General Comment:

The authors have implemented the GNSS tropospheric gradient operator into WRFDA version 4.4.1 and conducted single observation tests with ZTD data and tropospheric gradients. Three experiments, employing a rapid-update cycle throughout June and July 2021, were carried out to investigate the impact of assimilating tropospheric gradients. The analyses and simulations have been verified against GNSS data from 100 stations, ERA5 reanalysis, and radiosondes. It is nice that the authors integrated the new operator into the WRFDA data assimilation system, and the manuscript is well-written.

We thank the reviewer for the valuable time to evaluate the manuscript and appreciate the kind words. Our motive is to encourage the use of the code by the GNSS Meteorology community so that we can incorporate improvements in the future.

However, it is noted that the comparisons are primarily based on the control run with limited observations involved. Therefore, the impacts of additional observations overlaid on the control run could be overestimated. Specific comments are provided as follows.

Specific comments:

This study implemented the tropospheric gradient operator atop the GNSS ZTD modules in the WRFDA system. While the authors stated that the manuscript aims to test the functionality of the operator and assess the relative impact of tropospheric gradients, it is noted that the control run assimilated with surface stations and radiosondes only is limited and insufficient for the impact study. The comparing experiments (ZTD and ZTDGRA) added ZTD and tropospheric gradient data on top of the two types of observations in the control run, which could potentially enlarge the data impacts of ZTD and tropospheric gradient. A suggestion is to incorporate most of the observations adopted in the operational model for the control run. This aligns with the goal of the EGMAP, as mentioned in lines 97-98.

Thank you very much for the elaborative comment. First of all, we want to make a correction in the article text that the types of observations used for the assimilation experiment had Tropospheric Airborne Meteorological Data Reporting (TAMDAR) observations, too, along with the surface stations and radiosondes. We failed to mention this in the text since we had two versions of the impact study, of which this one is the refined version, which included TAMDAR too to incorporate more upper air observations apart from radiosondes. We have depicted a table showing the average number of observations assimilated at each time step in the responses to the first reviewer.

We agree with the reviewer that our motive was to test the functionality of the operator and assess the relative impact of the tropospheric gradients. However, we do not agree with the statement that the control run assimilated with surface stations and radiosondes is insufficient for the current impact study. Our research introduces the capability to incorporate a new observation type, i.e., tropospheric gradients, which have yet to be utilized by the operational forecast community or research groups. We are trying to show how the gradients impact the analyses, and that is why we wanted to keep only the critical observation types, that is, the surface stations and the radiosondes, in the control run. We acknowledge the reviewer's reasoning completely that significant improvement may not be visible if we incorporate observations like satellite radiances in the control run.

Nevertheless, we still expect a slight improvement if we add ZTDs and gradients on top of all the conventional observations. As a pioneering research using GNSS gradients, the first step through this article was to assimilate gradient observations through an observation operator. Quantifying the improvement made by gradients for the prediction of severe weather for operational purposes, as mentioned in EGMAP, is beyond the scope of this manuscript and will be a topic for another article with the use of an ensemble data assimilation system.

In addition, incorporating more observations into the data assimilation usually benefits the model's initial analysis. The study conducted a long period of cycling data assimilation within a model domain that covered a larger region than the assimilated observations' coverage. Is there a specific reason for not utilizing all the observations within the model domain?

We appreciate the reviewer for raising the question. We will further clarify the point in the manuscript.

We had approximately 380 globally distributed GNSS station provided by the GFZ. We created a homogenized array of observations within the region of interest (Germany), i.e., we removed collocated stations, clusters of stations etc. As stated in the manuscript we only selected GNSS stations with data availability above 75% Hence, we finally had slightly more than 100 GNSS stations within Germany for the assimilation experiment.

To evaluate the impact of tropospheric gradient data, the study compares the difference between ZTD and ZTDGRA rather than comparing the assimilation without ZTD data (i.e., only the conventional observations and tropospheric gradient) with the control run. On the other hand, section 4.3.1 discussed that the ZTD run adjusted not only the ZTDs but also the tropospheric gradients. When assimilating both ZTD and tropospheric gradient observations, would it be overweighting the effects of the tropospheric gradient? Could you further elaborate on the interaction and influence as both data are assimilated simultaneously?

