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Key Points:
• This paper analyzes the spatiotemporal distribution of zenith tropospheric delay with altitude variation coefficient $\beta$.
• The global altitude coefficient $\beta$ model is established by using the trigonometric function and seventh-order spherical harmonic function model.
• The new global tropospheric delay model $R_{GZTD}$ is reconstructed using altitude coefficient $\beta$, provided by Gbeta model.

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A New Global Tropospheric Delay Model Considering the Spatiotemporal Variation Characteristics of ZTD With Altitude Coefficient

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Abstract
Tropospheric delay error is independent of the signal’s frequency and has strong spatiotemporal variation. It is one of the most severe error sources of satellite navigation and spatial measurement. In view of the limitation of global zenith tropospheric delay (GZTD) model considering the altitude coefficient $\beta$ as a constant and ignoring its spatiotemporal variation, this paper analyzes the spatiotemporal distribution of zenith tropospheric delay (ZTD) with altitude variation coefficient $\beta$ based on the meteorological reanalysis data provided by the European Centre for Medium-Range Weather Forecasting from 2011 to 2015. The global altitude coefficient $\beta$ model is established by using the trigonometric function and seventh-order spherical harmonics function model, and then the global tropospheric delay model $R_{GZTD}$ (reconstruction GZTD) is reconstructed by using Gbeta (Global beta $\beta$) model. The $R_{GZTD}$ model gives high-accuracy global distribution of tropospheric delays without meteorological parameters. The results show that the internal accuracy of the $R_{GZTD}$ model is 3.22 cm, which has a good fitting effect. This paper uses the tropospheric delay products in 2016–2017 provided by the International GNSS Service, the tropospheric delay calculated by the European Centre for Medium-Range Weather Forecasting analysis data, and the radiosonde ZTD data in 2016–2017 as external compliance check data. The results show that the accuracy of the $R_{GZTD}$ model is better than that of the GZTD model, UNB3m model, and the global pressure and temperature 2 wet model in the global and regional scope. Especially in areas with a higher altitude, the correction effect of the $R_{GZTD}$ model is more significant. The root-mean-square error is 8.5% smaller than that of the GZTD model in the range of 0–500 m, 14.6% smaller in the range of 500–1,000 m, 12.5% smaller in the range of 1,000–2,000 m, and 16.8% smaller in the range above 2,000 m. The accuracy with the increase of height is due to the fact that the $R_{GZTD}$ model takes account of the spatiotemporal variation of $\beta$.

1. Introduction

When a radio signal passes through the neutral atmosphere, it is refracted by time delay and bending effect, which is called propagation delay. This kind of delay is called tropospheric delay in Global Navigation Satellite System (GNSS) positioning, which is one of the most severe error sources in precise positioning. Its value varies from 2 to 20 m depending on the elevation angle of the satellite (Penna et al., 2001). Since the tropospheric delay is independent of the signal’s frequency, the tropospheric delay cannot be eliminated by the dual-frequency observations. Usually, it is corrected with a priori model and the remaining should be further estimated together with other parameters. Studies confirm that the accuracy of the correction model has a crucial impact on high-precision positioning in terms of accuracy and convergence time. In general, we project the slant delay to zenith direction with mapping function in GNSS navigation and positioning, so modeling the zenith tropospheric delay (ZTD) is a common method to mitigate the tropospheric influence on signal traveling. In order to improve the accuracy and efficiency of the application in Earth science based on space geodesy techniques, it is necessary to establish a stable and reliable tropospheric delay model.

Traditional tropospheric delay models such as Hopfield model, Saastamoinen model, and Black model can achieve centimeter-level accuracy when applying accurate measured meteorological observations (Black, 1978; Hopfield, 1969, 1971; Saastamoinen, 1972). If the empirical meteorological values are used to replace the observed meteorological data, the accuracy of these models will decrease significantly (Li et al., 2012). At present, the application of the traditional tropospheric delay model may be limited due to the lack of...
meteorological measurement equipment at many GNSS stations and the low estimation accuracy of the delay correction model.

