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Atmospheric Measurement Techniques Discussions

Interactive comment on "4DVAR assimilation of GNSS zenith path delays and precipitable water into a numerical weather prediction model WRF" *by* Witold Rohm et al.

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Anonymous Referee #2

This manuscript presents Observing System Experiments (OSEs) with assimilation of GNSS Zenith Total Delay (ZTD) and Precipitable Water (PW) in the Weather Research and Forecasting model (WRF) over Poland for the period May-June 2013. The period was selected for a GNSS benchmark campaign during COST Action GNSS4SWEC and reported in the paper by Dousa et al (2016). To the best of my knowledge this is the only assimilation experiment conducted for this period and this makes the contribution of particular interest to the community. However, the benefits of the GNSS dataset

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collected during the benchmark campaign are not exploited fully (see 2) bellow), which is likely reflected in the results from OSEs.

[WR] Thank you for encouraging us to investigate COST Action GNSS4SWEC benchmark period with greater detail, hopefully by adding radiosonde observations and direct comparison of WRF derived PW and ZTD with GNSS-based counterparts we improved manuscript considerably.

Major comments/questions: 1) In the paper are used the "International GNSS Service (IGS) ultrarapid orbits, clocks and Earth rotation parameters are used." Please justify the selection of those products as their quality is likely having substantial impact on the OSEs. Please, provide a comparison to high quality near-real time estimates.

[WR] The data used in this study are covering May and June of 2013, and area of Poland it coincides with Benchmark campaign of COST Action GNSS4SWEC, but the data used in this study are directly taken from the NRT processing system as it was run in the 2013. The quality of retrieved troposphere parameters using the same setup as for data applied in this study are discussed in details in Bosy et al., (2012). We are not aware that there are other “higher quality near-real time estimates” as the 90 minutes latency constrain imposed on E-GVAP processing centre requires use of ultrarapid orbits, clocks and Earth rotation parameters. We are positive that application of the data as they were processed is a strong point of this paper, as it shows the exact impact one would get using operational (E-GVAP) product.

Bosy, J., Kaplon, J., Rohm, W., Sierny, J., & Hadas, T. (2012). Near real-time estimation of water vapour in the troposphere using ground GNSS and the meteorological data. In Annales Geophysicae (Vol. 30, No. 9, p. 1379). Copernicus GmbH.

2) The quality control of GNSS ZTD is a vital part of the assimilation process. Please, include a section covering the quality control and "black listing" strategy you used. The benchmark quality controlled data-set can be used as a reference.

[KW] The GNSS ZTDs are processed for the stations of European Position Determination System Active Geodetic Network (ASG-EUPOS, www.asgeupos.pl), which are continuously monitored for quality. Only the national reference stations of that system are taken into the assimilation. We added a reference in the data section. Moreover, we also adjust the formal errors for all stations by multiplying them by a factor of 10.5 mm (a standard deviation of the differences between WRF and ZTDs) and removing the observations (black listing) which errors exceed 20 mm.

3) In section 4 is missing the model performance for PW (ZTD). It is not expected to improve the model if it has a very good PW (ZTD), which is likely the case for most of the time. Please, consider including a section with PW comparison of reference (REF) model (without assimilation) and GNSS PW.

[WR] This is actually very good remark we extended the manuscript by adding additional section discussing comparison of GNSS based PW and WRF based PW

4) The reported OSE impact do not cover assessment of PW improvement/degradation. It is important to access both individual positive and negative PW assimilation cases as they can provide valuable insight about the model and the ways to improve it.

[KW] Thank you for the suggestion, it is also a very important aspect of GNSS data assimilation. We added the comparisons with the GNSS products, PW and ZTD with WRF before and after the assimilation.

5) The assimilation of GNSS data is limited to Poland while there are a large number of GNSS stations in the surrounding countries like Germany (over 500). For the large scale frontal processes the westerly flow modification (through data assimilation) is likely to be more valuable than the local modifications thus the question is if this has been considered. It is recommended to conducted OSEs for selected number of days with assimilation of GNSS data from the neighbouring countries.

