Review of “The impact of GNSS Zenith Total Delay data assimilation on the short-term precipitable water vapor and precipitation forecast over Italy using the WRF model” by Torcasio R.C., Mascitelli A., Realini E., Barindelli S., Tagliaferro G., Puca S., Dietrich S. and Federico S. (Manuscript ID: NHESS-2023-18)

First of all, we acknowledge the reviewer for the careful review of the paper. In the following our answers are in black and the reviewer comments are in blue. Before entering the discussion of the major and minor points, we answer to the first part of the reviewer comment, that is defined as critical by the reviewer. This answer should clarify better the novel aspects of this paper compared to previous papers over Italy.

The current study examines the impact of assimilating GNSS-ZTD data on the performance of the WRF model in terms of simulating PWV and rainfall. The topic may be of interest, but it has been quite extensively addressed in previous studies, even in Italy (Lagasio et al., 2019; Mascitelli et al., 2019, 2021), which is the study area of the present paper. Unfortunately, the current study does not add something new to the existing literature, either with respect to the methodology nor concerning the results.

We cannot agree with this comment. In this paper, for the first time over Italy, this amount of GNSS-ZTD data, the convective allowing horizontal resolution (3km), and the period of one month (we choose October because it is a rainy month over Italy) in Very Short Term forecast configuration (120 simulations for each type) are used to assess the impact of GNSS-ZTD data assimilation on the precipitation forecast. The impact of GNSS-ZTD data assimilation on the precipitation forecast has not been assessed thoroughly over Italy and work is still to be done (for example to assess the impact of GNSS-ZTD data assimilation on the precipitation forecast in different seasons). Considering the comparison with other studies around the world, this paper is a first step to fill the gap between what was done over Italy and other countries. We clarify better the comparison with existing literature over Italy below.

A widely used (and relatively simple compared to 4Dvar, 3D-EnVar etc.) data assimilation (DA) system has been employed for performing very short-term DA experiments that cover the period from 2 to 31 October, 2019.

The choice of 3D-Var is motivated by the fact that this data assimilation method is used in the agreement between the CNR-ISAC and the Department of Civil Protection (DPC) of Italy. In this agreement, CNR-ISAC provides to DPC a forecast that has the same configuration used in this paper (Very short-term forecast approach, i.e. 6 h of data assimilation is followed by 6h of forecast and four forecasts are issued for each day), with the same data assimilation scheme. In this agreement we assimilate radar reflectivity by 3D-Var and lightning by nudging, but not GNSS-ZTD. So, in this experiment we use same configuration as in the agreement with the DPC to evaluate the potential of GNSS-ZTD data assimilation in the operational context..

In the framework of highlighting the novelty of the current study (Lines 82-85), this period is characterized as “longer” compared to previous studies. However, Mascitelli et al., (2019, 2021) also performed 1-2 month-long DA experiments. Further, the use of 388 GNSS receivers in the current study is highlighted, but Lagasio et al. (2019) also used 375 GNSS stations (in addition to satellite data) for their DA experiments. Based on the above, it is clear that the novelty of the present paper is lacking. I suggest the authors to reframe the conceptualization of their work considering the notes on future studies they suggest (Lines 419-425), as well as other pathways that can add value and novelty to their study.

We know the three papers cited by the reviewer and these works were cited already in our paper. In addition, many of the authors of this paper also co-authored the papers Mascitelli et al., 2019 and 2021 and few authors of this paper co-authored the Lagasio et al., 2019 paper.

Considering the paper of Mascitelli et al. (2019) “only” 26 geodetic receivers and three single frequency receivers were used for data assimilation in the RAMS@ISAC model. All these receivers were over Lazio region (Central Italy). GNSS-ZTD was assimilated for more than one month using 3DVar however, because of the low number of receivers and because of the intermittent character of the precipitation, only the impact of GNSS-ZTD data assimilation on the integrated water vapor forecast was considered. In the conclusions of their paper the authors state: “The impact of the GPS-ZTD data assimilation must be studied for other parameters than IWV, in particular for precipitation.”

