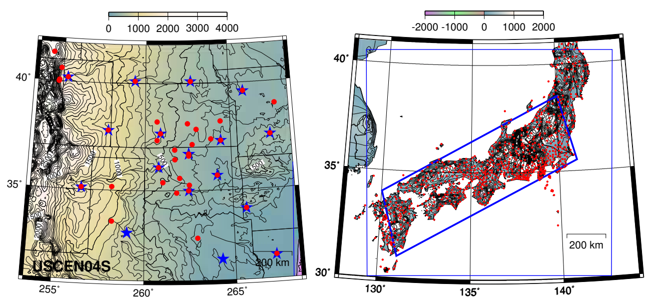


Figure 1: Model domains for the OSE and OSSE in the U.S. (left) and Japan (right). The red solid circles and blue stars show GPS sites and wind profiler sites (only for U.S. domain), respectively. The thin blue lines show actual model domain and thick blue lines in the Japanese domain (right) show the selected region used for RMS error computation.

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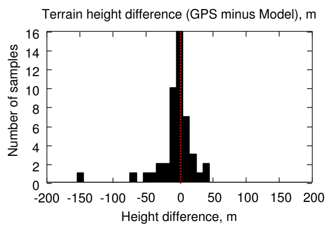


Figure 2: Terrain height difference between the GPS antenna (orthometric height) and model terrain height (GPS minus model) in the U.S. domain (left) and Japanese domain (right).

where $\rho(kg \cdot m^{-3})$ is density of air.

# 3. GPS Networks and Experiment

We used the two ground-based GPS networks in the central U. S. and GEONET (GPS Earth Observation NETwork) in Japan. Figure 1 shows the distribution of GPS sites in each domain used for the OSE and OSSE . The sizes of the model domain are 301x301x31 and 311x291x31 for the U. S. domain and Japanese domain, respectively, and the grid distance for the two domains is 4 km. The domain sizes used for real case experiments are a little larger than the those in OSE and OSSE.

Figure 2 shows height difference between actual GPS site (orthometric height (or sea level height) computed with GEOID height data) and model terrain height. The height differences were considered in the data assimilation of the all three kinds of GPS retrievals (ZTD, ZWD, and PWV). Such correction is important in the GEONET showing relatively large height difference because most of the sites have been deployed in the valley in the mountainous area.

# 4. Single point DA, OSE, and OSSE

Figure 3 shows vertical profiles of the increment (analysis minus background) of the wet refractivity by the singular site ZTD assimilation, where optimized scale length of the specific humidity by the minimization test of the cost function in the U. S. domain is 0.35. The ZTD information propagates smoothly, and the larger increment can be seen in near the scale height of water vapor. The pattern shown in Fig. 3 was almost same with that of the specific humidity. The similar patterns (not shown here) can be seen in the increment resulted in the assimilation of the other two retrievals, too.

The increment of temperature and pressure were negligible in the assimilation of the all three kinds of GPS retrievals.

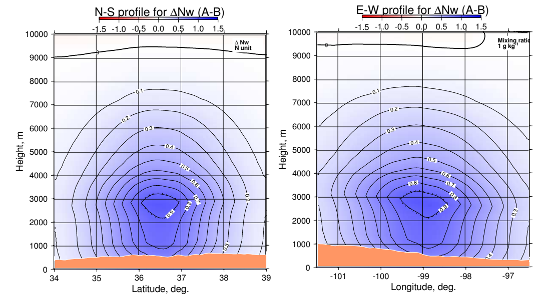


Figure 3: The profile of wet refractivity in N-S (left) and E-W (right) cross sections by the single point ZTD assimilation experiment in the U.S. domain.

We chose one case for the observation system experiment (OSE) in the U.S. domain and Japanese domain. The WRF control run for twelve hours are chosen as the real atmosphere (reference profile), and the ETA analysis and AVN analysis in the corresponding time for the control run forecast was set as the background for the data assimilation.

We computed ZTD, ZWD, and PWV at the real GPS sites from the reference profile, and assimilated the data into the background. The optimized scale length of the specific humidity in Japanese case with similar way of the U. S. domain is 0.07.

Figure 4 shows RMS errors in specific humidity [g/kg] at each vertical levels up to 18 (about 5 km). The positive impact can be seen in all the layers, and the impact seems to be corresponding to the first EOF mode for the specific humidity (Baker et al. (2004)).

The notable result is the RMS errors resulted from the the ZTD and ZWD assimilation are similar with each other. Also, the RMS error resulted from the PWV assimilation is also close to those of ZTD and ZWD assimilation, but shows small difference in higher altitude. Some of the difference in PWV probably comes from the difference of the used control variables.