In recent years, many scholars have developed a series of models without meteorological parameters, such as the UNB series models (Collins et al., 1996; Collins & Langley, 1997) and the European Geostationary Navigation Overlay Service model (Penna et al., 2001; Ueno et al., 2001). Li et al. (2012) established a new tropospheric delay model IGGtrop based on NCEP (National Centers for Environmental Prediction) reanalysis data. The results show that the average root-mean-square error (RMSE) is 4.0 cm (Zhang et al., 2016). Yao et al. (2013) used the Global Geodetic Observing System atmosphere data to analyze the spatiotemporal variation of tropospheric delay and established a global zenith tropospheric delay model, GZTD, by using spherical harmonics function. The accuracy of GZTD model is in accordance with the IGGtrop model, and it has fewer model parameters. Yao et al. (2016) established the GZTD2 model by modifying the model function on the basis of considering the diurnal variation of the tropospheric delay. It is proved that the global mean deviation is comparable to the GZTD model, and the global mean RMS has reduced by 3 mm.

Schüler (2014) fitted NCEP meteorological data to obtain seasonal and diurnal variation coefficients and established the TropGrid2 model. The accuracy of the TropGrid2 model was 3.8 cm. Böhm et al. (2015) proposed the global pressure and temperature 2 wet (GPT2w) model; the annual and semiannual variations of meteorological parameters were taken into account in the GPT2w model. The International GNSS Service (IGS) data are used to verify the model. The results show that the accuracy of GPT2w is about 3.6 cm. Assuming that the troposphere is a nonlinear system and can be handled as a black box, Sun et al. (2017) derived a global zenith tropospheric delay simplified model (GZTDS). The GZTDS and its variation with time can be expressed as a series of cosine components, which represent each period of tropospheric delay variation. It has been verified that the accuracy of the GZTDS model is comparable to that of GPT2w, and the GZTDS model does not require any weather data. Li et al. (2018) proposed two improved tropospheric correction models—I GGtrop_SH and IGGtrop_rH models—that are established based on empirical vertical reduction functions and capable of providing zenith tropospheric delay correction for radio space geodetic analysis without meteorological measurements. The verified accuracy of the IGGtrop_SH model is about 3.86 cm, and the accuracy of the IGGtrop_rH model is about 3.97 cm. The comparison between the IGGtrop_SH model and the previous IGGtrop model manifests that IGGtrop_SH model in consideration of variation in semiannual cycle has significantly improved the ZTD correction effect in the Northern Hemisphere, especially in the middle latitude regions, but there has been no significant change in the Southern Hemisphere.

Parameter $\beta$ is used as a modeling constant in the GZTD model, which converts the tropospheric delay of the global Global Geodetic Observing System atmosphere grid to mean sea level. However, the GZTD model has certain limitations especially at high altitudes due to the parameter $\beta$ changes with time and latitude and longitude. In view of the limitation of the GZTD model which regards the altitude correction coefficient as a constant, we will propose a global tropospheric delay model considering the spatiotemporal variation characteristics of ZTD with altitude coefficient. For this study, we use the 2011–2015 reanalysis data provided by the European Centre for Medium-Range Weather Forecasting (ECMWF) to study the spatiotemporal variation characteristics of parameter $\beta$. We adopt the spherical harmonics function to establish the global altitude coefficient $\beta$ model, and the Gbeta model is used to re-establish the global tropospheric delay correction model R_GZTD which can further improve the tropospheric delay correction effect of the model at high altitudes. The thesis is outlined as follows. Section 2 gives the data sources and processing strategy. In section 3 the spatiotemporal characteristics of altitude correction coefficient $\beta$ are introduced and the global altitude coefficient $\beta$ model is established. Section 4 explains the foundation of a global tropospheric delay correction model. The accuracy analysis of different models based on different data sources is given in section 5. Finally, section 6 provides the discussions and conclusions.

