

Article

Evaluation of the Zenith Tropospheric Delay (ZTD) Derived from VMF3_FC and VMF3_OP Products Based on the CMONOC Data

Haoran Zhang ¹, Liang Chen ², Fei Yang ^{1,3,*} , Jingge Ma ¹, Junya Zhang ¹, Wenyu Sun ¹ and Shiqi Xu ¹

¹ College of Geoscience and Surveying Engineering, China University of Mining and Technology—Beijing, Beijing 100083, China; 2110200329@student.cumtb.edu.cn (H.Z.)

² Guangzhou Marine Surveying and Mapping Center, Guangzhou 510320, China

³ Hubei LuoJia Laboratory, Wuhan 430079, China

* Correspondence: yangfei@cumtb.edu.cn

Abstract: Prior tropospheric information, especially zenith tropospheric delay (ZTD), is particularly important in GNSS data processing. The two types of ZTD models, those that require and do not require meteorological parameters, are the most commonly used models, whether the non-difference or double-difference mode is applied. To improve the accuracy of prior tropospheric information, the Vienna Mapping Functions (VMFs) data server provides a gridded set of global tropospheric products based on the ray-tracing technique using Numerical Weather Models (NWMs). Note that two types of gridded tropospheric products are provided: the VMF3_OP for the post-processing applications and the VMF3_FC for real-time applications. To explore the accuracy and adaptability of these two grid products, a comprehensive analysis and discussion were conducted in this study using the ZTD data from 255 stations of the Crustal Movement Observation Network of China (CMONOC) as references. The numerical results indicate that both VMF3_FC and VMF3_OP exhibit high accuracy, with RMSE/Bias values of 17.53/2.25 mm and 14.62/2.67 mm, respectively. Both products displayed a temporal trend, with larger RMSE values occurring in summer and smaller values in winter, along with a spatial trend of higher values in the southeast of China and lower values in the northwest of China. Additionally, VMF3_OP demonstrated superior performance to VMF3_FC, with smaller RMSE values for each month and each hour. For the RMSE difference between these two products, 108 stations had a difference of more than 3 mm, and the number of stations with a difference exceeding 1 mm reached 217. Moreover, the difference was more significant in the southeast than in the northwest. This study contributes to the understanding of the differences between the two precision products, aiding in the selection of suitable ZTD products based on specific requirements.

Keywords: GNSS; tropospheric products; zenith tropospheric delay (ZTD); VMF3_FC; VMF3_OP



Citation: Zhang, H.; Chen, L.; Yang, F.; Ma, J.; Zhang, J.; Sun, W.; Xu, S.

Evaluation of the Zenith Tropospheric Delay (ZTD) Derived from VMF3_FC and VMF3_OP Products Based on the CMONOC Data. *Atmosphere* **2024**, *15*, 766. <https://doi.org/10.3390/atmos15070766>

Academic Editors: Tin Lukić and Klaus Gierens

Received: 24 April 2024

Revised: 20 June 2024

Accepted: 23 June 2024

Published: 27 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

During the transmission from satellite to receiver, the Global Navigation Satellite System (GNSS) signals interact with water vapor and dry gases in the neutral atmosphere, causing speed retardation and path bending, known as tropospheric delay [1,2]. This delay is a substantial error factor in GNSS, varying from 2 m to 20 m as the elevation angle of a satellite changes [3]. Modeling the tropospheric delay in the zenith direction, known as zenith tropospheric delay (ZTD), is a common practice to simplify estimation [4]. ZTD consists of two components: zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD). ZHD refers to the delay attributed to the hydrostatic component of the atmosphere, while ZWD quantifies the delay associated with atmospheric water vapor [5–7]. Prior ZTD not only corrects errors in GNSS positioning, thereby improving accuracy, but it is also used in meteorological analysis [8,9], such as predicting precipitable water vapor (PWV) [10,11], monitoring drought [12,13], forecasting aerosol depth [14], and spatial interpolation of PM_{2.5} [15].

ZTD can be accurately determined by integrating atmospheric refractivity along the vertical path. The radiosonde and meteorological reanalysis data can provide meteorological profiles for ZTD calculation [16]. However, radiosonde data are available at specific locations and epochs, resulting in poor temporal and spatial resolution, while meteorological reanalysis data are difficult to obtain and do not provide real-time ZTD calculation [17,18]. Therefore, ZTD models were developed and can be classified into two categories: meteorological parameter models and empirical models.

Meteorological parameter models are created using measurable meteorological data, such as the Hopfield model [19], the Black model [20], the Askne and Nordius model [21], and the Saastamoinen model [22]. When using these models to calculate ZTD, inputs of temperature, air pressure, and water vapor pressure are necessary. By analyzing the ZTD time series, the ZTD empirical models were constructed, which no longer require the input of meteorological parameters. These types of ZTD empirical models include the Global Zenith Tropospheric Delay (GZTD) series models [23], the IGGtrop series models [24], and the Shanghai Astronomical Observatory Tropospheric Delay (SHATrop) series models [25]. In addition, the GPT series models [26–29] and the UNB3 [30] series models can also provide ZTD estimates.

On the other hand, the Vienna University of Technology (TU Wien, TUW) generated tropospheric delay products based on the Vienna Mapping Function using the ray-tracing algorithm called VMF3 products [31–33]. The VMF3 products have been used as prior tropospheric information in many GNSS data processing software, such as rPPPid [34], Pride [35], Gamit [36], and GIPSY [37]. In addition, the International GNSS service (IGS) has used VMF3 products for troposphere modeling in operational EPN analysis [38]. Yang et al. [39] utilized the observational data from IGS stations as references to assess the VMF3 products with eight ZTD models, including Saastamoinen, GPT, GPT2, GPT2w, GPT3, EGNOS, UNB3, and UNB3m. This global-scale study shows that the VMF3 products exhibited significantly superior performance with an RMSE of only 13.1 mm. Osah et al. [40] assessed the precision of VMF3 products in West Africa using five IGS stations and found that the RMSE was from 7.2 mm to 17.0 mm. Yang et al. [41] analyzed the precision of VMF3 products with different grid resolutions in China, and the results revealed that the RMSE ranged from 12 to 16 mm and from 16 to 28 mm for VMF3 products in 1° and 5° resolution, respectively. Li et al. assessed the accuracy of the ZTD products from TUW using a reference ZTD dataset created by the Karlsruhe Institute of Technology (KIT) team in 2020, but only one type of ZTD was compared, and the assessment lacked data from China [42].

