Response to Referee 1 Comments

General comments:

In this paper, the authors developed the IGPZWD model, which can effectively provide global tropospheric parameters and outperform multiple advanced models. The models and methods show noteworthy innovation and potential application value, but there are some aspects that need further improvement.

Thank you very much for the suggestions, which improve our manuscript greatly. We have systematically revised the manuscript to meet the publication standards. The corresponding modifications in the manuscript are marked in yellow. The followings are our specific responses to all the comments.

The specific comments are as follows:

Suggestion 1. In section 2, please clarify what specific ERA5 parameters are used to establish the surface model and how the wet refractivity of single-level is calculated. Does the author use surface pressure, 2m-temperature, etc.?

Response 1. Thank you for your suggestions. We have added detailed description of the ERA5 single-level parameters for modeling and algorithm for single-level water vapor pressure which is further used to calculate surface wet refractivity in Section 2. The specific content is as follows:

In this contribution, ERA5 hourly temperature, pressure, specific humidity and geopotential data on pressure-level, surface pressure, 2m-dewpoint temperature and 2m-temperature on single-level 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 ERA5 and radiosonde ZWD profiles are calculated according to the numerical integration method as follows (Thayer, 1974; Askne and Nordius, 1987; Jiang et al., 2023):

$$e = \begin{cases} PQ/(0.378 \times Q + 0.622) & Pressure-level \\ 6.112.\exp(17.62 \times Dew/(243.12 + Dew)) & Single-level \end{cases} \quad (1)$$

Suggestion 2. How to determine the vertical ranges of the fitting pressure and ZWD profiles in Figure 3 of Section 3.1, and why did the authors choose data profiles below 12 km instead of higher altitudes?

Response 2. Thank you for your suggestions. Pressure and ZWD exhibit significant vertical nonlinear (exponential) variations. Due to the different rate of decrease for atmospheric pressure in the upper troposphere compared to the lower troposphere, a fitting function with a single height scale factor cannot be used to characterize the vertical variation of atmospheric pressure throughout the neutral atmosphere. Besides, ZWD is almost zero beyond 10 km, so it's not meaningful to analyze the fitting effect of higher vertical ranges. Moreover, considering the vertical application space of airborne and high-altitude platforms, a height of 12 km is sufficient for use.

Suggestion 3. At the end of the section 3, it is recommended to insert a flowchart, so that readers can better understand the construction and application process of the IGPZWD model.

Response 3. Thank you for your suggestions. We have added a flowchart for the construction and use of IGPZWD model at the end of section 3. The corresponding content in the revised manuscript is as follows:

The development and use of the IGPZWD model are summarized in the flowchart depicted in Figure 8, including surface and vertical correction modules. With the geodetic location and time specified as DOY and HOD as inputs, the pressure and ZWD of the nearest four model grid points at the target height are determined according to equation

(17). Thereafter, a bilinear interpolation method is carried out to calculate the target pressure and ZWD. Furthermore, the target ZHD and ZTD are obtained based on the Saastamoinen model as follows:

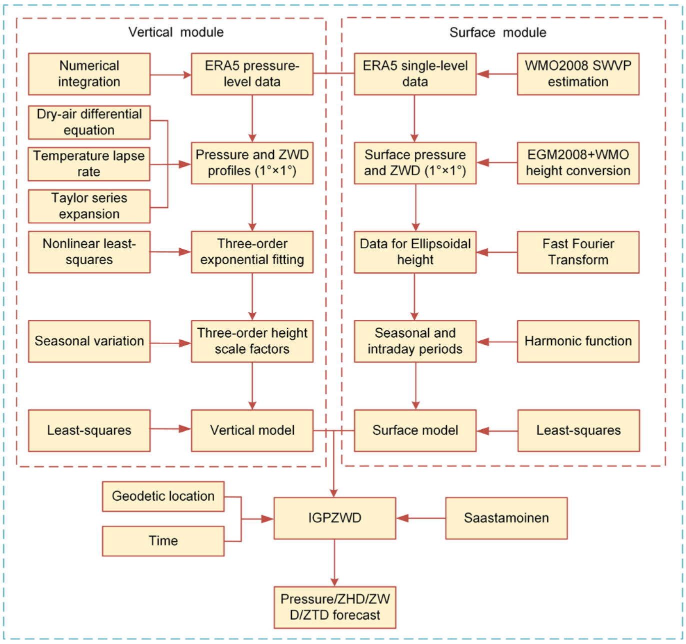

Figure 8: Flowchart depicting the development and use of the IGPZWD model.

Suggestion 4. Tm gradually decreases with increasing altitude in the troposphere. The GPT3 model did not consider the vertical correction of Tm, thus overestimating the Tm value in high-altitude areas. However, this will result in a smaller ZWD value according to the empirical expression proposed by Askne and Nordius. Therefore, in section 4.1, the missing vertical correction for GPT3 model-derived Tm may not be the main reason for the systematic positive bias of ZWD. Please provide reasonable explanation.