2. Data and Methodology for Calculating ZTD Using ECMWF Products

ERA-Interim is a reanalysis product of ECMWF. The ERA-Interim data used in this paper are stratified meteorological data for 2011–2015, with a time resolution of 6 hr (0, 6, 12, and 18 UTC) and spatial resolution of $5^\circ \times 5^\circ$ and vertical pressure level from 1,000 to 1 hPa for a total of 37 layers of data, each layer including high potential, temperature, specific humidity, and pressure.
There are two common categories to calculate tropospheric delay using ECMWF/NCEP meteorological data: integral method and Saastamoinen model method. Chen et al. (2011) exploited the integration method and Saastamoinen model method to calculate tropospheric delay with ECMWF data, respectively, and analyzed their accuracy; the results represent that the accuracy of the tropospheric delay obtained by the integration method is higher. In this paper, the integral method is applied to solve the tropospheric delay from ECMWF meteorological data. The ZTD calculated from meteorological data includes two parts, one is the total zenith tropospheric delay (ZTD₁) from the station location to the top and the other is the zenith hydrostatic delay above the top level (ZHD top) (there is almost no water vapor above this level). The ZHD top value depends on the top pressure value of the reanalysis data. Because the top pressure value of the ECMWF meteorological data is 1 hPa and the calculated ZHD top is only 2 mm, the ZHD top is ignored in this article. Integrating the interlaminar refractive index solved by equation (1) can acquire total tropospheric delay at the vertex of each grid point.

\[
N = \frac{k_1(P-e)}{T} + \frac{k_2e}{T} + \frac{k_3e}{T}
\]

\[
e = \frac{q \times P}{0.622}
\]

\[
ZTD = 10^{-6} \int N ds = 10^{-6} \sum_i N_i \Delta S_i
\]

where \(k_1 = 77.604\), \(k_1 = 64.79\), and \(k_1 = 377,600.0\) K/hPa; \(N\) is the interlaminar refractive index; \(T\) is the temperature (K); \(P\) is atmospheric pressure (hPa); \(e\) is vapor pressure (hPa); and \(q\) is specific humidity.

In this paper, the tropospheric products of eight IGS stations are selected to verify the accuracy of the tropospheric delay obtained by the integral method. The results illustrate that the tropospheric delay accuracy obtained by the integral method from the ECMWF meteorological data is 1.3 cm, which is consistent with the conclusions of Ma et al. (2012) and shows the accuracy of the integral method.

3. Establishment of the Global Altitude Coefficient β Model
3.1. Spatiotemporal Distribution Characteristics of Altitude Coefficient β

Since tropospheric delay is not only related to altitude but also affected by latitude. In order to better analyze the variation of tropospheric delay with altitude, this section selects the zenith tropospheric delay vertical profile of different latitude, as shown in Figure 1a. It can be seen from Figure 1a that the tropospheric delay is largest near the equator and minimum at the North and South Poles. It was also found that ZTD was not symmetrically distributed on the global scale, which is caused by the opposite seasons in the Northern and Southern Hemispheres. It can be seen from Figure 1b that the changing trend of ZTD has a certain correlation with latitude. ZTD/ZTD₀ gradually decreases as latitude increases; that is, the altitude correction coefficient \(\beta\) is different.

According to statistics, the standard deviation of exponential function fitting is 1.2 cm, and the RMS is 1.4 cm, indicating that the exponential function has a good effect on the fitting of ZTD distribution with altitude. It also shows that the distribution of ZTD with altitude is similar to that of atmospheric pressure and
decreases exponentially with the increase of altitude, which has agreement with the graphical representation of ZTD as a function of altitude given by Chen et al. (2011). Therefore, the relationship between tropospheric delay and elevation is represented in this paper as an exponential function, as shown in equation (2).

\[
ZTD = ZTD_0 \exp(-\beta h)
\]

where \(ZTD_0\) is the total delay at the mean sea level and \(h\) is the altitude (km).