Note that two types of ZTD products are provided each day by the VMF Data Server: one for real-time applications, released at UTC 9:00 the day prior, known as VMF3_FC, and the other released at UTC 18:00 on the subsequent day, known as VMF3_OP. Both VMF3_FC and VMF3_OP products are derived from the Numerical Weather Model (NWM) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) [43,44]. The forecast NWM is used to produce VMF3_FC, while the operational NWM is used for VMF3_OP. The accuracy and availability of the VMF3_OP are discussed in some of the research mentioned above, but there is a lack of analysis of the accuracy of the VMF3_FC. Given the high demand for real-time applications in GNSS, which require the VMF3_FC, it is essential to conduct a thorough investigation of its accuracy. Therefore, in this study, the accuracy of the VMF3_FC was analyzed in detail from multiple perspectives and compared comprehensively with the VMF3_OP using the ZTD values derived from the 255 sites of the Crustal Movement Observation Network of China (CMONOC) as references.

2. Materials and Methods

2.1. VMF ZTD Data

The VMF data service (<https://vmf.geo.tuwien.ac.at/>) (accessed on 23 April 2024)) provides two versions of VMF3 products, namely VMF3_FC and VMF3_OP. They are both presented in a 1° × 1° grid format, covering epochs of 0, 6, 12, and 18 UT daily and are

available for download at https://vmf.geo.tuwien.ac.at/trop_products/GRID/1x1/VMF3/VMF3_FC/ and https://vmf.geo.tuwien.ac.at/trop_products/GRID/1x1/VMF3/VMF3_OP/, respectively (accessed on 12 January 2024). Note that height adjustment, as well as horizontal and temporal interpolation, are needed to obtain ZTD values at a specific site using VMF products. In the process of height adjustment, the formulas for ZHD and ZWD height adjustment were used, as shown in the literature [45]. Bilinear interpolation was utilized at the four grid points surrounding the target site for horizontal interpolation, and linear interpolation was utilized between the ZTD values of the two epochs before and after the specified epochs for temporal interpolation.

2.2. CMONOC ZTD Data

The Crustal Movement Observation Network of China (CMONOC) was established between 1997 and 2000 and became operational in 2011. It comprises 260 continuously operating reference GNSS stations and 2000 regionally located GNSS stations subject to regular reevaluation. The primary goal of the CMONOC is to monitor crustal movements, gravity field shapes, and changes in mainland China [46]. It also observes variations in tropospheric water vapor content and ionospheric concentrations [47,48]. The observational data from the CMONOC GNSS stations were utilized to calculate hourly ZTD, which may be accessed at <ftp://ftp.cgps.ac.cn/> (accessed on 4 January 2024). The ZTD data from 255 CMONOC stations in 2020 were utilized as the reference data for this study. The distribution of these sites is shown in Figure 1. Additionally, to ensure data quality, a moving window outlier detection approach using the interquartile range (IQR) rule was applied to remove outliers in the ZTD time series of each station [49].

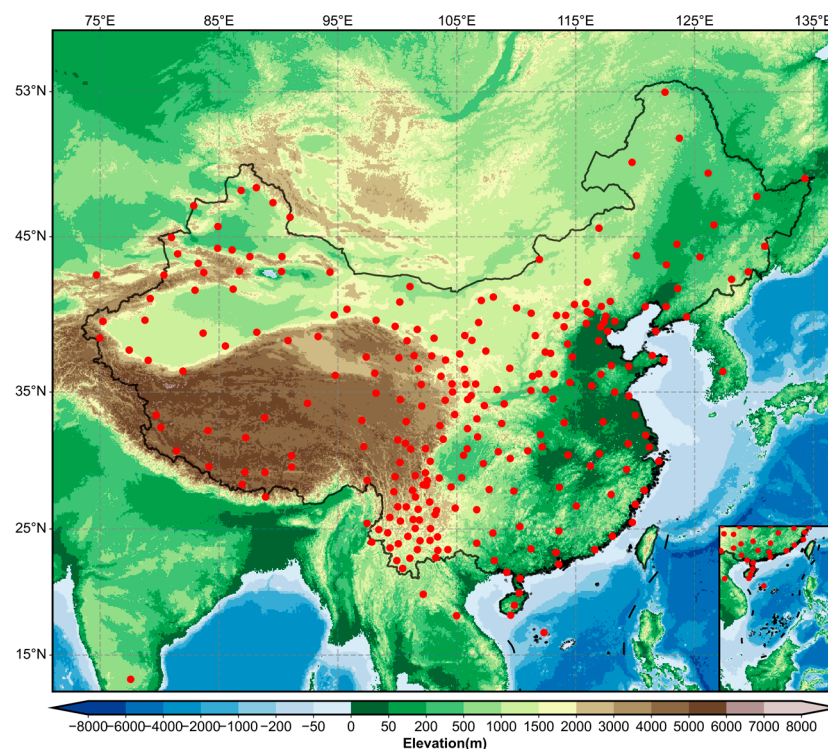


Figure 1. Geographic distribution of the 255 CMONOC stations (red dots indicate CMONOC stations).

2.3. Statistical Indicators

In order to evaluate the accuracy of the two ZTD products, Bias and Root Mean Square Error (RMSE) were used as the metrics. The formulas are expressed as follows:

$$\text{Bias} = \frac{1}{N} \sum_{i=1}^N (ZTD_i - ZTD_i^R) \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (ZTD_i - ZTD_i^R)^2} \quad (2)$$

where ZTD_i^R refers to the reference ZTD data supplied by the CMONOC, while ZTD_i refers to the ZTD data provided by VMF3_FC or VMF3_OP. i represents the i -th value in the sample set, while N denotes the total number of samples. And the workflow of this study can be referred in Figure 2.

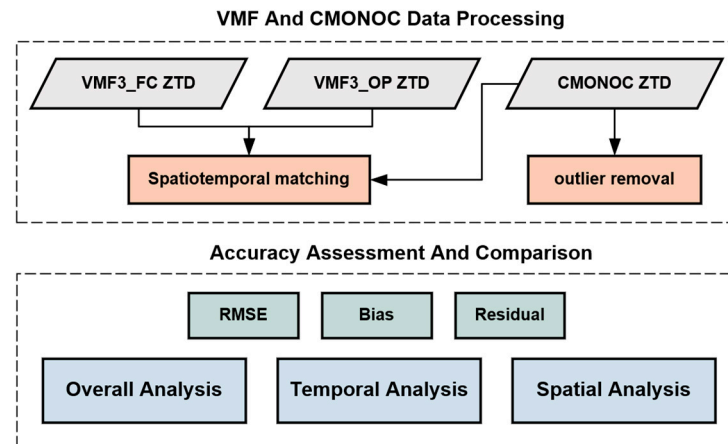


Figure 2. Workflow of this study.

