Response to Editor and Reviewers

Dear editor and reviewers,

Thank you for offering us an opportunity to improve the quality of our submitted manuscript titled "**A hybrid-grid global model for the estimation of atmospheric weighted mean temperature considering time-varying lapse rate in GNSS precipitable water vapor retrieval**" (gmd-2024-21). We appreciated very much the reviewers' constructive and insightful comments. In the following, we include a point-by-point response to the comments from each reviewer. In the revised manuscript, all the changes have been highlighted in red. We hope the revised manuscript has now met the publication standard of your journal.

Reviewer #1

Comment 1: Please correct the grammar errors, typo, or missing words in the For example, in line 109, "we aim to global Tm model that takes into account..." and in line 298, "surface-level…".

Response 1: Thank you for pointing this out. We agree with this comment. We have corrected the grammar errors, typo, and missing words. In the revised manuscript, the relevant content has been modified as follows: "our aim was to develop a global Tm model that takes into account time-varying lapse rate and high-precision capabilities" (see lines 108-109), "The surface gridded Tm data with a temporal resolution of 1 hour derived from the ERA5 reanalysis data in 2017 were selected as reference values" (see lines 312-313). In addition, we have carefully read the entire manuscript and corrected the remaining errors.

Comment 2: In section 3.3, the NGGTm-H model is validated by radiosonde. I suggest describing the vertical resolutions or the altitude of the record at the 378 radiosonde stations.

Response 2: Thanks for your suggestion. In Section 3.3, we have added descriptions of the altitude of the record at the 378 radiosonde stations. In the revised manuscript, the relevant content has been modified as follows: "The altitude of radiosonde stations ranges from 0 to 4500 m, mostly within 2000 m" (see lines 249-250).

Comment 3: In line 256-260, do the authors try to explain the reason why the positive biases are smaller than the absolute value of the negative biases? If yes, please explain the reason in more detail.

Response 3: Thanks for your comment. We have tried to explain the reason why the positive biases are smaller than the absolute value of the negative biases. The relevant content has been added in the revised manuscript: "The vertical correction values of Tm obtained using the

NGGTm-H model were slightly larger in land areas but smaller in marine areas than the reference values. However, a small number of radiosonde stations distributed in marine areas were susceptible to the influence of marine climate, resulting in the vertical correction values of the model was apparently smaller than the reference values. Therefore, the positive biases were smaller than the absolute value of the negative biases" (see lines 262-266). In future work, we will further investigate the reasons and develop solutions.

Comment 4: I suggest using the same color bar ranges in (a)-(d) of figure 5 and 6 to emphasize the result and avoid misunderstanding to readers, especially in figure 6.

Response 4: Thank you for pointing this out. We have changed the color bar ranges in two figures to be consistent (see lines 340 and 353). Indeed, it will mislead readers if the color bar ranges are inconsistent.

Reviewer #2

Comment 1: L15, What does "NGGTm-H" stand for?

Response 1: Thanks for the question you raised. The "NGGTm-H" stands for a new global grid Tm lapse rate model. Lapse rate is the rate at which Tm decreases with increasing height. We have added explanations in the revised manuscript (see lines 14, 16 and 110).

Comment 2: L39-40, "Microwave radiometers and satellite remote sensing, which rely on infrared band detection, offer high detection accuracies." This is logically misleading. Microwave radiometers operate in the microwave region of the electromagnetic spectrum, not the infrared.

Response 2: Thank you for pointing this out. We agree with this comment. In the revised manuscript, the relevant content has been modified as follows: "Microwave radiometers that operate in the microwave region of the electromagnetic spectrum, and satellite remote sensing that rely on infrared band detection, offer high detection accuracies" (see lines 38-40).

Comment 3: L45, "a high spatiotemporal resolution" this is not completely right. Globally speaking, the number of GNSS stations is still low.

Response 3: Thank you for pointing this out. We agree with this comment. We have replaced "a high spatiotemporal resolution" with "a high temporal resolution" (see line 44).