Figure 2 shows the global distribution of the mean altitude coefficient \(\beta\) for different seasons in 2013. It is obvious that the altitude coefficient \(\beta\) varies with the seasons. And the maximum value is \(-0.125\) km\(^{-1}\), the minimum value is \(-0.145\) km\(^{-1}\), and the mean value is \(-0.134\) km\(^{-1}\), which is different from the average altitude coefficient \(\beta\) value of \(-0.1317\) km\(^{-1}\) mentioned by Yao et al. (2013), owing to the choice of the data source and time span for solving the altitude coefficient \(\beta\). In addition, the distribution of the altitude coefficient \(\beta\) is related to the geographical location, and there is no symmetry between the North and South Hemispheres. The value in the Arctic region is larger than that in the Antarctic region. The minimum value of the altitude coefficient \(\beta\) appears in the vicinity of the equator and in the Antarctic region. The maximum value appears in the 20° to 40° region of the north and south latitudes, such as the Sahara Desert, the Arabia peninsula, the Taklimakan Desert in Xinjiang, China, and the desert region in Australia. This may be due to the fact that the delay between the troposphere in the desert region is affected by the subtropical high-pressure belt or the trade wind belt and the location of the land and sea junction. At the same time, it is found that the difference between the maximum and minimum values of altitude coefficient \(\beta\) is more than 0.01 km\(^{-1}\) at different longitudes and the same latitude between 40°S and 40°N, and the altitude coefficients of the same latitude are basically the same in other regions. From Figure 2, we figure out that the altitude coefficient \(\beta\) has an obvious seasonal variation in the Antarctic and Arctic regions but less obvious in the vicinity of equator. In addition, the changing trend of the altitude coefficient \(\beta\) in the Northern and Southern Hemispheres is just the opposite. It is worth noting that the variation trend of altitude coefficient \(\beta\) in the Antarctic region decreases first and then increases while in the Arctic region increases first and then decreases. In the low latitudes of the Southern Hemisphere, the variation trend of altitude coefficient \(\beta\) increases first and then decreases, and the trend in the low latitudes of the Northern Hemisphere first decreases and then increases, which is contrary to the trend of zenith tropospheric delay over time. This may be attribute to the rise of the zenith tropospheric delay caused by the change of temperature in low latitudes, demonstrating that the altitude coefficient \(\beta\) in low latitudes is greatly affected by temperature.
The zenith tropospheric delay has significant annual and semiannual periodic variations. To find out whether there is a periodic variation of the height coefficient $\beta$, this section randomly selects six grid points and the time series of altitude coefficients $\beta$ are displayed in Figure 3. As we can see from Figure 3 the time series of altitude coefficient $\beta$ are mainly annual and semiannual periodic.

### 3.2. Establishment of Gbeta Model

Based on the above analysis, the altitude coefficient $\beta$ is spatially related to the geographical location, and there is a significant annual and semiannual periodic variation in time. In this paper, we use trigonometric function and spherical harmonics function together to express the variation of global altitude coefficient, as shown in equation (4):

$$
\beta = \delta_0 + \delta_1 \cos\left(\frac{2\pi}{365.25} \text{doy} - \delta_2\right) + \delta_3 \cos\left(\frac{4\pi}{365.25} \text{doy} - \delta_4\right)
$$

(3)

$$
\delta_i = \sum_{n=0}^{7} \sum_{m=-n}^{n} P_{nm}(\sin\phi) \cdot \left[ W_{nm}^i \cos(m\lambda) + V_{nm}^i \sin(m\lambda) \right]
$$

(4)

where $\delta_0$, $\delta_1$, and $\delta_3$ denote the annual mean value of the altitude coefficient, the amplitude of the annual cycle, and the amplitude of the semiannual cycle, respectively. $\delta_2$ and $\delta_4$ represent the initial phases of the annual cycle and the semiannual cycle, and doy is the day of the year. $P_{nm}$ are the Legendre polynomials; $\phi$ is the latitude of the grid point; $\lambda$ is the longitude of the grid point; $W_{nm}^i$ and $V_{nm}^i$ indicate the spherical harmonics coefficients determined by least squares optimization. The parameter $\delta_i$ is introduced into equation (3) and linearized, and the unknown parameter is solved by the least squares method based on the altitude coefficient $\beta$ of the global grid points.

Figure 4 shows the comparison between observations of the altitude coefficient $\beta$ and results of Gbeta model for different grid points from 2011 to 2015. From Figure 4, we know that the altitude coefficient $\beta$ obtained by the Gbeta model is close to the measured value, which can better reflect the periodic variation of the altitude coefficient.
The global altitude coefficient $\beta$ grid data in 2016–2017 are regarded as the true data to verify the global accuracy of the Gbeta model. Figure 5 shows the global distribution of Gbeta model accuracy. Figure 5 exhibits that the altitude coefficient $\beta$ of the Gbeta model is close to the true value and the precision distribution is uniform globally, indicating that the Gbeta model can well express the spatial distribution characteristics of the global altitude coefficient $\beta$ with average bias of the Gbeta model that is 0 km$^{-1}$ and the average RMS that is 0.0029 km$^{-1}$. In addition, the RMS of the Gbeta model is relatively low in the middle and low latitudes, which may be ascribed to the violent delay variation in the middle-low latitudes and the overfitting of the Gbeta model.