We thank the reviewer for the valuable comment. We have now elaborated the article with one more run added to the list of experiments. We have now incorporated a Gradient-only run to show the impact of gradients exclusively in the revised manuscript. Through this run, we want to point out that ZTDs are not providing a weightage to improve the gradients. ZTD plays a role in the improvement of the gradient and vice versa. We have enhanced the manuscript with new plots for comparing four experiments. Please refer to the response to the following comment for the illustration with the new experiment run “GRA” included, which is the gradient-only assimilation.

Figures 9-11 indicate similar information. Merge the three figures into one would be clearer for comparison. For example, display the RMSE of ZTD for the control run, ZTD run, and ZTDGRA run by three curves on one panel. Similar processes for RMSEs of the North and East components on the second and third panels. The same suggestion is for Figures 12-14.

Thank you for the comment. In the updated manuscript, we have now combined all the similar plots into one plot. Figure 1, shown below, replaces figures 9, 10, and 11 in the manuscript, depicting the whitelisted station-specific RMSE of the ZTD and gradient North and East components for different runs, followed by a table summarizing the mean. Figure 2 (replacement for figures 12, 13 and 14) and Table 2 shows the comparison for the blacklisted stations.

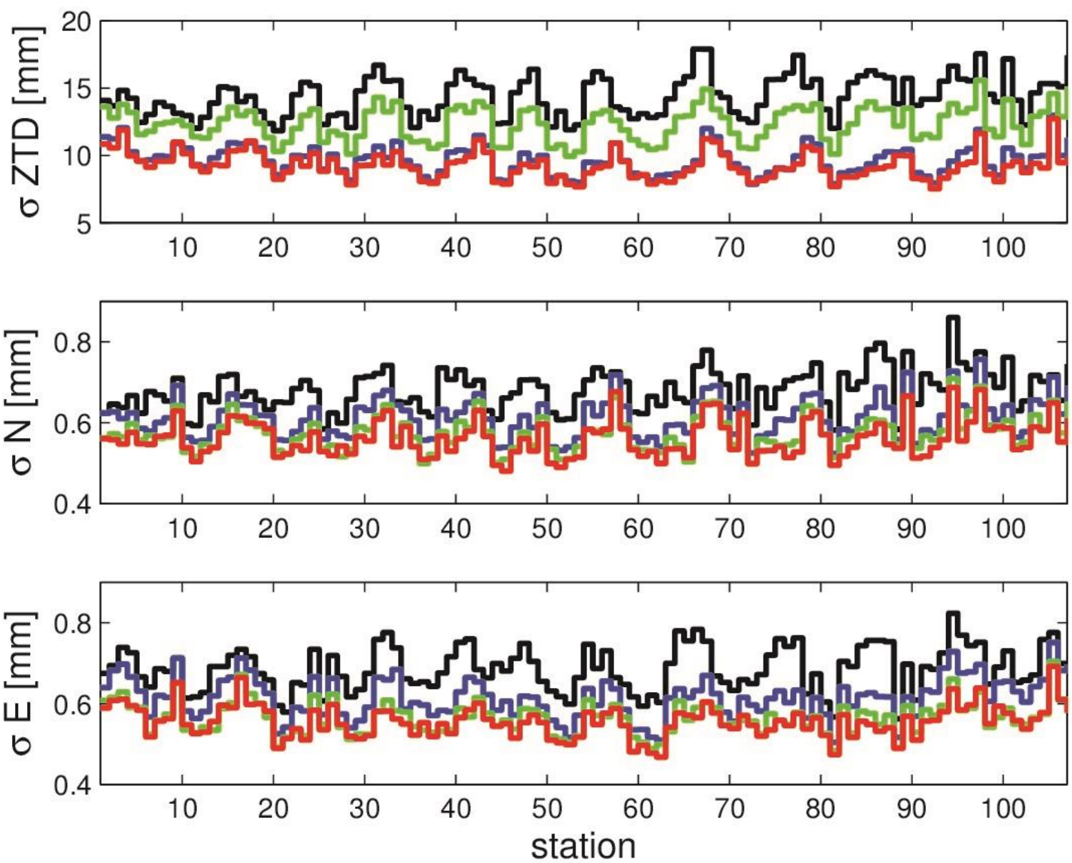

Figure 1. The station specific RMSE of the ZTD, North and East components (whitelisted stations): Control (black), GRA (green), ZTD (purple), and ZTDGRA (red).

