Reviewer #4

General Remarks

The manuscript provides a relevant overview of the state of the art regarding the assimilation of ZTD and tropospheric gradients, although the operational use of ZTD in major NWP centers could have been detailed further. The evaluation of the complementarity of gradients is an interesting topic, and the idea of two observation densities is insightful. The additional impact of gradients seems very positive and advocates for operational use, but the protocol implemented is not sufficiently detailed, and the results are sometimes lacking in clarity. The following review raises several questions, the answers to which could be usefully added to the manuscript.

Questions about the Dataset Used

- What conventional data were used?

Thank you for the comment. We have now written it more clearly in the manuscript. Please refer to the first comment of reviewer #2.

- Was it possible to use satellite data in the assimilation cycle? If so, why did you choose not to use them?

Thank you for the comment. Our goal in this study is to understand the impact of GNSS observations, i.e., the added value of assimilation TGs on top of ZTDs. However, assimilation of further data, such as satellite and radar, would be of interest in a future study.

- How was the geographical thinning performed to reduce the resolution of observation sets? Was it based solely on interdistance or also on quality criteria?

Thank you for the comment.
Please refer to the comment 8 of the reviewer #3 for a detailed explanation.

- Did you conduct prior monitoring of ZTD and gradient data? If so, what were the rejection thresholds in RMS and bias? Otherwise, what type of quality control is performed in the assimilation cycle?

Thank you for the comment. We have provided an explanation in the manuscript for the quality control of the observations prior to assimilation as follows. Please refer to **Lines 148 to 150.**
"To ensure a homogeneous set of observations across the domain, we excluded collocated and clustered stations and specifically chose GNSS stations with data availability exceeding 75%."

- Why did you choose such a limited sample of excluded stations?

Thank you for the comment. Please refer to the comment 14 of reviewer #3 for the explanation.

Questions and Comments on the Impact of the Data

- Why did you limit the forecast range to that of the assimilation cycle? This seems insufficient for drawing solid conclusions, knowing that a positive short-range impact calculated in the space of added observations can be misleading and unsustainable. At a minimum, forecasts with a 24-hour range should be performed to draw definitive conclusions.

Thank you for the comment. Please refer to comment 7 of reviewer #3 for a new figure depicting 24 hour forecast impact.

- The reference for RMSE calculations is unclear. It should be specified in every occurrence within the text and figures what is actually being calculated.

Thank you for the comment.
Please refer to comments 12 and 20 of reviewer #3 for detailed explanation of RMSE calculation in the two scenarios of the manuscript.

- Unless I missed it, why did you not use radiosonde data to evaluate the forecast impact in the various configurations?

Thank you for the comment. However we would refrain from deviating the main idea of the manuscript which is the sensitivity analysis of the TGs. For a detailed comparison to radiosondes we have made a two month comparison of model simulations (ZTDs, ZTDs + TGs, and TGs assimilation runs) with respect to independent radiosondes which were not assimilated into the model in our previous article Thundathil et al. (2024).

- Even though it is not the central topic of the study, it would be interesting to have details on the impact of gradients on the humidity field according to vertical levels. Where are they most informative? Perhaps adding the curve for the ZTD_1.0° experiment in Figure 5 would help?

Thank you for the comment. As per the suggestion of the reviewer, we have now replaced the plot with a new figure with all the experiment profiles as below:
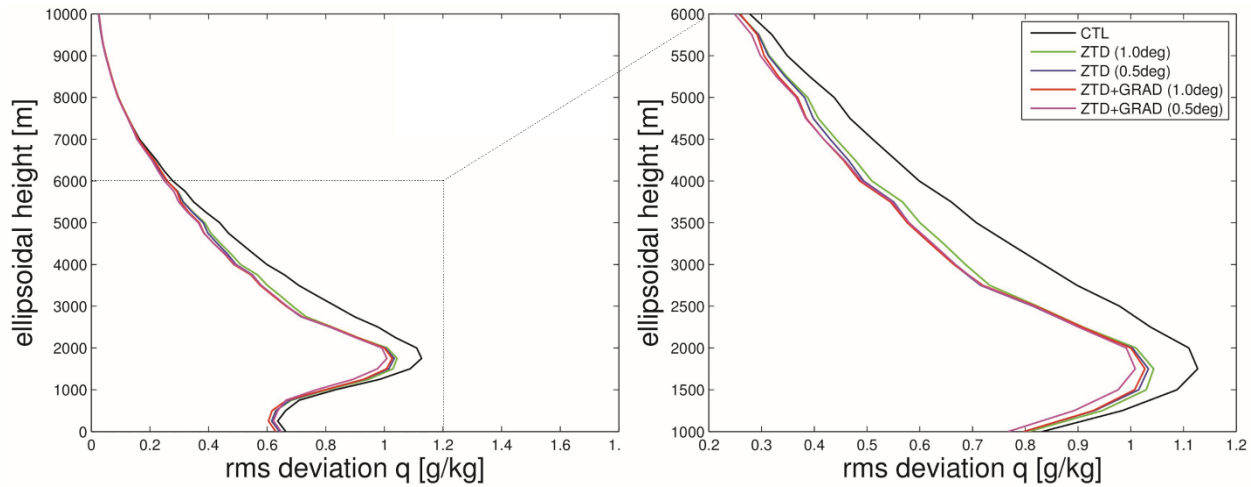

Figure 5. The RMSE of specific humidity profiles compared to ERA5 for Control run (black), ZTD_0.5° run (blue), ZTD_1.0° run (green), ZTDGRA_1.0° run (red), and ZTDGRA_0.5° run (purple). Profiles were compared at five selected stations for 220 DA cycles, totaling 1100 profiles for the average plot.

- Do you think ZTD and gradients would have had the same impact if satellite observations had been assimilated? The same question applies to radar data.

Thank you for the question. We expect a positive impact with the assimilation of GNSS ZTDs and TGs if satellite and radar data are assimilated. However we expect the scale of improvement to be less. The quantification of the relative improvement with satellite and radar data would be a topic for future research.