4. Establishment of R_GZTD Model

The tropospheric delay is not only related to latitude and longitude but also decreases with altitude. Moreover, the tropospheric delays differ in different longitude regions of the same latitude and have significant annual and semiannual periodic changes in time.

In this paper, the global nonmeteorological parameter tropospheric delay correction model R_GZTD (reconstruction global zenith tropospheric delay) is established by using global ZTD grid data calculated from ECMWF meteorological reanalysis data. The detailed modeling process is as follows:

1. The time, latitude, and longitude of the station are adopted as input value of the Gbeta model, calculate the altitude coefficient $\beta$ of the corresponding position, and normalize the tropospheric delay of the grid point to the mean sea level (equation (5)).
2. A trigonometric function is used to fit the periodic variation of tropospheric delay (equation (6)).
3. The spherical harmonic expansion of the parameters to be estimated is carried out by using a 10th-order spherical harmonics function (equation (7)).

\[ ZTD = ZTD_0 \cdot \exp^{ln} \]  

\[ ZTD_0 = \alpha_0 + \alpha_1 \cos \left( \frac{2\pi \text{doy} - \alpha_2}{365.25} \right) + \alpha_3 \cos \left( \frac{4\pi \text{doy} - \alpha_4}{365.25} \right) \]  

\[ \alpha_i = \sum_{n=0}^{10} \sum_{m=0}^{n} P_{mn} \left( \sin \varphi \right) \left[ A_{nm}^i \cos (n\lambda) + B_{nm}^i \sin (n\lambda) \right] \]  

In equations (5)–(7), \( \alpha_0 \) is the annual mean of ZTD on the mean sea level, \( \alpha_1 \) is the annual variation amplitude of ZTD, \( \alpha_2 \) is the initial phase of annual variation, \( \alpha_3 \) is the semiannual variation amplitude of ZTD, \( \alpha_4 \) is the initial phase of semiannual variation, \( \text{doy} \) is the day of the year, \( P_{mn} \) are the Legendre polynomials, \( \varphi \) is the latitude of the grid point, \( \lambda \) is the longitude of the grid point, and \( A_{nm}^i \) and \( B_{nm}^i \) are the coefficients of spherical harmonics determined by least squares optimization. The R_GZTD model established in this paper can provide the ZTD at any position and at any time only by providing the doy, latitude, longitude, and altitude. Thus, the model has the characteristics of no need to measure meteorological parameters, convenient calculation, few required parameters, and high correction accuracy.

5. Accuracy Validation and Analysis

In this chapter, the tropospheric delay products of 327 global IGS stations provided by IGS Analysis Center in 2016–2017, the tropospheric delay calculated by ECMWF meteorological reanalysis data (ECMWF_ZTD), and tropospheric delay calculated by radiosonde data (RAD_ZTD) in 2016–2017 are selected as the criteria for evaluating the accuracy of the R_GZTD model. In order to objectively verify the validity of the R_GZTD model, this paper introduces the GZTD model, GPT2w model, and UNB3m model to assesses the accuracy of four models under the same conditions. Figure 6 shows the distribution of selected IGS stations and radiosonde stations worldwide. The tropospheric delay can be estimated using the model based on the coordinates and time of the checkpoints of different data sources. The mean bias and RMS of the model are calculated by equation (8).

\[ \text{Bias} = \frac{1}{n} \sum_{i=1}^{n} \left( ZTD_{\text{model}}^i - ZTD_{\text{true}}^i \right) \]  

\[ \text{RMS} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( ZTD_{\text{model}}^i - ZTD_{\text{true}}^i \right)^2} \]  

In the formula, \( n \) is the number of stations, \( ZTD_{\text{model}}^i \) is the tropospheric delay of the station calculated by the model, and \( ZTD_{\text{true}}^i \) is the true tropospheric delay of the station.
In order to verify the validity and accuracy of the R_GZTD model, this paper calculates the annual mean bias and RMS of the four models based on the ZTD products of 327 IGS stations in 2016–2017. Table 2 shows the statistical results of bias and RMS for each tropospheric delay correction model. It can be seen from Table 2 that the accuracy of R_GZTD model (bias: 0.48 cm, RMS: 3.79 cm) is comparable to that of GPT2w model (bias: −0.23 cm, RMS: 3.56) and superior to that of GZTD model (bias: −0.24 cm, RMS: 4.04 cm) and UNB3m model (bias: 0.97 cm, RMS: 5.08 cm), manifesting that the tropospheric delay estimated by the R_GZTD model and the GPT2w model is closer to the true value. Besides, it is worth noting that the overall average bias of the R_GZTD model is positive, and the overall average bias of GZTD is negative, which may be caused by the height coefficient β, that is, when the height coefficient is less than the true value, the ZTD estimated by the model will be too small.