3. Comparison and Discussion

The ZTD values from the two products and the corresponding reference ZTD values are shown as scatter plots in Figure 3. The black dashed lines represent the 1:1 reference line, while the red solid lines indicate the fitted line. It can be seen that more scatter points for the VMF3_OP are concentrated around the 1:1 line than those for VMF3_FC, especially within the range where the reference ZTD exceeds 2100 mm. The difference in their Bias and correlation coefficients is not significant; the values are 2.25 mm/0.9986 and 2.67 mm/0.9991, respectively. For the RMSE, the VMF3_OP with a value of 14.62 mm performs better than the VMF3_FC, and the improvement reaches 2.91 mm.

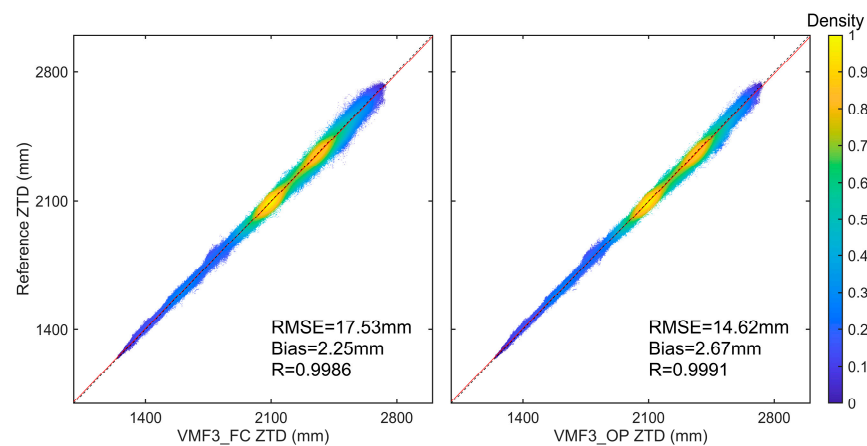


Figure 3. Scatter plots of the VMF3_FC and VMF3_OP ZTD products with reference values.

To further illustrate the differences between VMF3_FC and VMF3_OP, their ZTD residuals were calculated by subtracting the reference ZTD, and the histograms are presented in Figure 4. The red lines are normal distribution curves that were drawn based on the mean and standard deviation values of the residuals. The distribution of residuals for the two products resembled a normal distribution with a pronounced peak. It is shown that the mean values and standard deviations of the VMF3_FC and the VMF3_OP were

2.25/17.38 mm and 2.67/14.37 mm, respectively. This indicated that VMF3_OP was better than VMF3_FC, with more ZTD residuals concentrated near zero. In addition, the ZTD residuals were grouped into different ranges: from -5 to 5 mm and from -10 to 10 , and the percentages of the residuals were counted in Table 1. It can be seen that the percentages of residuals within the range of -10 to 10 mm were 56.22% and 61.86% for VMF3_FC and VMF3_OP, respectively. When the range was set from -30 to 30 , these percentages changed to 91.83% and 94.98%.

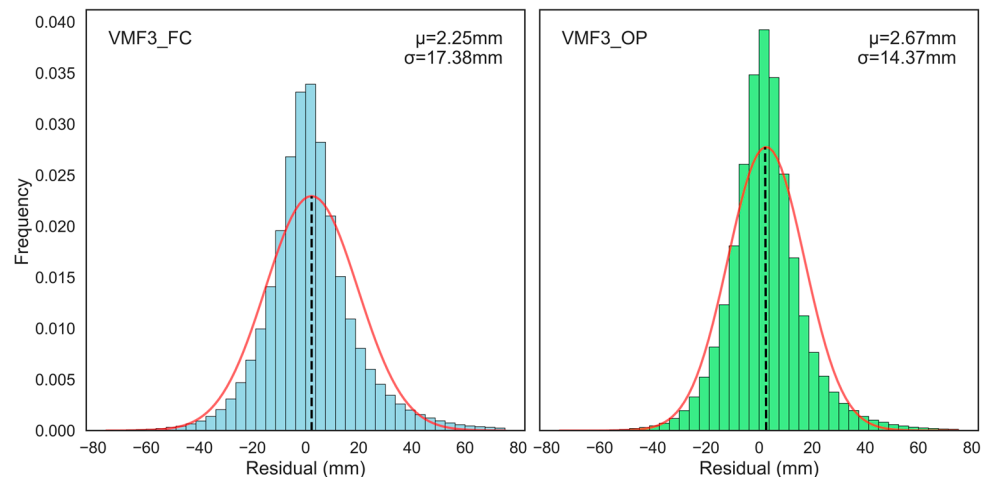


Figure 4. Residual frequency distribution histograms of the two ZTD products.

Table 1. Percentage of the ZTD residual for the two products.

Residual	VMF3_FC	VMF3_OP
($-5, 5$)	32.48%	36.02%
($-10, 10$)	56.22%	61.86%
($-15, 15$)	71.62%	77.53%
($-20, 20$)	81.48%	86.63%
($-25, 25$)	87.80%	91.91%
($-30, 30$)	91.83%	94.98%

The reference ZTD values ranged from 1240.9 to 2759.9 mm, and they were grouped into individual bins of 10 mm, i.e., all ZTD with values between 1240.9 and 1250.9 mm were evaluated as a single unit. The RMSE and Bias of each ZTD bin were calculated and plotted in Figure 5 and are represented by the solid and dotted lines, respectively. As shown in the figure, these two products have similar trends both in RMSE and Bias. Note that the accuracy of both products quickly deteriorated when the reference ZTD exceeded 2650 mm. Although it can be seen that the differences in Bias between the two products vary in different ZTD bins, the RMSE of the VMF3_OP is better than that of the VMF3_FC in each bin.

The ZTD residuals of the two products at all reference stations at the same epoch were counted, the RMSE was calculated, and the corresponding time series were plotted, which is shown in Figure 6. It is clear that the RMSE of the two products exhibited a pattern of initially increasing and then decreasing, with the largest and smallest RMSE appearing in summer and winter, respectively. This is mainly because the ZTD true value is larger in summer and smaller in winter. The RMSE of the VMF3_OP is smaller than that of the VMF3_FC at each epoch, with the mean values being 13.96 mm and 16.62 mm, respectively. In addition, a smaller fluctuation was observed in the RMSE time series of the VMF3_OP, demonstrating better stability.

