Response to Referee 2 Comments

The authors describe a new model of pressure and zenith wet delay (ZWD) estimations focused on high-altitude areas. This work can be an interesting contribution to the field but the results are not properly represented and the validation is poorly explained. Please consider the following improvements:

Thank you very much for the comments and suggestions, which improve our manuscript greatly. We have systematically revised the entire manuscript and conducted more clear and scientific conclusions. The corresponding modifications in the manuscript are marked in yellow. The followings are our specific responses to all the comments.

Suggestion 1. Many acronyms are not defined

Response 1. Thank you for your suggestions. We have carefully checked the manuscript and defined all abbreviations. The specific modifications are as follows:

The zenith hydrostatic delay (ZHD) can be accurately determined according to the Saastamoinen model with measured instantaneous pressure as the input, while the zenith wet delay (ZWD) is generally estimated as an unknown parameter (Saastamoinen, 1972., Hadas et al., 2017., Zhang et al., 2021., Yang et al., 2023).

The fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5) benefits from four-dimensional variational (4D-Var) assimilation solution and integrated forecasting system (IFS) forecast systems, which provides high spatial-temporal resolution and high-accuracy atmospheric state variables over globe (Hersbach et al., 2020; Jiang et al., 2023).

Atmospheric temperature, pressure and water vapor pressure data profiles at 0:00 coordinated universal time (UTC) and 12:00 UTC in 2020 are obtained from the Integrated Global Radiosonde Archive (IGRA).

Suggestion 2. Introduction should include studies about ZTD and its derivates. There are good examples in South America and Europe.

Response 2. Thank you for your suggestions. In the introduction, we have provided the description of precipitable water vapor (PWV) which can be derived from ZTD. The specific modifications are as follows:

Besides, the troposphere contains diverse atmospheric information. Accurate precipitable water vapor (PWV) can be derived by the combination of ZTD, atmospheric pressure and weighted mean temperature, and can be applied as an important indicator for regional and global numerical weather forecasting and meteorological monitoring (Wang et al., 2016; Li et al, 2022).

Suggestion 3. Figures do not represent the results. If the paper is focused on high-altitude zones, I recommend showing these areas in more detail.

Response 3. Thank you for your suggestions. We have added two sets of the experiment results in Section 3.1. We evaluated the vertical (1000 hPa-200 hPa) accuracies of each model in three representative regions (Tibet Plateau, Andes mountains and Antarctica) and provided interesting conclusions and analysis. In addition, we retain relevant experiments and discussions of the four representative pressure levels over the globe. In this way, readers can simultaneously obtain the horizontal and vertical spatial applicability and accuracy information of the IGPZWD model through the four figures (8-11) and related analysis in Section 3.1. The corresponding content in the revised manuscript is as follows:

Figure 9 depicts the vertical accuracies of pressure profiles predicted by GTP3, GTrop and IGPZWD models in three representative regions with different climatic environments and geographical locations. IGPZWD model exhibits overall optimal accuracy and stability with no significant sudden change. In the Tibet Plateau and Antarctic, the RMS and bias values of GPT3 model show evident and sharp trends of first decreasing and then increasing with altitude due to unreasonable pressure extrapolation method. Above 800 hPa, IGPT model tends to underestimate the pressure in the Andes mountains region, inducing systematic negative bias and relatively poorer RMS. Overall, the IGPZWD model achieves great pressure prediction on both the surface and the upper air, which benefits from the consideration of the seasonal variations for the pressure height scale factors.