To further verify the stability of the R_GZTD model, Figure 7 summarizes the number of IGS stations within each error interval of each tropospheric delay model. It can be seen from Figure 7 that the deviations of the R_GZTD, GZTD, and GPT2w models are all concentrated at −2 to 2 cm, accounting for 81.35%, 76.82%, and 96.02%, respectively. The RMS is concentrated at 2–6 cm, accounting for 96.03%, 90.52%, and 96.33%, respectively, indicating that the R_GZTD, GZTD, and GPT2w models have good stability, and the stability of the R_GZTD model is slightly worse than the GPT2w model but better than the GZTD model. The deviation of UNB3m model is concentrated at −4 to 4 cm, and the RMS is concentrated at 2–8 cm, which illustrates that the stability of UNB3m model is poor.

In order to analyze the accuracy of each model at different altitudes, 327 IGS stations around the world are arranged according to altitude, and bias and RMS of each model at different altitudes are counted. Table 3 shows the error statistics of each model at different altitudes, which displays that the accuracy of R_GZTD model in different elevation intervals is not much different from that of the GPT2w model, and the accuracy of R_GZTD model is better than that of GZTD model and UNB series model when the altitude is greater than zero, but the bias and RMS of the R_GZTD model are worse than that of GZTD model when altitude is less than zero. This may be due to some errors of the Gbeta model at stations with elevation lower than mean sea level. At the same time, the RMS of each model decreases as the station elevation increases. Compared to the GZTD model, it is worth noting that the bias and RMS of the R_GZTD model decreased by 24.4% and 8.5% in the 0–500 m range, by 51.5% and 14.6% in the 500–1,000 m range, and by 65.7% and 12.5% in the 1,000–2,000 m range, respectively. Above 2,000 m, the bias and RMS of the R_GZTD model decreased by 30.8% and 16.8%, respectively. As altitude ascents, the increasing percentage of RMS also raises, which is because the R_GZTD model takes into account the spatiotemporal variation of the altitude coefficient β. The higher the altitude, the greater the effect of altitude coefficient β on ZTD.

### 5.2.2. Error Statistics Based on ECMWF _ZTD_

The tropospheric delay solved by the ECMWF reanalysis products has high precision and can be used as the true value for verifying the accuracy of the tropospheric model. Table 4 shows the bias and RMS statistics for different model data with respect to the ECMWF ZTD data. It is worth mentioning that the average bias and RMS of the R_GZTD model are smaller than other models, showing that the estimated value of the R_GZTD model is close to the global ECMWF_ZTD data. The accuracy of the GZTD model is the second, and the UNB3m model has the worst accuracy. In addition, the accuracy of the GPT2w model is worse than that of the R_GZTD model and the GZTD model, which may be due to the different grid sizes and tropospheric delay calculation methods.

Figure 8 shows the global distribution of the bias and RMS of the R_GZTD model, the GZTD model, the GPT2w model, and the UNB3m model. It is

| Table 1 |
|-----------------------------------------------|
| Internal Error Statistics of R_GZTD Model (Unit: cm) |
| Bias | RMS |
| Max | 6.43 | 8.71 |
| Min | −9.74 | 1.21 |
| Mean | −0.15 | 3.22 |

| Table 2 |
|-----------------------------------------------|
| Error Statistics of Tropospheric Delay Models With Respect To IGS ZTD Products in 2016–2017 (Unit: cm) |
| Bias | RMS |
| R_GZTD | 0.48 | 3.79 |
| GZTD | −0.24 | 4.04 |
| GPT2w 5°×5° | −0.23 | 3.56 |
| UNB3m | 0.97 | 5.08 |
shown that the overall bias of $R_{GZTD}$ is small, and most of them are within 2 cm, which is closer to the true value than the GZTD model. From Figures 8a and 8b, we can see that the bias of the GZTD model is approach $-8$ cm in Antarctica and near the equator, while the bias of $R_{GZTD}$ in those regions is significantly smaller. In addition, the bias distribution of the $R_{GZTD}$ model is more uniform, and the overall bias is less than that of the GZTD model. The maximum bias of the $R_{GZTD}$ model appears in the center of the Pacific region and is smaller than that of the GZTD model. The improvement effect of the $R_{GZTD}$ model in the central Pacific region, the western region of South America, the southern region of North America, the central region of Africa, and the southern region of Asia is significantly better than that of the GZTD model.