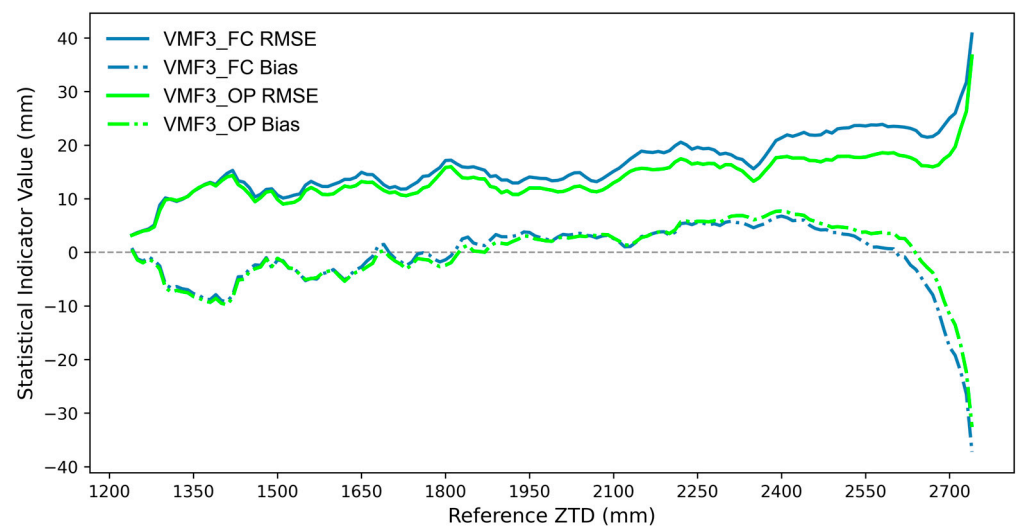


Figure 5. Variation in RMSE and Bias for VMF3_FC and VMF3_OP with changing reference ZTD.

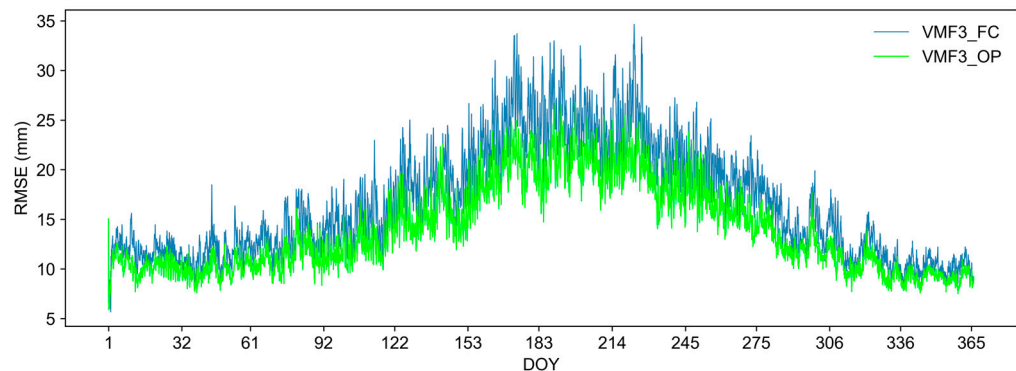


Figure 6. RMSE time series for VMF3_FC and VMF3_OP.

To better evaluate the performance of the two products in different months and hours, boxplots of the RMSE between the ZTD estimates and the reference values were generated for each month and each hour, which is shown in Figure 7. The center of the box features three horizontal lines representing the upper quartile (Q3), median (Q2), and lower quartile (Q1). The difference between Q3 and Q1 is known as the interquartile range (IQR). The upper and lower boundaries of the box are calculated as $Q3 + 1.5 \times IQR$ and $Q1 - 1.5 \times IQR$, respectively, remaining within the minimum and maximum values of the RMSE. The length of the box boundary reflects the range in which the majority of the RMSE values are distributed. The left panel, according to Q2 value and RMSE range, shows apparent seasonal trends and that both the products have a smaller value in winter and a larger value in summer, which is similar to Figure 6. The higher temperatures in summer lead to increased water vapor content in the atmosphere, making it challenging to accurately estimate the ZTD. More importantly, the boxes for the VMF3_OP, represented by greens, outperformed those for the VMF3_FC, represented by blues, every month in terms of Q1, Q2, Q3 values, and RMSE range. It can be seen in the right panel that the accuracy of the two products tends to deteriorate from UTC 0:00 to UTC 12:00, while the accuracy tends to improve from UTC 12:00 to UTC 23:00. Note that the phenomenon mentioned above is not particularly significant. This indicates that the performance of any product varies at different hours. What is more evident in the right panel is that the VMF3_OP product has a better RMSE range at each hour compared with those of the VMF3_FC product.

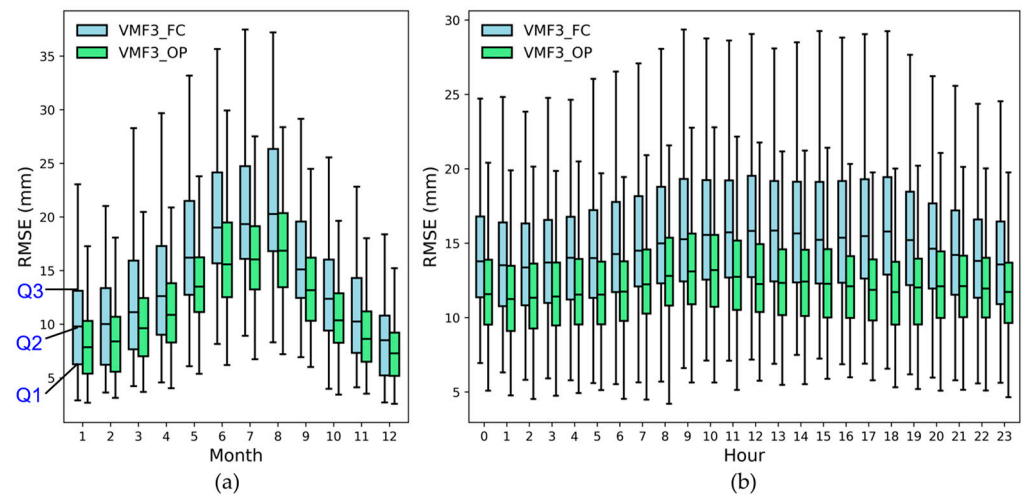


Figure 7. (a) Monthly RMSE Boxplots for VMF3_FC and VMF3_OP; (b) hourly RMSE Boxplots for VMF3_FC and VMF3_OP. Q3, Q2, and Q1 represent the upper quartile, median, and lower quartile, respectively.