The RMS errors change by depending on scale length. For example, when we used the 0.35 for the scale length of specific humidity in the Japanese domain, the resulted profiles of the water vapor showed negative impact when all model domain was used for the RMS error computation. We confirmed that the moisture information at the coastal sites propagates into the ocean in the case. The facts indicate that the optimization of the scale length for each model domain is one of the important tunings for the WRF/3DVAR system. The OSE in each domain is thus an important validation of the data assimilation for the final purpose of data assimilation, that is, to produce better initial condition for the better forecasts.

Figure 5 shows PWV distribution in the reference field

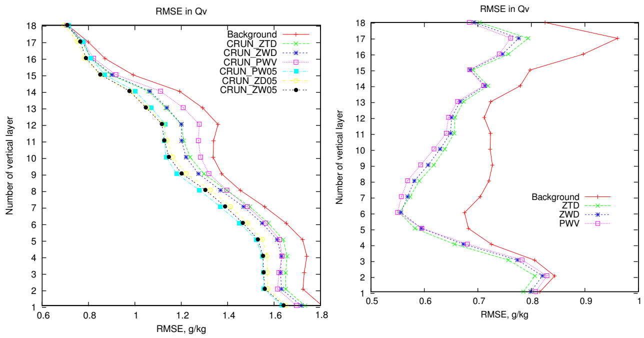


Figure 4: RMS errors of specific humidity between the reference profile and the profiles by assimilation of GPS retrievals to the background. The left and right panels are for the U.S. domain and Japanese domain, respectively. The red curve is for the background without assimilations, and the green, blue, and pink curves are for ZTD, ZWD, and PWV assimilation in the OSE. Additional light blue, yellow, and black curves in the U. S. domain (left) are for ZTD, ZWD, and PWV assimilation in the OSSE.

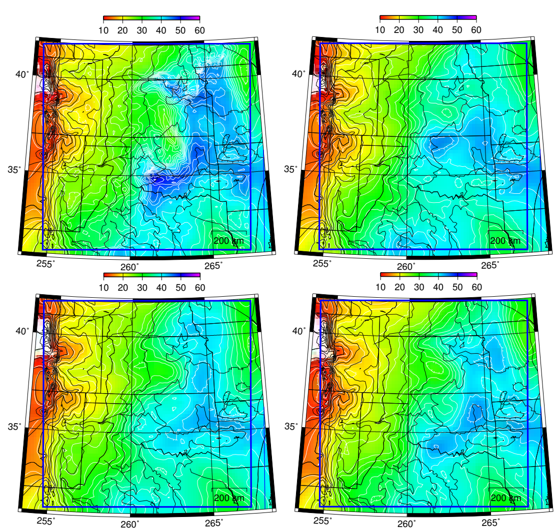

Figure 5: PWV distributions in the reference field (upper left), in the background (upper right), in the field by the assimilation of ZTD in the OSE (lower left), and in the field by the assimilation of ZTD with the 0.5 deg. gridded distribution of GPS sites in the OSSE (lower right).

and the fields resulted from the ZTD data assimilation. The profile of ZTD data assimilation in the OSE shows large scale distributions of PWV with about 100 km seen in the reference field. The pattern shown here is also similar with those in the assimilation of ZWD and PWV, too.

The observation system simulation experiments (OSSE) were also conducted to estimate anticipated impacts by the future ground-based GPS network.

Fig. 4 shows RMS errors in the OSSE with 0.5 deg. gridded spacing of the imaginary GPS sites in the U. S. model domain. Also, fig. 5 shows the PWV distribution by the OSSE (lower right). As easily expected, the denser GPS network can capture more detailed water vapor profiles. Note that observation area in the GPS can be expressed as the beam width. The diameter in the inverse cone is about 50km at the 3-km height from GPS antenna when the minimum elevation angle for GPS satellites is 7 degrees. The slant wet delay, integrated wet refractivity for each GPS satellite, will probably work in the denser GPS network to bring out potential of the dense network.

## 5. Impact on Rainfall Forecast

Because GPS retrievals improve moisture fields as seen in the OSE study, they should improved rainfall forecast. We performed case studies for several cases in 2003, both for the U.S. domain and the Japanese domain. The parameter setting and scheme used for the forecast were exactly same with 4-km real-time WRF forecast experiment conducted by NCAR (http://www.mmm.ucar.edu/wrf/REAL_TIME/real_time.html). We show here the results of cycling 3DVAR because larger impact for the rainfall forecast could be seen in the cycling 3DVAR than cold 3DVAR.