Similarly, the paper of Mascitelli et al. (2021) considers 46 GNSS-ZTD receivers over central Italy (Lazio, Abruzzo and Sardinia regions). Data assimilation is performed by nudging for one month and the variable assimilated is the integrated water vapor (IVW). The analysis of both water vapor and precipitation is considered only for the assimilation phase, i.e. in the experiment considered in Mascitelli et al. (2021) IWV data are continuously assimilated without considering the forecast phase. Again, from their conclusions: “It is noted that the application shown in this paper does not consider the impact of GPS-ZTD assimilation on the precipitation forecast, but only on the simulation of the precipitation field (during the analysis phase). Future studies will consider the impact of GPS-ZTD data assimilation on RAMS@ISAC precipitation forecast.”.

The paper of Lagasio et al. (2019) is very interesting because it assesses the impact of GNSS-ZTD data assimilation on the precipitation forecast but for two cases (Silvi Marina and Livorno). So, the sentence that we put into the paper about the novelty aspects and that is reported here “*This paper goes in a similar direction in the sense that it uses the GNSS-ZTD data assimilation to improve the precipitation and water vapor forecast over Italy. Compared to similar studies, however, it uses a longer period and/or a larger number of GNSS receivers widespread over the country, giving a robust assessment on the impact that GNSS-ZTD data assimilation can have on the forecast at the local scale.*” seems to us valid.

However we agree with the reviewer comment that something could be added to the paper in the direction of Lines 419-425. For this purpose we will add the results of a data thinning experiment. In this experiment a subset of the GNSS receivers is used instead of the 388 receivers used in the paper. Due to the limited time, the data thinning experiment is focused on the 10 days of the month (14-23 October 2019). These days were chacterized by intense precipitation over the NW of Italy with damages to infrastructures.

Importantly, we note an error in writing the paper: in discussing the results of Mascitelli et al (2021) we will change the sentence: ”In both cases the assimilation showed a significant improvement in the short-term prediction of water vapor with smaller impact on the precipitation **forecast**.” to “In both cases the assimilation showed a significant improvement in the simulation of water vapor with smaller impact on the precipitation simulation **during the assimilation period**.”

Besides the above critical issue, other major and minor review points are highlighted below.

Major points

- Study period: Please provide more information on the “moderate to intense precipitation events” that took place within October 2019 (dates, sums of precipitation, synoptic conditions etc.). This is important, because previous studies showed mixed ZTD DA impact, depending on the characteristics of the simulated events (e.g. synoptic-scale vs. convective).

We will discuss the precipitation for the month of October 2019, better defining the number of rainy days (all 30 days, i.e. 2-31 October 2019, were rainy if we consider the whole Italian territory) the precipitation for October 2019 and its comparison with the last 11 years of data (for these years a comparable number of raingauges, as those used in the paper, is available). Some discussion about the synoptic conditions will be added. We will give a short summary of these results in the paper but, because it is a considerable amount of material, we will add it as supplement of the paper. To have an idea about the number of events considered in the paper we show here a table with the number of rainy events for different precipitation classes.

Table 1: Number and distribution of the rainfall events for 2019 and for 2012-2022.

Rainfall Threshold (mm/3h)	Number - 2019	Fraction - 2019	Fraction – 11 years
0-1	5316582	93.63	92.04

1-5	284420	3.87	4.92
5-10	96070	1.29	1.66
10-20	56509	0.84	0.98
20-30	13872	0.22	0.24
30-50	6782	0.11	0.12
50-70	1522	0.02	0.02
> 70	889	0.02	0.02

In the above table the fractions are computed compared to the total number of reports for 2019 (662759) and to the total number of events in the database for the last 11 years (5316582). Compared to the last 11 years the rainfall distribution for 2019 shows a larger fraction of events for very small or no rainfall (0-1 mm/3h) class, while it has lower fraction of events from 1-5 mm/3h up to 10-20 mm/3h. For larger thresholds the fraction of events occurred in 2019 is like the last 11 years. In any case the number of events considered in this work is high. For example, the events with rainfall larger than 30 mm/3h (i.e. the most intense threshold showing a significant difference between the control and the forecast using GNSS-ZTD data assimilation) are 9193.