In addition, the performance of the two products during day and night time was counted, and the RMSE values were listed in Table 2. In this computation, UTC 0:00–12:00 was regarded as the daytime, and the other epochs were considered night. It can be seen that the VMF3_OP outperformed the VMF3_FC both during the day and at night, with an improvement of 14.43% and 18.61%, respectively. It also showed that the VMF3_FC performed better during the daytime, and the VMF3_OP had a better performance at night. However, the difference in the performance of each product during the day and night is not significant.

Table 2. RMSE in the day and night time for the two products.

Case	VMF3_FC	VMF3_OP
day	17.25	14.76
night	17.79	14.48

Considering that both the VMF3_FC and VMF3_OP products only provide ZTD values at four epochs, i.e., UTC 0:00, 6:00, 12:00, and 18:00, the ZTD at other epochs need to be interpolated. Thus, the two types of RMSE, including the interpolated ZTD and the ZTD without interpolation, were computed for the two products and are listed in Table 3. It is shown that the RMSE for interpolated ZTD and non-interpolated ZTD were 17.48/17.76 mm for VMF3_FC and 14.64/14.51 mm for VMF3_OP, respectively. The difference in RMSE between interpolated and non-interpolated ZTD was not significant, only -0.28 mm for VMF3_FC and 0.13 mm for VMF3_OP, which indicates that both products maintained high accuracy after interpolation. Additionally, the RMSE for ZTD is influenced by various weather factors, which could explain the slightly larger RMSE observed in the interpolation scenario for the VMF3_FC product.

Table 3. RMSE under interpolation and non-interpolation scenarios for the two products.

Case	VMF3_FC	VMF3_OP
non-interpolation	17.76	14.51
interpolation	17.48	14.64

After obtaining the ZTD residuals at each hour, a new type of RMSE value was calculated for every month at each hour, and the results of these two products are presented

in the form of contour maps in Figure 8. The RMSE of ZTD derived from the two products illustrates the same trends, with large RMSE values concentrated in the central region, especially between UTC 5:00 and 15:00 from May to September. The smaller RMSE values were observed to be scattered along the upper and lower edges; namely, the RMSE of both products is relatively small at any time during winter. It can still be observed that there are different performances at different hours in the same month, especially for the VMF3_FC. The overall performance of the VMF3_OP is better than the VMF3_FC. Specifically, the smallest and largest RMSE values are 9.76 and 27.58 mm at UTC 5:00 in December and UTC 12:00 in June for the VMF3_FC, respectively. For the VMF3_OP, these values are 8.73 mm at UTC 6:00 in December and 23.31 mm at UTC 10:00 in June, respectively.

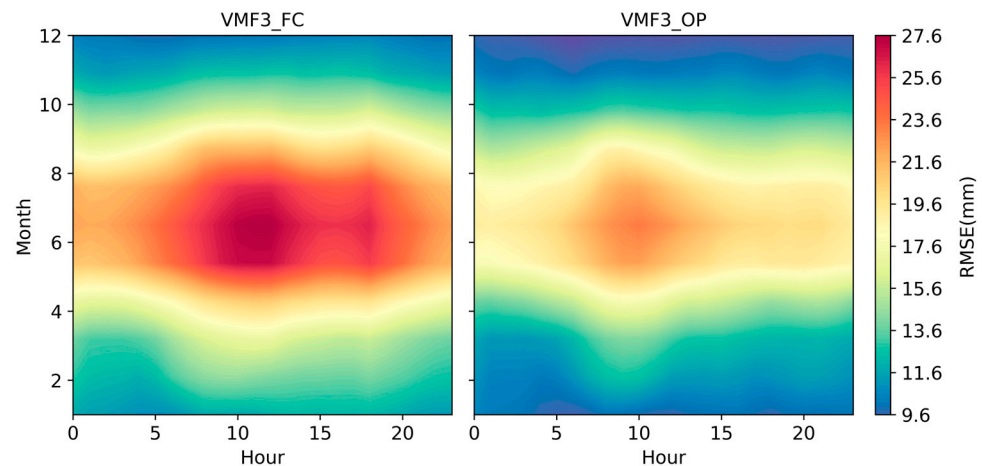


Figure 8. The RMSE values of the two products at different hours and months.

The ZTD RMSE at each CMONOC site was calculated, and its distribution is illustrated in Figure 9, in which the RMSE differences at each site are also shown. It can be seen that the RMSE of the ZTD derived from the two products showed consistent spatial distribution, with larger RMSE appearing in the southwest. In this region, both products have several stations with RMSE values exceeding 30 mm. More specifically, the worst performance for the two products was observed at the same station, namely, the SCSM (29.23° N, 102.35° E), with an RMSE of 52.59 mm for VMF3_FC and 46.37 mm for VMF3_OP, respectively. The VMF3_OP performed best in the QHMD (34.92° N, 98.21° E) station with an RMSE of 5.56 mm, and XZSH (33.20° N, 88.84° E) with a RMSE of 6.42 mm is the best performing station for the VMF3_FC. The right panel shows that the VMF3_OP outperformed the VMF3_FC at the vast majority of stations. The differences were more pronounced in the southeast, where the majority of stations fell within the range of 3 to 7 mm, while in the northwest, the majority of stations fell within the range of 0 to 3 mm. Note that there were still seven stations that had a better performance using the VMF3_FC product, but their RMSE differences were relatively small.

To better illustrate the different performances at the CMONOC sites, the number of sites with different RMSE values was counted and is shown in Figure 10. In this figure, the blue, green, and orange histograms represent the VMF3_FC, the VMF3_OP, and the differences between these two products, respectively. It can be seen that the results of both products are similar to a normal distribution, and the RMSE of more stations in the VMF3_OP is distributed in the smaller range. For example, 83.92% of the stations for the VMF3_FC have RMSE values ranging from 5 to 20 mm, and the percentage increases to 89.02% for the VMF3_OP. More specifically, the number of sites with an RMSE larger than 20 mm is 28 for the VMF3_OP, and the number reaches 41 for the VMF3_FC. When setting the RMSE ranges from 5 to 10 mm and from 10 to 15 mm, the number of sites is 21/58 and 113/144 for the VMF3_FC and the VMF3_OP, respectively. From the orange histograms in the figure, we can see that the majority of sites for VMF3_OP perform better than for VMF3_FC, and their RMSE differences are also approximately a normal distribution. The

number of sites with RMSE differences greater than 3 mm between the two products was 108, and the number of sites increased to 217 when the RMSE difference was set to greater than 1 mm.