Comment 4: L54, "However, the variation law of ZWD influenced mainly by water…" What is the variation law of ZWD? If there is such a law, then the ZWD variation can be well known.

Response 4: Thanks for your comment. We apologize for that our description is misleading. The meaning we want to express is that the variation in ZWD is mainly influenced by precipitable water vapor (PWV). There is a relationship between ZWD and PWV (ZWD=PWV/K). Variation in PWV can cause variation in ZWD. In reality, PWV changes rapidly, which leads to rapid changes in ZWD. Therefore, it is difficult to investigate the variation law of ZWD. We do not emphasize which variation law ZWD has. In the revised manuscript, the relevant content has been modified as follows: "However, the variation in ZWD influenced mainly by water vapor is difficult to investigate" (see line 53).

Comment 5: L58, "The accuracy of GNSS tropospheric water vapor retrievals can be significantly improved by using high-precision Tm data." How is the accuracy of PWV affected if different Tm values are used? Please provide numerical examples.

Response 5: Thanks for the question you raised. Huang et al. (2019) studied the impact of Tm on GNSS-PWV using the relationship of RMSE between Tm and PWV. The results indicated that the RMSE of Tm for their proposed GGTm model was 3.54 K, and the RMSE of inverted PWV was 0.26 mm. However, the RMSE of Tm for Bevis model was 4.1K, and the RMSE of inverted PWV was 0.31 mm.

Huang, L. K., Jiang, W. P., Liu, L. L., Chen, H., and Ye, S. R.: A new global grid model for the determination of atmospheric weighted mean temperature in GPS precipitable water vapor, J. Geod., 93, 159–176, https://doi.org/10.1007/s00190-018-1148-9, 2019.

Comment 6: L63, "it is necessary to build a real-time and high-precision Tm." I concur that a high-precision Tm is needed. Is it really necessary to build a real-time Tm model?

Response 6: Thanks for the question you raised. It is necessary to build a real-time Tm model in the application of GNSS-PWV inversion. PWV is closely related to atmospheric circulation, climate change and extreme rainstorm. Corresponding measures can be taken to address the aforementioned natural phenomena according to the prediction of future PWV content and variations. The Tm models built earlier were meteorological parameter models that relied on measured meteorological parameters, which could not calculate Tm in real-time. Later, many scholars built nonmeteorological parameter models to achieve real-time calculation of Tm and real-time inversion of PWV.

Comment 7: L64, "Existing Tm models can be divided into two categories: meteorological parameter models and nonmeteorological parameter models." What are the representative models for the meteorological parameter models and what are the representative models for the nonmeteorological parameter models? Do you have reference papers?

Response 7: Thanks for your comment. We listed some representative meteorological and nonmeteorological parameter models after this sentence (see lines 63-88). Representative meteorological parameter models such as Bevis (Bevis et al., 1992) model and GTm-I (Yao et al., 2014c). Representative nonmeteorological parameter models, such as the Emardson model (Emardson & Derks, 2000).

Bevis, M., Businger, S., Herring, T. A., Rocken, C., Anthes, R. A., and Ware, R. H.: Remote sensing of atmospheric water vapor using the Global Positioning System, J. Geophys. Res.: Atmos., 97, 787–15, https://doi.org/10.1029/92JD01517, 1992.

Emardson, T. R. and Derks, H. J.: On the relation between the wet delay and the integrated precipitable water vapour in the European atmosphere, Meteorol. Appl., 7, 61–68, https://doi.org/10.1017/S1350482700001377, 2000.

Yao, Y. B., Zhang, B., Xu, C. Q., and Yan, F.: Improved one/multi-parameter models that consider seasonal and geographic variations for estimating weighted mean temperature in ground-based GPS meteorology, J. Geod., 88, 273–282, https://doi.org/10.1007/s00190-013-0684-6, 2014.

Comment 8: L85-89, "The nonmeteorological parameter Tm model (named the Emardson model) was developed to take the annual cycle variation into account by using radiosonde data collected in Europe over many years, which was capable of meeting the requirement for GNSS water vapor detection (Emardson & Derks, 2000). Therefore, the model has been widely used in real-time GNSS meteorology research." The Tm model was developed based on the radiosonde data collected in Europe. Does it really meet the accuracy requirement for GNSS water vapor detection out of Europe?