Table 1. Comparison of the mean (μ) of station specific RMSE of ZTD and Gradients (whitelisted stations).

Mean (μ)	ZTD	North Gradient	East Gradient
Control	14.4	0.68	0.69
GRA	12.4	0.58	0.57
ZTD	9.7	0.61	0.62
ZTDGRA	9.3	0.56	0.56

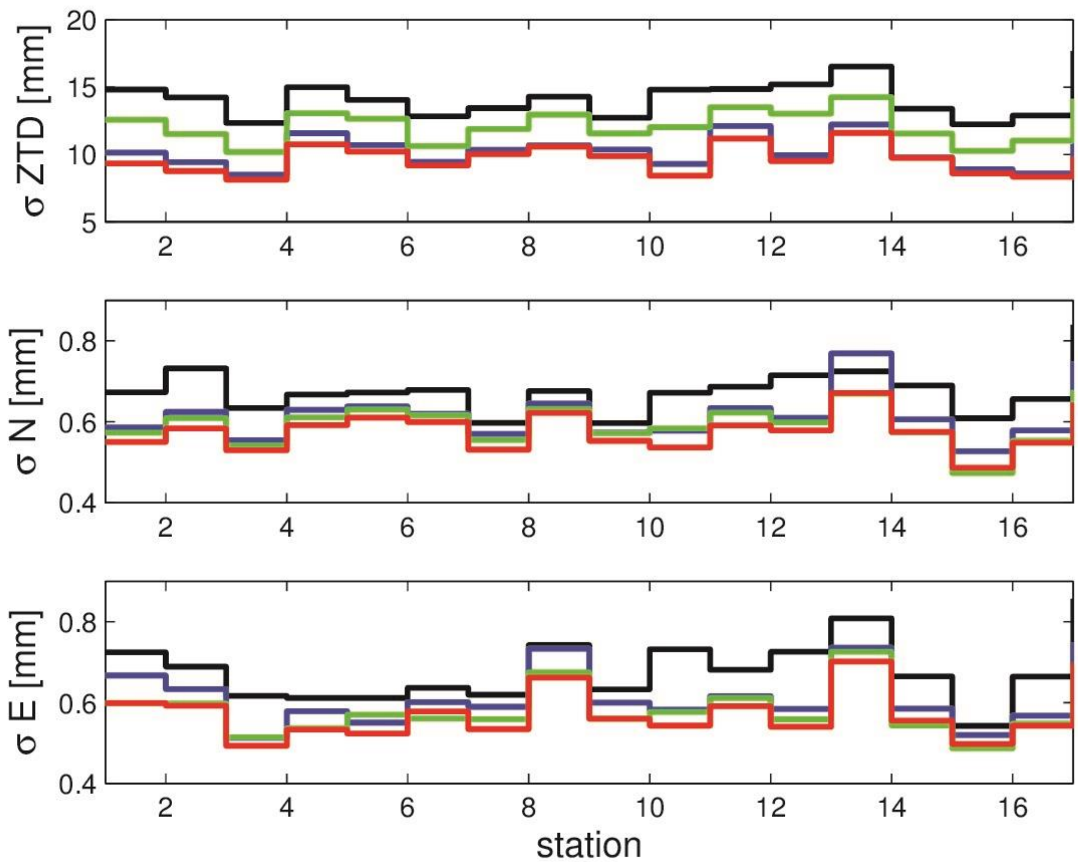

Figure 2. The station specific RMSE of the ZTD, North and East components (blacklisted stations): Control (black), GRA (green), ZTD (purple), and ZTDGRA (red).

Table 2. Comparison of the mean (μ) of station specific RMSE of ZTD and Gradients (blacklisted stations).