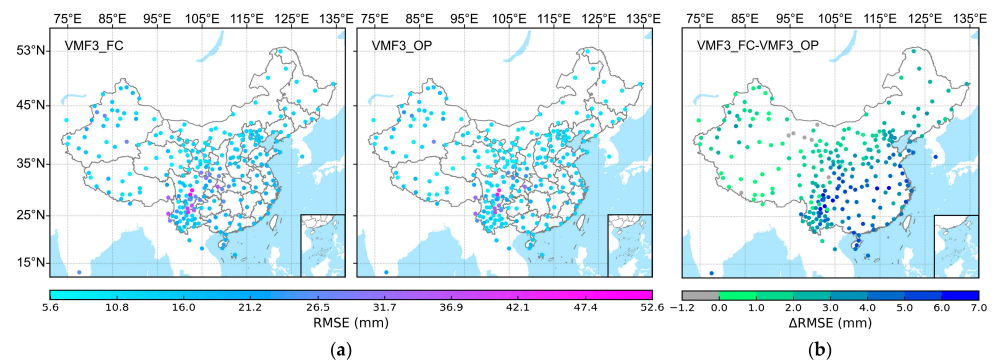


Figure 9. (a) Distribution of RMSE for VMF3_FC and VMF3_OP; (b) distribution of the RMSE differences between VMF3_FC and VMF3_OP.

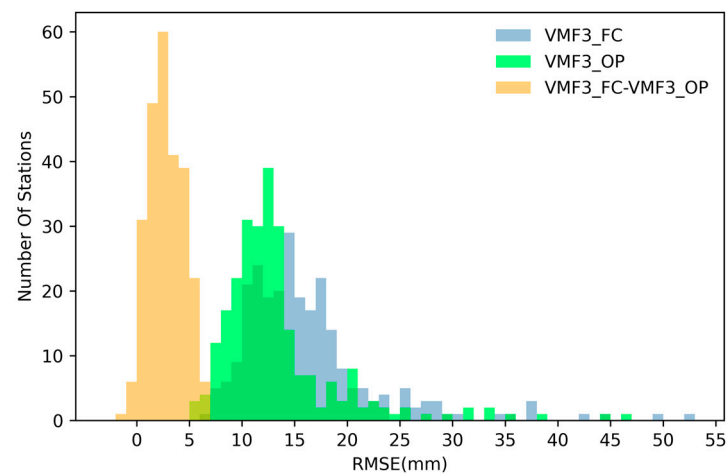


Figure 10. Number of sites with different RMSE for VMF3_FC and VMF3_OP.

4. Conclusions

This study assesses the accuracy of two ZTD grid products from the VMF data service, namely VMF3_FC and VMF3_OP, using the CMONOC ZTD 2020 as a reference. The results indicate that the RMSE/Bias values of VMF3_FC and VMF3_OP were 17.53/2.25 mm and 14.62/2.67 mm, respectively. For the distribution of ZTD residuals, the mean value and standard deviation of VMF3_FC and VMF3_OP were 2.25/17.38 mm and 2.67/14.37 mm, respectively. The percentages of residuals within the range of -10 to 10 mm for the two products were 56.22% and 61.86%. Moreover, VMF3_OP had better performance than VMF3_FC across nearly all reference ZTD ranges. The temporal analysis from January to December 2020 showed that the RMSE of the two products exhibited the same trend of initially increasing and then decreasing, with the highest RMSE in summer and the lowest in winter. From the boxplots, the VMF3_OP outperformed VMF3_FC every month and at each hour with lower mean RMSE values and narrower distribution ranges. The RMSE difference at each epoch was relatively small compared to monthly variations. For the epochs that required temporal interpolation, the RMSE for VMF3_FC and VMF3_OP was 17.48 mm and 14.64 mm, respectively, maintaining high accuracy consistent with the non-interpolation scenario. From the spatial analysis, the accuracy of both products in the southeast of China was lower than that in the northwest. The VMF3_OP exhibited superior performance to VMF3_FC across various regions in China, with an RMSE lower than the VMF3_FC at 97% of the stations. In the southeast, the majority of stations had VMF3_OP

RMSE reductions of more than 3 mm compared to VMF3_FC, while the majority of stations in the northwest had RMSE reductions ranging from 0 to 3 mm.

In summary, the VMF3_OP exhibits superior accuracy and adaptability compared to the VMF3_FC in China, making it suitable for high-precision GNSS data post-processing. On the other hand, the VMF3_FC also has the ability to offer ZTD estimates with high accuracy, and it is especially irreplaceable in real-time applications.

Author Contributions: Conceptualization, H.Z. and F.Y.; data curation, L.C., J.M., J.Z. and S.X.; formal analysis, H.Z., J.M. and W.S.; funding acquisition, F.Y.; methodology, H.Z.; resources, L.C., J.Z., W.S. and S.X.; software, L.C.; supervision, F.Y.; validation, H.Z.; writing—original draft, H.Z. and F.Y.; writing—review and editing, H.Z., L.C., F.Y., J.M., J.Z., W.S. and S.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 42204022; the Open Research Fund of State Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, grant number 23P02; the Fundamental Research Funds for the Central Universities, grant numbers 2024ZKPYDC02, 2023ZKPYDC10; Open Fund of Hubei LuoJia Laboratory, grant number 230100031, China University of Mining and Technology-Beijing Innovation Training Program for College Students, grant number 202402010, 202402008.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The VMF3_FC and the VMF3_OP data can be downloaded from https://vmf.geo.tuwien.ac.at/trop_products/GRID/1x1/VMF3/VMF3_FC/ and https://vmf.geo.tuwien.ac.at/trop_products/GRID/1x1/VMF3/VMF3_OP/, respectively (accessed on 12 January 2024). The ZTD data from the CMONOC can be downloaded from <ftp://ftp.cgps.ac.cn/> (accessed on 4 January 2024).