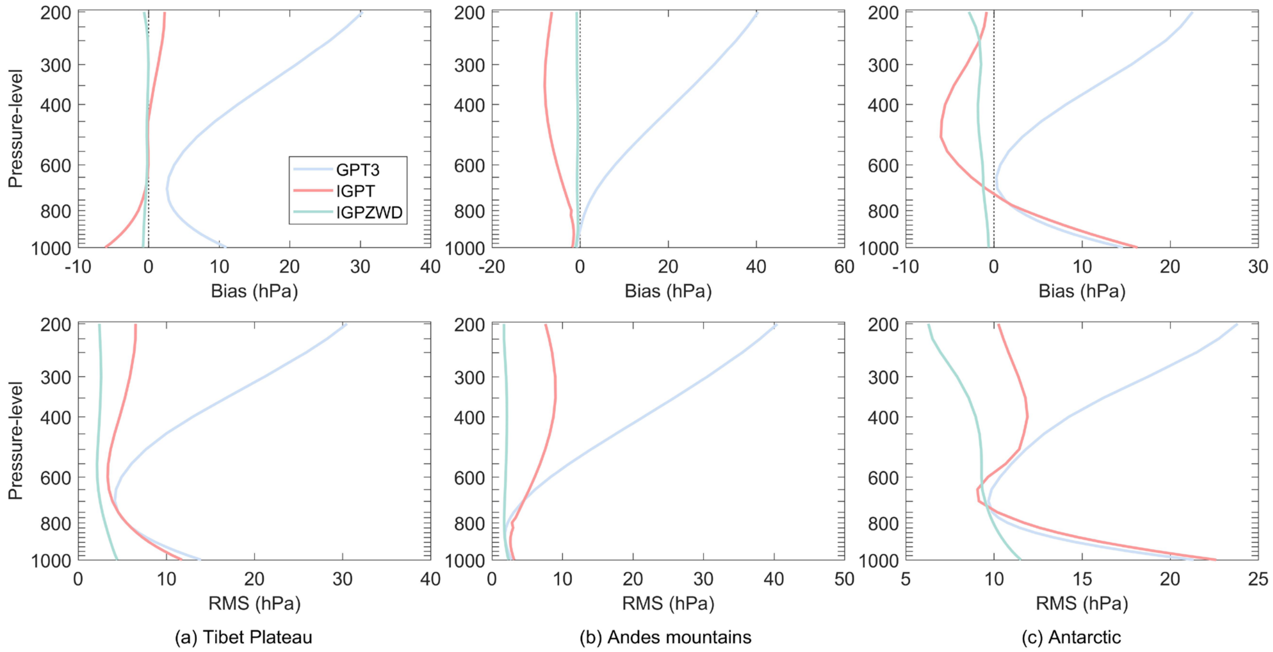

Figure 9: Bias and RMS of pressure profiles predicted by the GPT3, IGPT, and IGPZWD models validated using the ERA5 pressure from 1000 to 200 hPa in 2020. The three selected regions are Tibet Plateau (a), Andes mountains (b) and Antarctica (c).

Figure 11 illustrates that the GPT3 and GTrop models exhibit obviously positive bias in the Andes Mountains and Tibet Plateau below 800 hPa, and the RMS values of GPT3 exceeds 100 mm in the Tibetan Plateau region. In contrast, the IGPZWD model exhibits smaller bias values in these regions, and the RMS values are less than 40 mm. In the Antarctica, IGPZWD outperform all the other two models, achieving overall unbiased ZWD prediction above 400 hPa. It is concluded that IGPZWD model-predicted ZWD has a certain vertical accuracy advantage compared to GTrop and it is significantly more accurate than GPT3.