Mean (μ)	ZTD	North Gradient	East Gradient
Control	14.2	0.68	0.68
GRA	12.4	0.58	0.57
ZTD	10.2	0.62	0.61
ZTDGRA	9.7	0.58	0.57

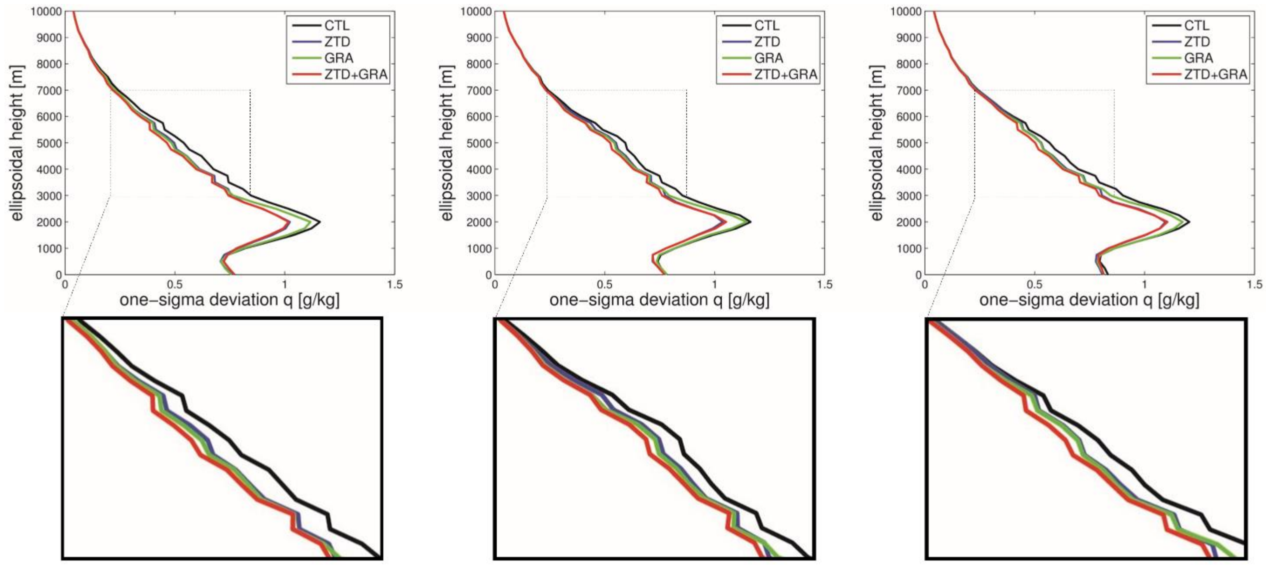

Figure 3. ERA5 profile comparison. The statistics of 1220 profiles for the Control run (black), GRA (green), ZTD run (purple), and ZTDGRA run (red) is shown for the analyses (00 UTC) on the left-most, 3-hour time-lead on the middle, and 5-hour time-lead on the right-most.