Acknowledgments: The authors express their gratitude to the Vienna University of Technology for supplying tropospheric products and to the Crustal Movement Observation Network of China for providing ZTD data. Appreciation is also given to the anonymous reviewers for their careful review and constructive suggestions to improve the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Bevis, M.; Businger, S.; Herring, T.A.; Rocken, C.; Anthes, R.A.; Ware, R.H. GPS meteorology: Remote sensing of atmospheric water vapor using the global positioning system. *J. Geophys. Res. Atmos.* **1992**, *97*, 15787–15801. [\[CrossRef\]](#)
2. Dodson, A.; Shardlow, P.; Hubbard, L.; Elgered, G.; Jarlemark, P. Wet tropospheric effects on precise relative GPS height determination. *J. Geod.* **1996**, *70*, 188–202. [\[CrossRef\]](#)
3. Yang, F.; Meng, X.; Guo, J.; Yuan, D.; Chen, M. Development and evaluation of the refined zenith tropospheric delay (ZTD) models. *Satell. Navig.* **2021**, *2*, 21. [\[CrossRef\]](#)
4. Bock, O.; Doerflinger, E. Atmospheric modeling in GPS data analysis for high accuracy positioning. *Phys. Chem. Earth Part A Solid Earth Geod.* **2001**, *26*, 373–383. [\[CrossRef\]](#)
5. Bevis, M.; Businger, S.; Chiswell, S.; Herring, T.A.; Anthes, R.A.; Rocken, C.; Ware, R.H. GPS meteorology: Mapping zenith wet delays onto precipitable water. *J. Appl. Meteorol. (1988–2005)* **1994**, *33*, 379–386. [\[CrossRef\]](#)
6. Yang, F.; Sun, Y.; Meng, X.; Guo, J.; Gong, X. Assessment of tomographic window and sampling rate effects on GNSS water vapor tomography. *Satell. Navig.* **2023**, *4*, 7. [\[CrossRef\]](#)
7. Yang, F.; Gong, X.; Wang, Y.; Liu, M.; Li, J.; Xu, T.; Hao, R. GNSS water vapor tomography based on Kalman filter with optimized noise covariance. *GPS Solut.* **2023**, *27*, 181. [\[CrossRef\]](#)
8. Vaquero-Martínez, J.; Antón, M. Review on the role of GNSS meteorology in monitoring water vapor for atmospheric physics. *Remote Sens.* **2021**, *13*, 2287. [\[CrossRef\]](#)
9. Li, H.; Choy, S.; Zaminpardaz, S.; Carter, B.; Sun, C.; Purwar, S.; Liang, H.; Li, L.; Wang, X. Investigating the inter-relationships among multiple atmospheric variables and their responses to precipitation. *Atmosphere* **2023**, *14*, 571. [\[CrossRef\]](#)
10. Li, L.; Wu, S.; Zhang, K.; Wang, X.; Li, W.; Shen, Z.; Zhu, D.; He, Q.; Wan, M. A new zenith hydrostatic delay model for real-time retrievals of GNSS-PWV. *Atmos. Meas. Tech.* **2021**, *14*, 6379–6394. [\[CrossRef\]](#)
11. Li, L.; Wang, X.; Wei, Y.; Wang, H. The New PWV Conversion Models Based on GNSS and Meteorological Elements in the China Region. *Atmosphere* **2022**, *13*, 1810. [\[CrossRef\]](#)