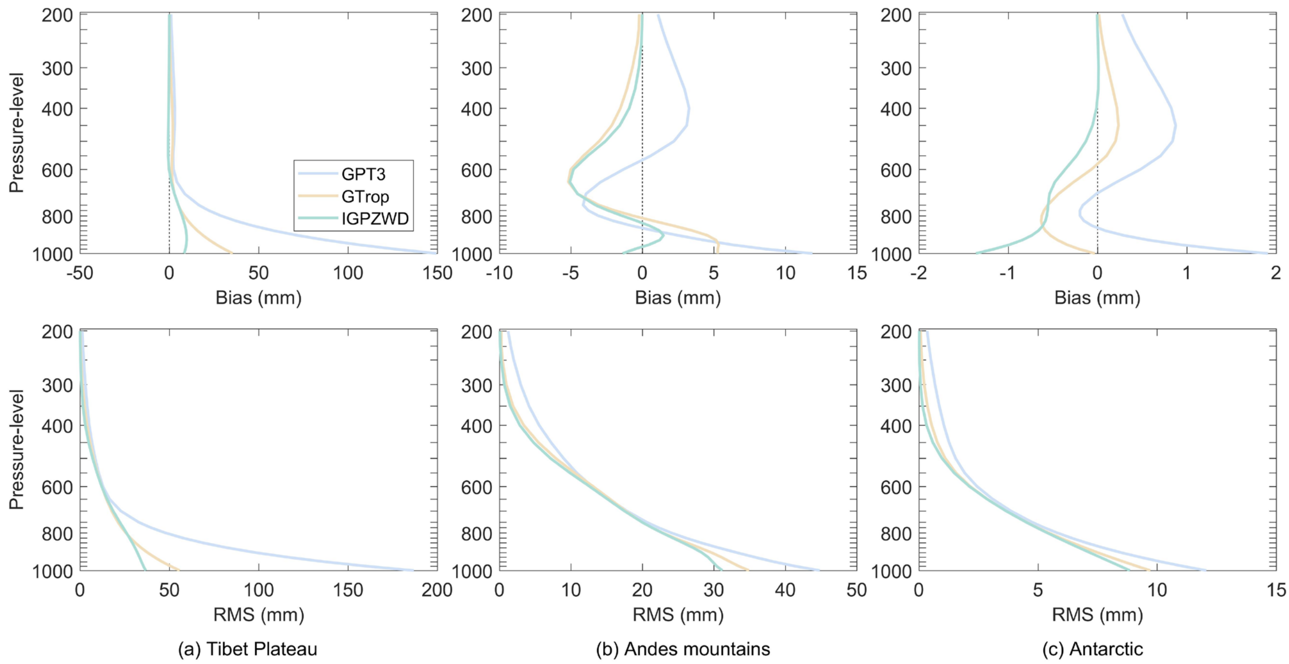

Figure 11: Bias and RMS of ZWD profiles predicted by the GPT3, IGPT, and IGPZWD models validated using the ERA5 ZWD from 1000 to 200 hPa in 2020. The three selected regions are Tibet Plateau (a), Andes mountains (b) and Antarctica (c).

Suggestion 4. There are no descriptions of the data sets used for validation beyond their names.

Response 4. Thank you for your suggestions. We have provided a more detailed introduction to the data. The corresponding content in the revised manuscript is as follows:

The fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5) benefits from four-dimensional variational (4D-Var) assimilation solution and integrated forecasting system (IFS) forecast systems, which provides high spatial-temporal resolution and high-accuracy atmospheric state variables over globe (Hersbach et al., 2020). ERA5 provides 3D pressure-level products with a vertical resolution of 37 levels and 2D single-level data. The atmospheric parameters are provided with a horizontal resolution of 0.25°×0.25°, and the hourly data can more accurately reflect the short-term variation of meteorological parameters (Jiang et al., 2023). In this contribution, ERA5 hourly temperature, pressure, specific humidity and geopotential data from 2015 to 2019 are utilized to construct the IGPZWD model, and the accuracy of the new model is verified using data in 2020.

The Integrated Global Radiosonde Archive (IGRA) consists of radiosonde and pilot balloon observations from more than 2800 globally distributed stations, and surface and upper-air meteorological data become available in near real-time from about 800 stations worldwide (Ingleby et al., 2016). Atmospheric temperature, pressure and water vapor pressure data profiles at 0:00 coordinated universal time (UTC) and 12:00 UTC in 2020 are obtained from the IGRA.

Suggestion 5. Considering radiosonde data: Have you removed outliers? Did you apply a filter to exclude sites with a low amount of registers?