- ZTD observations: National and regional networks were used for deriving the ZTD observations. Thus, a critical question arising is related to the accuracy of each network. This is important because the observational errors affect the DA process and the final outcomes. Please clarify if any accuracy assessment and pre-processing was performed for the ZTD observations and justify the selection of a fixed value of 5 mm as ZTD error for all networks.

  Even though different regional networks are considered in this paper, to reach the considerable number of GNSS-ZTD receivers used, the software and the processing method is the same for all the receivers. The GNSS-ZTD time series were visually checked and no specific differences among network arose. This justifies the choice of a constant error. The value of 5 mm was not specifically computed for this experiment but comes from previous comparisons that, in any case, do not extend to the whole Italy (Tagliaferro, 2021; Krietemeyer et al. 2018.; Mascitelli et al. 2019 and 2021). In these works, the GNSS-ZTD retrieved with the method used in our paper was compared with other methods and with radiosoundings. In general comparison with radiososondes shows differences in the range 1.0-1.5 cm (i.e. larger than the error used in this paper), while differences with other methods show differences between 0.1 and 0.8 cm. Now, the comparison with radiosondes is less representative of the GNSS-ZTD error because radiosondes can move far from the GNSS receiver, while the 0.5 cm used in this paper come from the comparison of the method used in this paper to estimate ZTD with other methods. A paragraph will be added to the paper to explain this point. Thanks for noting it.

- Lines 211-221: Please clarify why PWV is calculated using the observed ZTD and WRF-modeled ZHD. Is this computation corresponds to the forecasted PWV? Please clarify how the observational based PWV is computed.

We don't know the values of surface pressure and temperature for each receiver, and we use the output of the control model to get these values. Then we use the Saastamoinen (1972) formula to estimate ZHD, as in other papers (Rohm et al., 2019, for example). The observed PWV is retrieved from the ZTD observation and ZHD estimated by the WRF model. The modeled PWV is retrieved using both ZTD and ZHD from the WRF model. We will clarify this point in the revised version of the paper. The method used by WRF to compute ZTD is clearly explained in Rohm et al. (2019). We will use this reference. Thanks for noting this point.

- Case study analysis: The case study results are examined on the basis of maps comparison. Please provide a statistical evaluation of the results (as in the whole period analysis).

  Yes, we agree with the reviewer. We will put the precipitation score for the case study in the supplemental material of the paper. Instead of the performance diagrams, we will show the FBIAS, ETS, POD and FAR for different precipitation threshold (1mm/3h and from 2 to 60 mm/3h every 2mm/3h). The example for the POD is shown below.

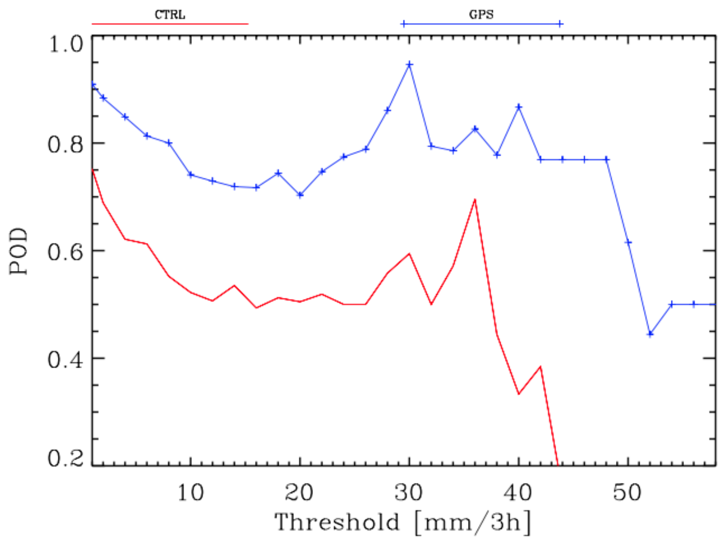


Figure: POD score for the rainfall forecast between 18 and 21 UTC on 15 October 2019.