[MK] We have re-investigated the literature and OSEs for assimilation of GNSS, it is clear that Lindskog et al., (2017) were taking observations across whole Scandinavia; Bennitt and Jupp (2012) were using observations from UK and Netherlands with large density and sparse across Europe, and Poli et al. (2007) adopted in their study pan European network. This allowed to modify large scale flows e.g. westerly flow as it passes over Europe for few days up to 3 days. However, in case presented in this manuscript what we have is only small section of European troposphere covered by GNSS observations mainly Poland. Therefore we agree with the reviewer to study impact of GNSS data on longer forecasts than 12-24h, one would need to extend the area covered with observations. In our case this is not easy achievable, as we don't have available GNSS data from other countries of Europe beside Poland in 2013. Even attaining access to the troposphere retrieval for the selected time period and location (May and June, 2013 in Europe), will result in non-uniform processing strategies and hence quality of assimilated GNSS data in two ends of the WRF model. Therefore we decided to reduce the studied impact to 24hours which is reasonable assumption, keeping in mind the typical weather situation in May and June as well horizontal extend of Poland.

Minor comments/questions:

1) Please consider revising the following paragraph in the abstract as it is not fully in line with the state of the art: "The GNSS data assimilation is currently widely discussed in the literature with respect to the various applications in meteorology and numerical weather models. Data assimilation combines atmospheric measurements with knowledge of atmospheric behavior as codified in computer models. With this approach, the 'best' estimate of current conditions consistent with both information sources is produced. Some approaches allow assimilating also the non-prognostic variables, including remote sensing data from radar or GNSS (Global Navigation Satellite System).These techniques are named variational data assimilation schemes and are based on a minimization of the cost function, which contains the differences be-

tween the model state (background) and the observations."

[WR] The following sentence was added: “The variational assimilation is a first choice for data assimilation in the weather forecast centres, however current research is consequently looking into use of iteratice, filtering approach such as Extended Kalman Filter(EKF).

2) Page 1 line 27: Please specify if "20% improvement in bias of humidity forecast," is at surface or in 3D.

[WR] This improvement is visible in the surface data as in the initial submission we only considered for validation SYNOP observations. In the revised manuscript we also used for validation two other data sources GNSS and Radiosondes.

3) Page 2 line 21: Please correct "Authors".

[WR] Corrected to: “(Bennitt and Jupp, 2012)”

4) Page 4 line 13: Please correct the colloquial language use in "PW into the very popular WRF model using the WRFDA package".

[WR] Corrected to: ”assimilation of GPS ZTD and PW into widely adopted WRF model using the WRFDA package.”

5) In section 4 it can be suggest to use the widely accepted terms REF run and OSE1, OSE2 etc instead of "base run".

[WR] We understand the need to keep the manuscript language to mostly used in the data assimilation community terms, however this study is on the edge between GNSS and assimilation community and all labels as wells as reference in the manuscript were called “base run”.

6) It is not really clear what is displayed and how probability of detection and success ratio are computed in figure 3, 6, 7 and 8. The figures can be combined in one figure and referred as figure a), b), c) and d) as they show similar information. Figure captions

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are not of sufficient detail.

[MK] We would like to refrain from merging these figures, it is already quite difficult to keep the number of observations visible on all figures (with often overlap between rain rates with and without assimilation). The performance diagrams are tool that help to identify whether the improvement after assimilation of observations. The easiest first glance approach is to verify whether the marked data sets are close to the intersection line and close to the top right corner.

7) Page 16 line 10: Please explain why is ZTD impact much higher (43%) compared to PW (2%). "Relative humidity MEs are reduced by assimilation of PW by 2% and up to 43% while ZTD is used."

[WR]This might be an side-effect to alternation by the ZTD operator not only the humidity like PW, but also pressure and temperature. Which in turn alternates advection of the humidity.

8) Page 18 line 9: "Adding SYNOP stations and radiosonde did not bring any further improvements in forecasting humidity or rain but reduced the errors in wind speed and temperature data." One reason can be that the driving initial and boundary conditions are with assimilated SYNOP and RS data. Please comment on this.

[JG] You remark is correct, we used in this study initial and boundary conditions from National Center for Environmental Prediction Final Analysis, Operational Model Global Tropospheric Analyses and it is widely known that these data contain radiosonde observations and SYNOPs, however the exact number and names of observations taken into account are not available for public discussion.

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