Response 5. Thank you for your suggestions. Strict quality control schemes have been applied to the radiosonde data to ensure its accuracy as reference values. We have added specific standards in the revised manuscript as follows:

Generally, sensor quality and weather events have a serious impact on raw measurements, which result in missing data and outliers. Hence, the low-quality radiosonde data profiles which meet the following quality control standards are eliminated. (1) The height difference between two successive levels is greater than 2 km. (2) The pressure difference between two successive levels is greater than 200 hPa. (3) The height of the top-level data is less than 10 km. (4) The effective observation records of the profile are less than 20.

Suggestion 6. Furthermore, radiosondes in South America are few in comparison with North America and Europe, and many of them are located in low-altitude areas. Which criteria are used to describe the good fit of the model there?

Response 6. Thank you for your suggestion. We are sorry that we didn't clearly illustrate the verification method for radiosonde data, and our expression is not clear enough. The radiosonde data used in the study are the atmospheric pressure, ZWD and ZTD integration values of all observation records on the vertical profile at each radiosonde station below 15 km, not only the surface data. Therefore, all radiosonde stations can provide large vertical range profiles data and be regarded as reference values to evaluate the accuracy of models in high-altitude areas. Furthermore, we have simplified the images in section 3.2 to demonstrate the accuracy advantages of IGPZWD at different height ranges and Temperature zones, and added more detailed accuracy analysis and discussion for high-altitude areas. The corresponding content in the revised manuscript is as follows:

Initially, different height systems between radiosonde and model have been unified according to the Earth Gravitational Model (EGM) 2008 model (Pavlis et al., 2012) and World Meteorological Organization (WMO) 2018 standard measurement (Yuan et al., 2023). Subsequently, taking the longitude, latitude, heights, DOY and UTC of each data point on the filtered radiosonde profiles below 15 km as inputs, four models are employed to predict the corresponding ZWD and atmospheric pressure. Thereafter, the pressure and ZWD profiles derived from radiosonde observation in 2020 are used as references to evaluate the model-predicted pressure and ZWD. To investigate the applicability of the three models at different height ranges below 15 km, the accuracies are statistically analyzed with a vertical sampling interval of 3 km.

The bias and RMS values of pressure predicted by GPT3, IGPT and IGPZWD models at three Temperature zones are presented in figure 12. It can be seen that the GPT3 model exhibits a systematic positive bias above 3 km, with a large mean bias value of 29 hPa in the temperate zone at the range of 12-15 km. Evidently, the accuracy of the GPT3 model gradually decreases with the increase of altitude, indicating that its pressure extrapolation scheme is inapplicable when the height difference is large. The IGPT model exhibits superior accuracy than the GPT3 model in the temperate and tropical regions where the intraday variations of pressure are strong, which benefits from the consideration of diurnal and semi-diurnal terms in pressure. IGPZWD model further effectively improves the accuracy compared to IGPT model, achieving almost unbiased estimation of pressure with RMS improvements of 21.8-41.1% in tropical and 68.7-82.9% in temperate zones. In addition, the RMS of IGPZWD model has improved by over 94% compared to GPT3 model beyond 6 km in tropical regions, indicating the feasibility of the proposed vertical correction algorithm.