- Results and discussion: Please enrich this section in terms of interpreting the results and placing them in in the context of the related literature.

Ok. We will enrich the discussion.

Minor points

Overall, the paper is well written and structured, but some points can be improved. These include the frequent use of separate lines instead of longer paragraphs. For instance, the Abstract should be a single paragraph. Further,

- Abstract: Lines 23-25 (about the results) should be placed before Lines 21-22 (about the results). Further, it seems that there is repetition in Lines 21-22 and 28-30. Please be more specific concerning "showed an improvement of the precipitation forecast in different ways". Please revise "model 4.1.3" to "model, version 4.1.3,".

OK.

- Introduction: The first paragraph lacks a conceptual connection to the content provided in the next paragraphs. This is also true for the sentence in Lines 68-69 (please refer to the countries) in relation to the previous paragraph. Please make clear that the studies of Lagasio et al. (2019) and Mascitelli et al. (2019, 2021) were performed over Italy (Lines 76-81). Please provide abbreviations for the terms 3DVar, 4DVar etc.

OK

- Lines 112-113: The "background simulations" usually refer to those for deriving the model background errors for DA. Thus, I suggest renaming the experiments without DA to "control simulations".

Ok, we will implement this naming.

- Please provide a map in Appendix A showing the locations of the rain gauges used for evaluating the model results.

We will add the following figure:

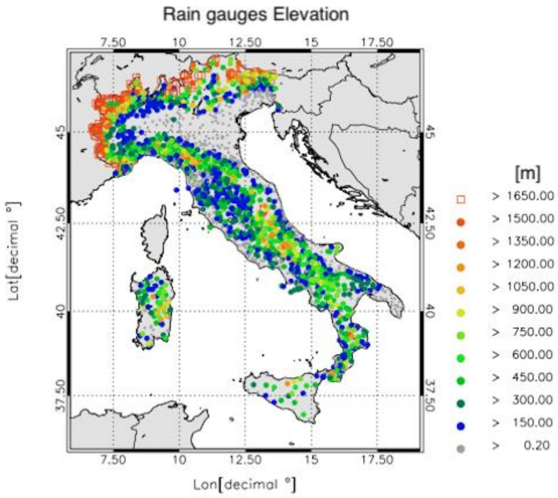


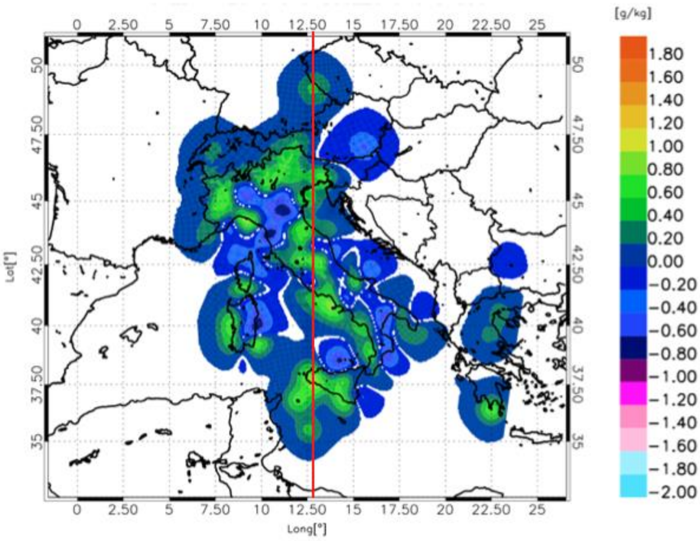
Figure: Elevations of the raingauges.

- Please specify the reason of examining the innovations during the case study analysis (Lines 248-262). To my understanding this is done to highlight that the ZTD DA assimilation leads to actual modeled differences related to PWV that are not random.

The reason for showing the innovation for the case study is that the difference between the precipitation with or without data assimilation can be well interpreted considering these innovations. A better explanation will be given in the paper.

- Figure 5: Please indicate the axis of the cross-section.

We will use the following figure:



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