Response 4. Thank you for your suggestions. According to Böhm et al, the water vapor decrease factor in the GPT3 model is calculated by water vapor pressure for any pair of pressure levels near the surface, thus only ensuring the accuracy of surface ZWD. In high-altitude areas, inaccurate decrease factors can cause significant extrapolation errors of water vapor pressure, leading to the accumulation of errors in ZWD. The corresponding content in the revised manuscript is as follows:

The statistical results of model-predicted ZWD validated using ERA5 profiles are shown in Figures 11 and 12. The magnitude of ZWD gradually decreases with increasing altitude, but the GPT3 model still shows a significant systematic positive bias at 350 hPa. This may be due to inaccurate estimation of the water vapor decrease factor, resulting in the accumulation of vertical errors. In contrast to GPT3 model, the GTrop and IGPZWD perform better at 550 and 350 hPa, showing smaller bias and RMS values in low latitudes.

Suggestion 5. Line 344, "Equation (20) is essentially based on the assumption of isothermal atmosphere". -replace (20) by (19).

Response 5. Thank you for your suggestions. We have made corresponding modifications and carefully checked all sections to avoid such errors. The corresponding content in the revised manuscript is as follows:

Equation (19) is essentially based on the assumption of isothermal atmosphere, but the actual atmospheric state does not meet the condition, except for the tropopause.

Suggestion 6. Please clarify the shortcoming of the new model in the conclusion.

Response 6. Thank you for your suggestions. We revealed the shortcomings of the IGPZWD model. The corresponding content in the revised manuscript is as follows:

Despite the complexity of the inversion process for tropospheric parameters, the overall performance of IGPZWD model is encouraging. In the future, the model coefficients will be further simplified to balance the computation efficiency and accuracy.

Response to Referee 2 Comments

This manuscript presents an improved global pressure and ZWD model that takes into account the spatiotemporal variability of multiple height scale factors, as well as its optimized vertical correction work, which has positive value for GNSS motion accuracy positioning and atmospheric water vapor detection. This manuscript is a revised version and has been carefully revised based on the comments of the reviewers. Regarding the revised manuscript, I have only two suggestions.

Thank you for your gradual processing and valuable suggestions, which has once again improved the quality of this paper. We have further revised the discussion, conclusions and outlook to better demonstrate the value and significance of this contribution. The corresponding modifications in the manuscript are marked in yellow. The followings are our specific responses to all the comments.

Suggestion 1. The outlook section should be included in the discussion section, not in the conclusion section.

Response 1. Thank you for your suggestions. We have simplified the conclusion section and included the outlook section in the discussion. The specific modifications are as follows:

Line 395:

To sum up, the proposed IGPZWD model can provide high-quality tropospheric parameters prediction below 15 km on a global scale. The IGPZWD model will be of great significance for the tropospheric augmentation in real-time GNSS positioning, and it has broad application prospects in real-time water vapor sounding and extreme weather forecasting. Despite the complexity of the inversion process for tropospheric parameters, the overall performance of IGPZWD model is encouraging. In the future, the model coefficients will be further simplified to balance the computation efficiency and accuracy.

Line 420:

In summary, the proposed optimized vertical correction algorithm weakens the cumulative error caused by large correction height difference, which effectively improves the accuracy and stability of pressure, ZWD and ZTD in high-altitude areas.

Suggestion 2. The discussion section is weak, and it is suggested that the author should combine the excellent research references of predecessors in this field more, rather than just talking to themselves. In summary, it is recommended to undergo moderate revision.

Response 2. Thank you for your suggestions. We carefully revised the discussion section and combined the analysis and conclusions of other studies to further evaluate the algorithm advantages and feasibility of the IGPZWD model. We hope that our comprehensive assessment can provide important reference value for the application of scholars. The specific modifications are as follows:

Line 290:

Figure 12 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. Although IGPZWD-predicted ZWD exhibit superior performance in high-altitude areas, the improvement in surface is negligible. It is concluded that developing surface

ZWD models is challenging. Nevertheless, substantial studies have proven that the cubic polynomial can effectively improve the fitting effect of ZWD profiles at low altitudes, which can be the algorithm reference for future enhanced model construction (Li et al., 2023; Xu et al., 2023).

Line 315:

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. In summary, it has been verified that exponential function with three orders has stronger accuracy advantages and robustness in vertical pressure extrapolation compared to existing models such as virtual temperature and the adiabatic models. In addition, we further achieved accurate prediction of the height scale factor time series for pressure.

Line 340:

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, confirming the advantages of high-order exponents in simulating ZWD profiles. Previous scholars have used piecewise and high-order functions to characterize the vertical nonlinear variation of ZWD (Hu and Yao, 2019; Zhu et al., 2022). We have also verified the feasibility of this kind of algorithm using 1-year radiosonde data. Moreover, it has been proven that considering time-varying height scale factor can further improve the long-term forecasting accuracy.