Figure 6 depicts one hour integrated rainfall from 13 to 14 of May 24, 2003, in the U.S. domain. The rainfall forecasts in the GPS PWV assimilation is closer to observation than those in control run. The further improvement can be seen in the forecast by assimilating both GPS and wind profiler.

Figure 7 shows the one hour integrated rainfall from 14 to 15 of June 3, 2003, in the Japanese domain. The forecast with GPS data assimilation prevent false severe rain forecast shown in the central west coast of Japan in the control run.

## 6. Summary and Discussions

We performed data assimilation experiments of the three kinds of ground-based GPS retrievals; ZTD, ZWD, and

PWV, in the WRF/3DVAR system. The OSE results show positive impacts on moisture field in all levels by assimilating all the three kinds of GPS retrievals, and the impact by assimilating the three kinds of retrieval was similar.

The results suggest ZTD or ZWD is preferable GPS retrieval to be assimilated into WRF/3DVAR system because ZTD is an original retrieval by the GPS analysis, and ZWD is a function of moisture and temperature and the ZHD which roughly accounts for 90% of the ZTD is subtracted with very fine approximation. Thus, the quality check of the pressure sensor is important when we use ZWD. The GPS sites in GEONET does not have pressure sensor, but ZTD works for such networks.

As GPS PWV is computed from the ZWD with the empirical factors and climatological assumptions, there are some potentials of large errors in specific weather conditions and some topographic conditions. The (dynamic) parameters computed by the model profile (background) can be considered to be better than climatological parameters used in the data conversion.

The results of the case studies showed that multiple (cycling) ingestion of GPS retrievals improve rainfall forecast in the WRF/3DVAR system and the combination of GPS retrievals with the wind profiler worked well. We thus should confirm optimal duration for the cycling 3DVAR for the real-time forecast using GPS retrievals. Also, the statistical validation of the impact with long periods will be needed.

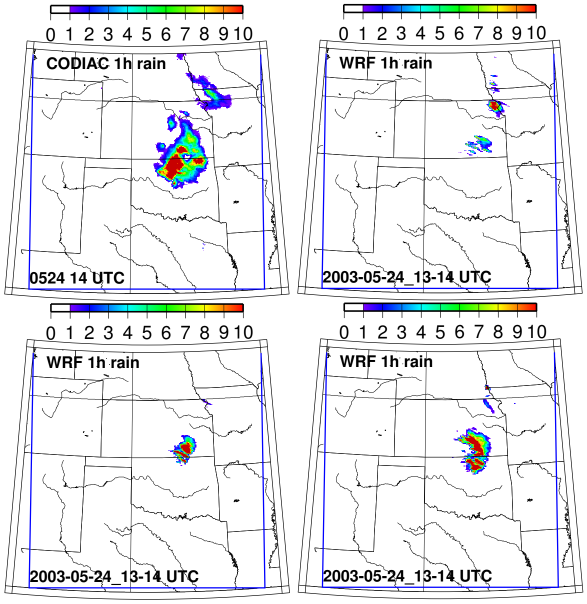


Figure 6: One hour integrated rainfall from 13 to 14 of May 24, 2003, in the U.S. domain. The upper left panel shows the observation (analysis rainfall with radar plus rain gauge), the upper right panel shows the forecasted rainfall in the control run, the lower left panel shows that in the cycling 3DVAR with GPS PWV only, and the lower right panel shows that in the cycling 3DVAR with GPS PWV plus wind profiler. The cycling period is six hours every 1 hour.

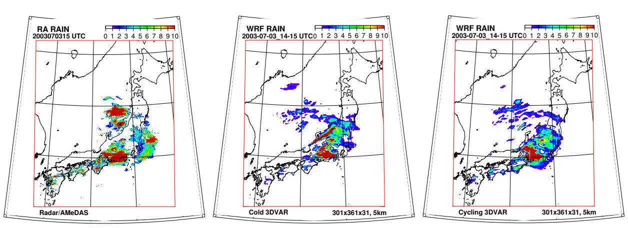


Figure 7: One hour integrated rainfall from 13 to 14 of May 24, 2003, in the Japanese domain. The left panel shows the observation (analysis rainfall with radar plus rain gauge by JMA), the middle panel shows the forecasted rainfall in the control run, and right panel shows that in the cycling 3DVAR of GPS PWV. The cycling period is six hours every 1 hour.

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