From Figures 8e and 8f, it is found that the average RMS of the $R_{GZTD}$ model is smaller than that of the GZTD model on a global scale, especially in the region where the accuracy of the GZTD model is poor. And the RMS of the GZTD model is larger in the middle and low latitudes; the maximum value is 14.3 cm in the central Pacific, western South America, and southern Asia. The accuracy of the GZTD model in Antarctica is also poor, and the RMS is about 8 cm. In addition, the overall distribution of the $R_{GZTD}$ RMS is approximately symmetrical in the Northern and Southern Hemispheres, which means that the accuracy of the model is similar in the Southern and Northern Hemispheres. The $R_{GZTD}$ model is slightly worse in middle and low latitudes but better than the GZTD model. Both the $R_{GZTD}$ model and the GZTD model have poor correction accuracy in middle-low latitudes, which may owe to the fact that the tropospheric delay in the middle and low latitudes is greatly affected by the distribution of land and sea as well as temperature, resulting in poor-fitting effect.

In Figures 8c and 8g, the accuracy of the GPT2w model is zonally distributed in low latitudes, especially at the land-sea junction, which may be attribute to two factors, one is that the tropospheric delay changes drastically because of the influence of land-sea distribution and topography, resulting in a poor-fitting effect. The other is that the GPT2w model has a poor-fitting effect on meteorological parameters in low latitudes. Comparing the GPT2w model with the GZTD model, we can see that the overall accuracy of the GPT2w model is better than that of the GZTD model, especially in middle and high latitudes. Furthermore, the accuracy of GPT2w is slightly lower than that of the $R_{GZTD}$ model due to the different schemes for obtaining tropospheric delays and data sources.

As can be seen from Figure 8, the accuracy of UNB3m is the worst as a whole, which can be caused by the default global tropospheric delay of the UNB series model that is symmetrical in the Northern and Southern Hemispheres, while the Southern Hemisphere is mostly in the ocean. UNB3m has better accuracy in the

**Table 3**

| Altitude (m) | Station number | $R_{GZTD}$ Bias | $R_{GZTD}$ RMS | GZTD Bias | GZTD RMS | GPT2w Bias | GPT2w RMS | UNB3m Bias | UNB3m RMS |
|--------------|----------------|----------------|---------------|-----------|----------|------------|-----------|------------|-----------|
| <0           | 22             | 1.30           | 5.08          | 0.72      | 4.16     | -0.34      | 4.36      | 4.05       | 7.06      |
| 0–500        | 222            | 0.59           | 4.11          | -0.78     | 4.49     | -0.65      | 3.95      | 0.61       | 5.69      |
| 500–1,000    | 43             | 0.32           | 3.52          | -0.66     | 4.12     | -0.41      | 3.49      | 0.89       | 4.74      |
| 1,000–2,000  | 28             | 0.12           | 3.36          | -0.35     | 3.84     | -0.44      | 3.26      | 0.43       | 4.07      |
| >2,000       | 12             | -0.09          | 2.82          | -0.13     | 3.39     | 0.68       | 2.76      | -1.11      | 3.83      |
Northern Hemisphere than that in the Southern Hemisphere. From the left panel of Figure 8d, we can see that the model in the Southern Hemisphere has large deviation, demonstrating that the tropospheric delay in the Southern Hemisphere is smaller than that in the Northern Hemisphere, and the global tropospheric delay is not symmetrically distributed in the Northern and Southern Hemispheres. From Figure 8h, it can be seen that the average accuracy of the model in the Northern Hemisphere is about 5.5 cm, but the accuracy is lower than the average in the middle and low latitudes of the Northern Hemisphere, which may be due to the fact that the UNB model only considers the meteorological changes in North America.