Response 8: Thanks for the question you raised. Based on our experience, the Tm model developed using data from a certain region has higher accuracy in GNSS water vapor detection in this region, but lower accuracy in other regions. To achieve high accuracy in other regions, we can use the data from the target region and refer to the Emardson model expression to develop a new model. Therefore, when the natural geographical conditions of the target regions differ significantly from Europe, the Emardson model may not meet the accuracy requirements of GNSS water vapor detection. In this case, we can consider developing a new Emardson model.

Comment 9: L98-100, "This new model can estimate the Tm value at any location by simply inputting the station location and the annual product day, which have been applied to real-time GNSS PWV inversion studies worldwide." Are there any reference papers? What is the accuracy of Tm used in GNSS PWV inversion?

Response 9: Thanks for the question you raised. The new model and its applications we described are refered to the article by Yao et al. (2012). They developed the GWMT model and applied it to GNSS PWV inversion. We have not yet found any scholars who have applied the Tm model to GNSS PWV inversion. The Tm model (GWMT model) proposed by Yao et al. (2012) has an internal accuracy of 4 K and an external accuracy of 4.6 K.

Yao, Y. B., Zhu, S., and Yue, S. Q.: A globally applicable, season-specific model for estimating the weighted mean temperature of the atmosphere, J. Geod., 86, 1125–1135, https://doi.org/10.1007/s00190-012-0568-1, 2012.

Comment 10: L104-106, "Although the GPT3 model is currently the most representative empirical model with a high precision on the global scale, GPT3 model dose not take into account elevation correction or detailed Tm lapse rate." The current GPT3 can get a high precision on global scale, though it didn't consider the Tm lapse rate. Justify why you need to do this work.

Response 10: Thanks for your comment. We compared the accuracy of the proposed NGGTm model (considering the Tm lapse rate) with the GPT3 model (no considering the Tm lapse rate). In Section 5.1, when using gridded data as reference values, the mean RMSE of GPT3-1 and GPT3-5 were 2.90 and 3.02 K, respectively, whereas the mean RMSE of the NGGTm model was 2.84 K. In Section 5.2, when using radiosonde data as reference values, the mean RMSE of GPT3-1 and GPT3-5 were 3.48 and 3.65 K, respectively, whereas the mean RMSE of the NGGTm model was 3.30 K. The accuracy of the NGGTm model is higher than that of the GPT3 model. Therefore, it is necessary to do this work.

Comment 11: L109, "we aim to global Tmmodel that takes into account time-varying…" This sentence is grammatically erroneous.

Response 11: Thank you for pointing this out. We agree with this comment. we have corrected the grammar errors. In the revised manuscript, the relevant content has been modified as follows: "our aim was to develop a global Tm model that takes into account time-varying lapse rate and high-precision capabilities" (see lines 108-109).

Comment 12: Eqs. (5) and (6), why is the variable KP used? What is the rational of using KP, not Tm?

Response 12: Thanks for the question you raised. The meaning of variable KP is key parameter . In order to make it easy for readers to understand its meaning, we have modified it to Tm according to your suggestion (see lines 153-156).

Comment 13: The paragraph (around L185) discussed the result of Fig. 2. However it is very hard to understand. You should cite the Fig. 2(a)… Fig. 2(f) in the discussion.

Response 13: Thanks for your valuable suggestion. Indeed, this makes it difficult for readers to understand. We have cited specific figures in the discussion (see lines 183-187).

Comment 14: L211, "we focused on optimizing the model coefficients solely for these cycles to improve the calculation efficiency when developing the Tm lapse rate model." Why is the calculation efficiency so critical? What is the normal calculation efficiency? Is the current calculation not fast or efficient enough?