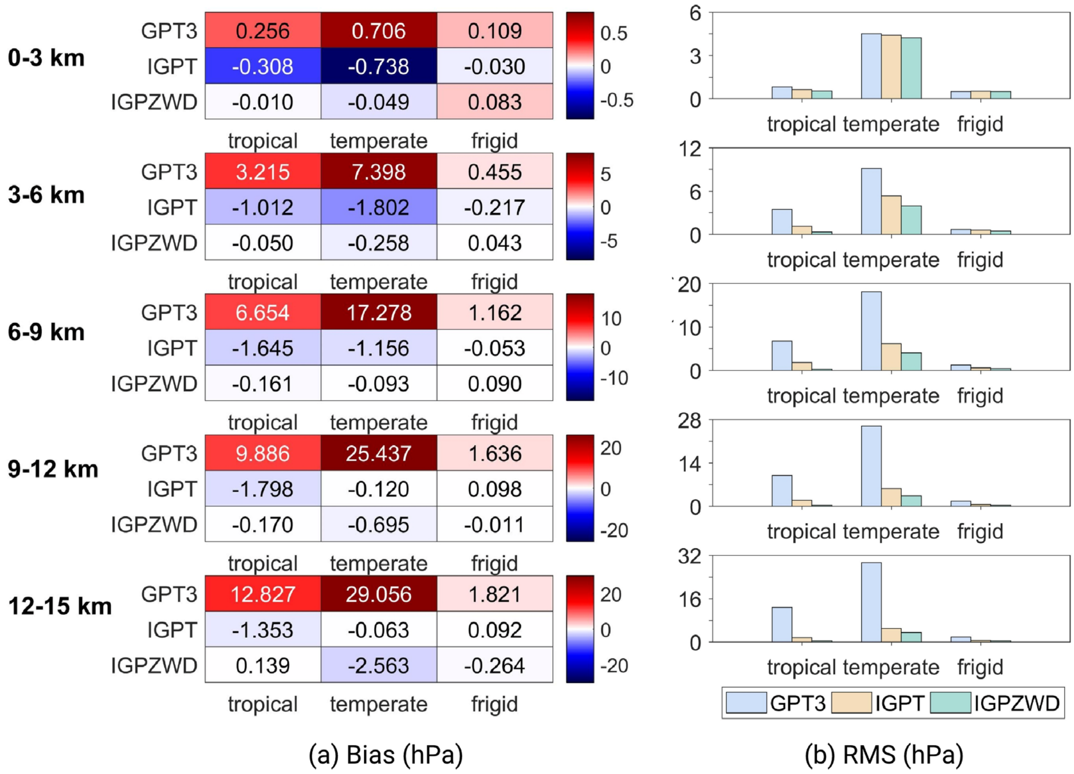

Figure 12: Mean bias (a) and RMS (b) values (d1-d5) for pressure predicted by the GPT3, IGPT and IGPZWD models validated using the radiosonde pressure data at five height ranges of the tropical, temperate, and frigid zones.

Table 1 summarizes the mean pressure bias and RMS values of each height range. The RMS values of IGPZWD do not exceed 5.3 hPa at five height ranges, showing a significant accuracy advantage compared to GPT3, with an improvement of up to 90% for 12-15 km. In contrast to the IGPT model, the IGPZWD model exhibits smaller negative bias values and further improves the performance beyond 3 km with RMS improvements of 32.4-51.8%, indicating the feasibility of the proposed vertical correction algorithm. The magnitude of ZWD in high altitude is small, and thus the pressure is the main factor restricting the accuracy of ZTD according to the rule of uncertainty propagation. It is implied that IGPZWD may provide superior prior tropospheric constraints for GNSS positioning of high-altitude platforms.

Table 1: Mean bias and RMS values for pressure predicted by the GPT3, IGPT and IGPZWD models at five height ranges.

Height (km)	Bias (hPa)			RMS (hPa)		
	GPT3	IGPT	IGPZWD	GPT3	IGPT	IGPZWD
0-3	1.1	-1.1	0.0	5.8	5.6	5.3
3-6	11.1	-3.0	-0.3	13.3	7.1	4.8
6-9	25.1	-2.9	-0.2	26.2	8.6	4.8
9-12	37.0	-1.8	-0.9	37.5	8.3	4.0
12-15	43.7	-1.3	-2.7	44.0	7.0	4.2

The bias and RMS values of pressure predicted by GPT3, IGPT and IGPZWD models at three Temperature zones are presented in figure 13. Significant negative bias values of the three models are observed in Southeast Asia below 3 km, which is attributed to the local strong annual and semi-annual amplitudes of ZWD. The GPT3 model exhibits generally positive bias values and large RMS values above 3 km in tropical and temperate zones, which again demonstrate that it can't provide reliable ZWD information in high-altitude areas. Although the GTrop model shows slight accuracy advantage below 3 km, while it performs worse than the IGPZWD model above 3 km. Compared to the GTrop model, IGPZWD model achieves RMS improvements of 14.5-27.8% and 10.6-48.5 % beyond 6 km in temperate and tropical zones, respectively, and the order of magnitude of improvement increases with height.