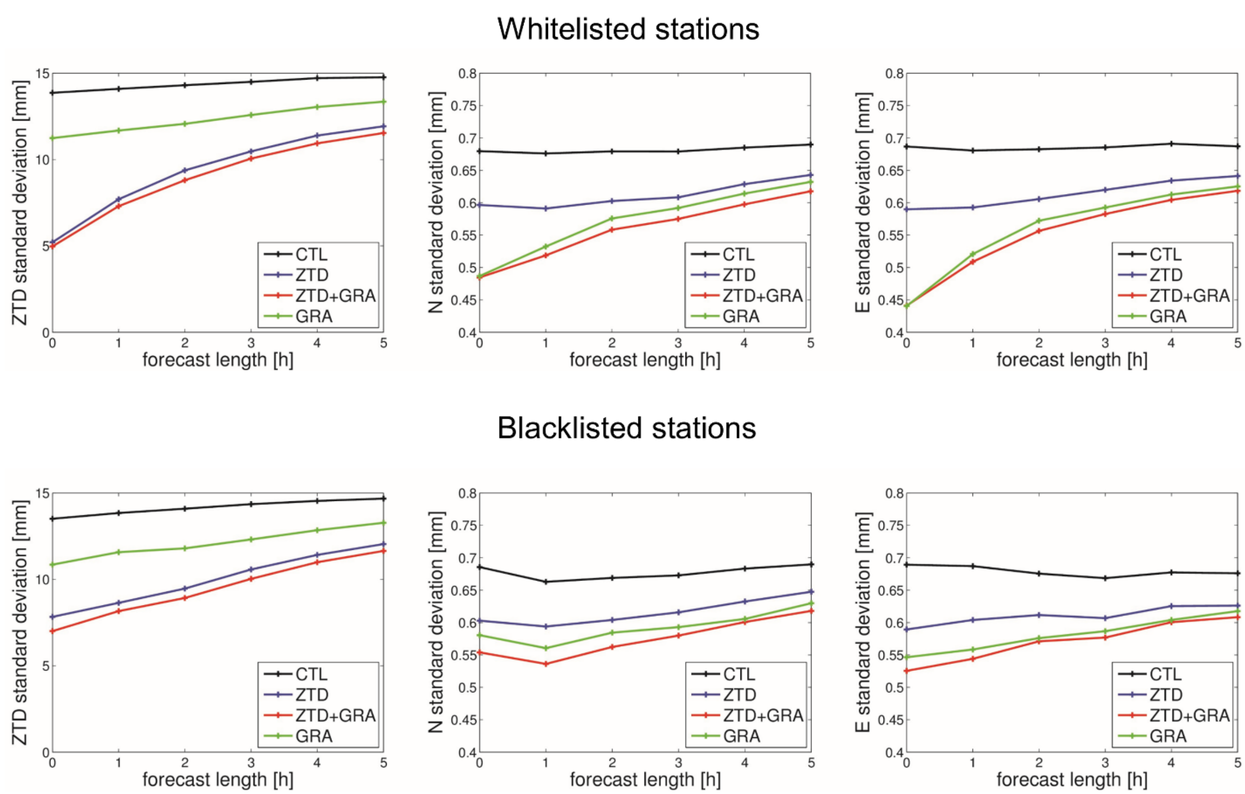

Figure 4. Average impact with respect to forecast lead times from analyses for two months of simulation. The Control run (black), GRA run (green), ZTD run (purple), and ZTDGRA run (red) is shown for the whitelisted stations (top row) and for the blacklisted station (bottom row).

Figures 3 and 4 clearly show that ZTDs do not provide a weightage to improve the gradients. The gradient observations alone have an individual impact on the analyses. Both the observations, ZTDs, and gradients improve each of the variables in the analyses. We hope the explanation with the GRA run provides clarity to the previous comment.

In WRFDA, it has converted geometric height to the geopotential height for GNSS refractivity, not as the description in the manuscript to ignore the conversion. It can be found in da_fill_obs_structures.inc. Ignoring the conversion could result in some errors, particularly at higher altitudes (Scherlllin-Pirscher et al. 2017).

We work with the geometric height. I.e. we convert the geopotential height (stored in ‘grid%xb%h’ or for the mpi-routine ‘glob_h’) to the geometric height. However, when we approximate refractivity above the model top utilizing the hydrostatic equation we use for simplicity the geometric height and not the geopotential height (see eq 10 in the manuscript). This approximation is not problematic as the horizontal refractivity gradients at height altitudes are small and hence the contribution to the tropospheric gradient (integral) is negligible. For details on the implementation see ‘da_get_innov_vector_gpsztd.inc’.

Scherllin-Pirscher, B., A. K. Steiner, G. Kirchengast, M. Schwärz, and S. S. Leroy (2017), The power of vertical geolocation of atmospheric profiles from GNSS radio occultation, J. Geophys. Res. Atmos., 122, 1595–1616, doi:10.1002/2016JD025902.

Typos:

Line 241. The NMC method is widely used for generating B by … --> Please revise B to bold B.

Thanks. This is now corrected.

Figure 6. A real …. component equals0.099 mm. --> Please add a blank between equals and 0.099 mm.

Thanks. This is now corrected.