Response 14: Thanks for the question you raised. After our testing, it takes 650 seconds to calculate the lapse rate of Tm at about 260,000 center points of window and 8760 hours of one year when taking into account annual and semiannual cycles. It takes 630 seconds when considering annual, semiannual, daily, and semidaily cycles. The difference in computational efficiency between the two methods is not significant. Therefore, we believe that there is no need to emphasize computational efficiency here. What we should pay more attention to is the simplification of the model. As mentioned in lines 209-211, the daily variation in lapse rate of Tm can be overshadowed by annual and semiannual variations, so there is no need to consider daily variations. In the revised manuscript, the relevant content has been modified as follows: "Since the daily variation in the lapse rate of Tm can be overshadowed by the annual and semiannual variations, we focused on optimizing and simplifying the model coefficients when developing the Tm lapse rate model" (see lines 209-211).

Comment 15: L219, "Note that, the sliding window algorithm has been used in the previous study, which exhibits a superior performance" What is the difference between the sliding window algorithm in the previous study and that in this submission?

Response 15: Thanks for the question you raised. In the previous study, the horizontal resolution of grid data is 2.5°×2° (lon.×lat.) and the sliding window size is 5°×4° (lon.×lat.). In this study, the horizontal resolution of grid data is 0.25°×0.25° (lon.×lat.). To investigate the influence of the window size on the model precision and optimize the model coefficients as much as possible, three different window sizes with resolutions of 0.5°×0.5°, 1°×1° and 2°×2°, were selected to develop the model. Due to the improved horizontal resolution of the grid data used in this study, the size of the sliding window had been adjusted.

Comment 16: L224, "by using the data of 9 gridded points in each window," Explain what the 9 gridded points in each window? What is the window? It is better to have figure illustration.

Response 16: Thanks for your comment, it is a very valuable suggestion. We have added a figure illustration and explained what 9 gridded points and windows are (see lines 225-226 and 239).

Comment 17: Eq. (9), what is the # of windows for different grids 0.5°x0.5°, 1°x1° and 2°x2°?

Response 17: We apologize for not understanding your meaning. May we ask what # represents?

Comment 18: L241, "Finally, a global real-time and high-precision Tm lapse rate model was developed and" How can you get the gamma γ (the lapse rate of Tm) in real-time? How can you get the TmG value at the height of the gridded points from the reanalysis data in real-time? In what applications, the real-time Tm is really needed?

Response 18: Thanks for the question you raised. Eq. (9) can be used to calculate the gamma γ (the lapse rate of Tm) in real-time. The use of Eq. (9) only requires the input of the day of the year (DOY), so it can achieve real-time calculation for γ. For example, entering today's DOY can calculate today's γ.

In addition, obtaining real-time Tm at the height of gridded point requires Eq. (11) and (12). The use of these two equations only requires input of the hour of the day (HOD) and the day of the year (DOY), so it can achieve real-time calculation for Tm. The integration of reanalysis data to obtain the Tm at the height of gridded point cannot be achieved in real-time because the release of reanalysis data has a time delay.

Finally, real-time Tm is required in the application of extreme weather forecast such as rainstorm.

Comment 19: L267, "…daily cycle amplitude, and semidaily cycle amplitude at all grid points using the least-squares adjustment using surface-level gridded Tm data calculated from all the ERA5 reanalysis data" In L210, you wrote "Since the daily variation in the lapse rate of Tm can be overshadowed by the annual and semiannual variations." Thus you didn't model the daily cycle amplitude, or semidaily cycle amplitude at all grid points in the Section 3.2. I can't understand why you bring up the daily cycle amplitude, and semidaily cycle amplitude in this Section 4.1.

Response 19: Thanks for the question you raised. The NGGTm-H model was developed in Section 3, which can calculate the lapse rate of Tm (γ). The NGGTm model was developed in Section 4, which can directly calculate Tm. The research objects in Section 3 and 4 are different. The research objects in Section 3 and 4 are the γ and Tm, respectively. The statement that "daily variation may be overshadowed by annual and semiannual variations" in Section 3.1 refers to the γ rather than Tm. According to Fig. (5) and reference (Sun et al., 2019), it is necessary to consider the daily variation of Tm. The relationship between Sections 3 and 4 is as follows: the NGGTm-H model in Section 3 (composed of Eq. (9) and (10)) is part of the NGGTm model in Section 4 (composed of Eq. (9), (10), (11) and (12)). The NGGTm model is the final model of this study.