12. Zhao, Q.; Ma, Y.; Li, Z.; Yao, Y. Retrieval of a high-precision drought monitoring index by using GNSS-derived ZTD and temperature. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2021**, *14*, 8730–8743. [\[CrossRef\]](#)
13. Zhao, Q.; Liu, K.; Sun, T.; Yao, Y.; Li, Z. A novel regional drought monitoring method using GNSS-derived ZTD and precipitation. *Remote Sens. Environ.* **2023**, *297*, 113778. [\[CrossRef\]](#)
14. Zhao, Q.; Su, J.; Li, Z.; Yang, P.; Yao, Y. Adaptive aerosol optical depth forecasting model using GNSS observation. *IEEE Trans. Geosci. Remote Sens.* **2021**, *60*, 1–9. [\[CrossRef\]](#)
15. Wei, P.; Xie, S.; Huang, L.; Liu, L. Ingestion of GNSS-Derived ZTD and PWV for spatial interpolation of PM_{2.5} concentration in Central and Southern China. *Int. J. Environ. Res. Public Health* **2021**, *18*, 7931. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Davis, J.; Herring, T.; Shapiro, I.; Rogers, A.; Elgered, G. Geodesy by radio interferometry: Effects of atmospheric modeling errors on estimates of baseline length. *Radio Sci.* **1985**, *20*, 1593–1607. [\[CrossRef\]](#)
17. Yang, F.; Wang, L.; Li, Z.; Tang, W.; Meng, X. A weighted mean temperature (T_m) augmentation method based on global latitude zone. *GPS Solut.* **2022**, *26*, 141. [\[CrossRef\]](#)
18. Sun, Y.; Yang, F.; Liu, M.; Li, Z.; Gong, X.; Wang, Y. Evaluation of the weighted mean temperature over China using multiple reanalysis data and radiosonde. *Atmos. Res.* **2023**, *285*, 106664. [\[CrossRef\]](#)
19. Hopfield, H. Two-quartic tropospheric refractivity profile for correcting satellite data. *J. Geophys. Res.* **1969**, *74*, 4487–4499. [\[CrossRef\]](#)
20. Black, H.; Eisner, A. Correcting satellite Doppler data for tropospheric effects. *J. Geophys. Res. Atmos.* **1984**, *89*, 2616–2626. [\[CrossRef\]](#)
21. Askne, J.; Nordius, H. Estimation of tropospheric delay for microwaves from surface weather data. *Radio Sci.* **1987**, *22*, 379–386. [\[CrossRef\]](#)
22. Saastamoinen, J. Atmospheric correction for the troposphere and stratosphere in radio ranging satellites. *Use Artif. Satell. Geod.* **1972**, *15*, 247–251. [\[CrossRef\]](#)
23. Yao, Y.; He, C.; Zhang, B.; Xu, C. A new global zenith tropospheric delay model GZTD. *Chin. J. Geophys.* **2013**, *56*, 2218–2227. [\[CrossRef\]](#)
24. Li, W.; Yuan, Y.; Ou, J.; Li, H.; Li, Z. A new global zenith tropospheric delay model IGGtrop for GNSS applications. *Chin. Sci. Bull.* **2012**, *57*, 2132–2139. [\[CrossRef\]](#)
25. Chen, J.; Wang, J.; Wang, J.; Tan, W. SHAtrop: Empirical ZTD model based on CMONOC GNSS network. *Geomat. Inf. Sci. Wuhan Univ.* **2019**, *44*, 1588–1595. [\[CrossRef\]](#)
26. Böhm, J.; Heinkelmann, R.; Schuh, H. Short note: A global model of pressure and temperature for geodetic applications. *J. Geod.* **2007**, *81*, 679–683. [\[CrossRef\]](#)
27. Landskron, D.; Böhm, J. VMF3/GPT3: Refined discrete and empirical troposphere mapping functions. *J. Geod.* **2018**, *92*, 349–360. [\[CrossRef\]](#)
28. Yang, F.; Guo, J.; Zhang, C.; Li, Y.; Li, J. A regional zenith tropospheric delay (ZTD) model based on GPT3 and ANN. *Remote Sens.* **2021**, *13*, 838. [\[CrossRef\]](#)
29. Fei, Y.; Jiming, G.; Ming, C.; Di, Z. Establishment and analysis of a refinement method for the GNSS empirical weighted mean temperature model. *Acta Geod. Et Cartogr. Sin.* **2022**, *51*, 2339–2345. [\[CrossRef\]](#)
30. Collins, P.; Langley, R.; LaMance, J. Limiting factors in tropospheric propagation delay error modelling for GPS airborne navigation. In Proceedings of the 52nd Annual Meeting of The Institute of Navigation (1996), Cambridge, MA, USA, 19–21 June 1996; pp. 519–528.
31. Boehm, J.; Werl, B.; Schuh, H. Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data. *J. Geophys. Res. Solid Earth* **2006**, *111*, B02406. [\[CrossRef\]](#)
32. Nafisi, V.; Urquhart, L.; Santos, M.; Nievinski, F.; Böhm, J.; Wijaya, D.; Schuh, H.; Ardalan, A.; Hobiger, T.; Ichikawa, R. Comparison of ray-tracing packages for troposphere delays. *IEEE Trans. Geosci. Remote Sens.* **2012**, *50*, 469–481. [\[CrossRef\]](#)
33. Boisits, J.; Landskron, D.; Böhm, J. VMF3o: The Vienna Mapping Functions for optical frequencies. *J. Geod.* **2020**, *94*, 57. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Glaner, M.F.; Weber, R. An open-source software package for Precise Point Positioning: raPPPid. *GPS Solut.* **2023**, *27*, 174. [\[CrossRef\]](#)
35. Geng, J.; Chen, X.; Pan, Y.; Mao, S.; Li, C.; Zhou, J.; Zhang, K. PRIDE PPP-AR: An open-source software for GPS PPP ambiguity resolution. *GPS Solut.* **2019**, *23*, 91. [\[CrossRef\]](#)
36. King, R.; Bock, Y. *Documentation for the GAMIT GPS Processing Software Release 10.2*; Mass. Inst. of Technol.: Cambridge, MA, USA, 2005.
37. Gandolfi, S.; Tavasci, L.; Poluzzi, L. Improved PPP performance in regional networks. *GPS Solut.* **2016**, *20*, 485–497. [\[CrossRef\]](#)
38. Dach, R.; Brockmann, E. *International GNSS Service Technical Report 2022 (IGS Annual Report)*; IGS Central Bureau and University of Bern/Bern Open Publishing: Bern, Switzerland, 2023. [\[CrossRef\]](#)
39. Yang, L.; Wang, J.; Li, H.; Balz, T. Global assessment of the GNSS single point positioning biases produced by the residual tropospheric delay. *Remote Sens.* **2021**, *13*, 1202. [\[CrossRef\]](#)
40. Osah, S.; Acheampong, A.A.; Fosu, C.; Dadzie, I. Evaluation of zenith tropospheric delay derived from ray-traced VMF3 product over the West African region using GNSS observations. *Adv. Meteorol.* **2021**, *2021*, 8836806. [\[CrossRef\]](#)

41. Yang, F.; Guo, J.; Li, J.; Zhang, C.; Chen, M. Assessment of the troposphere products derived from VMF data server with ERA5 and IGS data over China. *Earth Space Sci.* **2021**, *8*, e2021EA001815. [[CrossRef](#)]
42. Li, J.; Yang, F.; Yuan, D.; Wang, H.; Song, S.; Tan, J.; Wen, Z. Unraveling the Accuracy Enigma: Investigating ZTD Data Precision in TUW-VMF3 and GFZ-VMF3 Products using a Comprehensive Global GPS Dataset. *IEEE Trans. Geosci. Remote Sens.* **2024**, *62*, 5800710. [[CrossRef](#)]
43. Molteni, F.; Buizza, R.; Palmer, T.N.; Petroliagis, T. The ECMWF ensemble prediction system: Methodology and validation. *Q. J. R. Meteorol. Soc.* **1996**, *122*, 73–119. [[CrossRef](#)]
44. Jung, T.; Balsamo, G.; Bechtold, P.; Beljaars, A.; Koehler, M.; Miller, M.; Morcrette, J.J.; Orr, A.; Rodwell, M.; Tompkins, A.M. The ECMWF model climate: Recent progress through improved physical parametrizations. *Q. J. R. Meteorol. Soc.* **2010**, *136*, 1145–1160. [[CrossRef](#)]
45. Kouba, J. Implementation and testing of the gridded Vienna Mapping Function 1 (VMF1). *J. Geod.* **2008**, *82*, 193–205. [[CrossRef](#)]
46. Yu, J.; Tan, K.; Zhang, C.; Zhao, B.; Wang, D.; Li, Q. Present-day crustal movement of the Chinese mainland based on Global Navigation Satellite System data from 1998 to 2018. *Adv. Space Res.* **2019**, *63*, 840–856. [[CrossRef](#)]
47. Liang, H.; Cao, Y.; Wan, X.; Xu, Z.; Wang, H.; Hu, H. Meteorological applications of precipitable water vapor measurements retrieved by the national GNSS network of China. *Geod. Geodyn.* **2015**, *6*, 135–142. [[CrossRef](#)]
48. Yuan, Y.; Li, Z.; Wang, N.; Zhang, B.; Li, H.; Li, M.; Huo, X.; Ou, J. Monitoring the ionosphere based on the Crustal Movement Observation Network of China. *Geod. Geodyn.* **2015**, *6*, 73–80. [[CrossRef](#)]
49. Dash, C.S.K.; Behera, A.K.; Dehuri, S.; Ghosh, A. An outlier detection and elimination framework in classification task of data mining. *Decis. Anal. J.* **2023**, *6*, 100164. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.