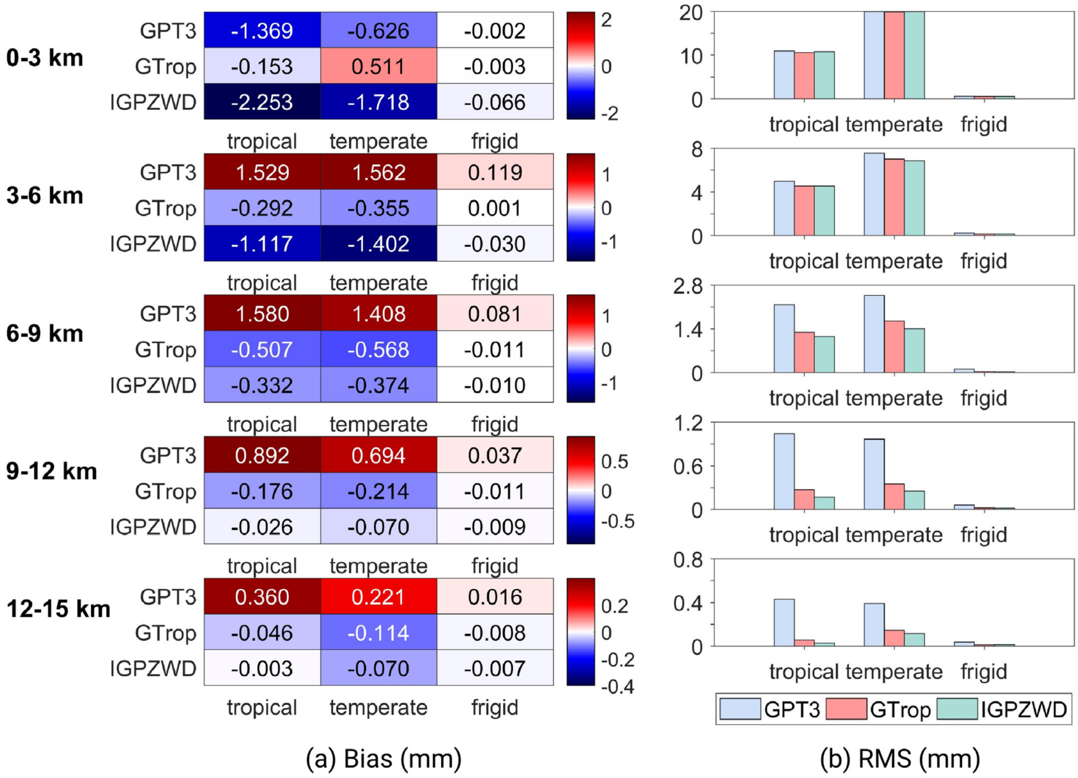

Figure 13: Mean bias (a) and RMS (b) values (d1-d5) for pressure predicted by the GPT3, IGPT and IGPZWD models validated using the radiosonde ZWD data at five height ranges of the tropical, temperate, and frigid zones.

Suggestion 7. If this paper wants to focus on height altitude sites, I recommend to analyze these areas separately.

Response 7. Thank you for your suggestions. Below 15 km, all observation records on the vertical profile of each radiosonde are used, which can provide large vertical range data and be regarded as reference values to evaluate the accuracy of models in high-altitude areas. We have systematically revised most of the content and added more results and discussions of high-altitude areas (3-15 km) to comprehensively demonstrate the wide spatial applicability and accuracy advantages of the proposed IGPZWD model. Thank you again for your valuable suggestion.