Sun, Z. Y., Zhang, B., and Yao, Y. B.: An ERA5-based model for estimating tropospheric delay and weighted mean temperature over China with improved spatiotemporal resolutions, Earth Space Sci., 6, 1926–1941, https://doi.org/10.1029/2019EA000701, 2019.

Comment 20: In Eq. (9) of Section 3.2, you estimated the annual cycle amplitude and semiannual cycle amplitude of the lapse rate gamma γ of Tm. However in the Figure 4 of Section 4.1, you showed the annual cycle amplitude and semiannual cycle amplitude of Tm. I know the lapse rate gamma γ of Tm is closely related to Tm. But they are not the same thing. You need to state clearly in the submission what you want to study: lapse rate or Tm.

Response 20: Thank you for pointing this out. We agree with this comment. Indeed, our description makes it difficult for readers to understand the relationship between γ and Tm. We have added some statements at the beginning of Section 4.1 (see lines 271-273). In addition, the steps for calculating the Tm at user's location using the NGGTm model have been explained in detail (see lines 302-308). Thank you again for your suggestion. Your suggestion made us think deeply and realize that we should explain clearly the writing ideas of the article from the perspective of the readers.

Comment 21: L276, "In summary, Tm not only undergoes significant annual and semiannual variations but also experiences significant daily and semidiurnal variation." Again, it is quite perplexing to me that you stated that significant daily and semidiurnal variations here but you didn't study it in Section 3.2.

Response 21: Thanks for the question you raised. As mentioned in Response 19, the research subjects in Sections 3 and 4 are different. The research subjects in Section 3 and 4 are γ and Tm, respectively. In Section 3, we only consider the annual and semiannual variations of γ, because its daily variation may be overshadowed by annual and semiannual variations . In Section

4, we consider the daily variation of Tm because it cannot be ignored according to Fig. 6 and reference (Sun et al., 2019).

Sun, Z. Y., Zhang, B., and Yao, Y. B.: An ERA5-based model for estimating tropospheric delay and weighted mean temperature over China with improved spatiotemporal resolutions, Earth Space Sci., 6, 1926–1941, https://doi.org/10.1029/2019EA000701, 2019.

Comment 22: L282, “Since the significant variations in the horizontal direction of Tm compared to lapse rate, the estimation of Tm at the gridded points did not use the sliding window algorithm.” It is hard to understand. Rephrase it.

Response 22: Thanks for your valuable suggestion. We have rephrased this sentence. In the revised manuscript, the relevant content has been modified as follows: "Since the significant variations in the horizontal direction of Tm compared to lapse rate according to Fig. 5 (a) and Fig. 6 (a), it is necessary to develop surface Tm models at each gridded point instead of using sliding windows" (see lines 291-293). As shown in Fig. 5 (a), the annual average value of γ is approximately -6 K/km in Qinghai Tibet Plateau with the high-altitude and -5 K/km in eastern China with the low altitude. The difference between them is approximately 1 K/km, which means that altitude variation of 1 km leads to a difference in Tm variation of 1 K. As shown in Fig. 6 (a), the annual average value of Tm is approximately 260 K in Qinghai Tibet Plateau with the high-altitude and 280 K in eastern China with the low altitude. The difference between them is approximately 20 K. This indicates that the significant variations in the horizontal direction of Tm compared to lapse rate. Therefore, it is necessary to develop surface Tm models at each gridded point instead of using sliding windows.

Comment 23: This submission has an unusually high frequency of self-citation (e.g. Huang, L. K., Yao, Y. B.).

Response 23: We apologize for this question you raised. Due to the significant reference value of the Tm research created by scholars Huang, L. K. and Yao, Y. B., we frequently cited their articles. To avoid any doubts from readers, we have reduced the frequency of citations in their articles.