Figure 9 depicts the accuracy of each model varies with the longitude in the Northern and Southern Hemispheres. Figure 9 exhibits that the accuracy of the R_GZTD model, and the GZTD model does not

| Model          | Bias | RMS  |
|----------------|------|------|
| R_GZTD         | 0.10 | 3.92 |
| GZTD           | -1.97| 4.68 |
| GPT2w 5°×5°   | -1.56| 5.86 |
| UNB3m          | 1.85 | 6.61 |

Figure 8. (a–h) Distribution of bias and RMS in R_GZTD/GZTD/GPT2w/UNB3m models.
change with the longitude, and the overall precision of the R_GZTD model is better than that of the GZTD model, which further proves that the new model has better stability.

By comparison, we figure out that the UNB3m model has better stability in the Northern Hemisphere than that in the Southern Hemisphere. It can be seen from Figures 9c and 9d that the UNB3m model has a poor accuracy between 60°W and 60°E, which may be affected by the temperature and land-sea distribution as well as the defects of the models themselves. Additionally, the accuracy of the GPT2w model is greatly affected by longitude in the Southern Hemisphere. Combined with Figure 8, the accuracy of the GPT2w model in low latitudes is poor, which may be caused by the severe variation of tropospheric delay in low latitudes and the overfitting of meteorological parameters by GPT2w model.

5.2.3. Error Statistics Based on RAD_ZTD

In the first two sections, the accuracy of the four models is evaluated and analyzed, which shows the superiority of the R_GZTD model. In order to further verify the accuracy and reliability of the R_GZTD model, the above five models are evaluated and analyzed based on 714 global radiosonde stations data from 2016 to 2017. Table 5 shows the statistical results of bias and RMS for each model with respect to radiosonde ZTD. As can be seen from Table 5, the accuracy of the R_GZTD model (bias: 1.25 cm, RMS: 5.35 cm) is better than other models under the same conditions. Simultaneously, it is found that the accuracy of each model is worse than the accuracy when using IGS data as the benchmark. On the one hand, it is caused by the systematic deviation between radiosonde data and IGS data. On the other hand, it is affected by the number of stations and the distribution of the stations; it can be seen from Figure 6 that the radiosonde station is mainly distributed in the middle and low latitudes.

The preceding sections validate the superiority and reliability of the R_GZTD model on a global scale. To further verify the applicability of the model in different regions, the accuracy of the above model in different regions is calculated in this section, as shown in Table 6. It shows that the bias and RMS of the R_GZTD model are smaller than those of the other models in all continents, which indicates that the R_GZTD model has good regional applicability and can greatly improve the correction effect of the regional troposphere. The accuracy of the GZTD model and the GPT2w model is comparable in

| Model        | Bias (cm) | RMS (cm) |
|--------------|-----------|----------|
| R_GZTD       | 1.25      | 5.35     |
| GZTD         | 3.17      | 6.26     |
| GPT2w 5° × 5°| 2.31      | 5.87     |
| UNB3m        | 2.42      | 6.56     |

Figure 9. (a–d) The variation of each model’s accuracy with the longitude in the Northern and Southern Hemispheres
each region, indicating that the two models have limitations in the region. The UNB3m model has the highest accuracy in the North American region, while the accuracy in other regions is poor, further illustrating the limitations of the UNB series model in other regions, especially in the Southern Hemisphere, which is related to the use of North American meteorological data for the UNB series of models.

6. Conclusions

Aiming at the limitation of the altitude coefficient $\beta$ of the GZTD model, this paper analyzes the spatiotemporal variation characteristics of the zenith delay with altitude coefficient by using the ECMWF reanalysis meteorological data from 2011 to 2015 and uses trigonometric function and spherical harmonics function to establish global Gbeta model. It has been verified that the Gbeta model can well reflect the spatiotemporal distribution characteristics of the global altitude coefficient $\beta$. Then, this paper uses the Gbeta model to establish a global nonmeteorological tropospheric delay model R_GZTD. The internal and external accuracy of the R_GZTD model is verified by different data source and compared with the GZTD model, UNB3 model, UNB3m model, and GPT2w model. The conclusions are as follows:

1. The global nonmeteorological model R_GZTD based on Gbeta model is not only simple in modeling and concise in parameters but also effective in reflecting the spatiotemporal characteristics of global tropospheric delay.
2. The product data of the global IGS station are used for external accuracy verification. It is verified that the accuracy of the R_GZTD model (bias: 0.48 cm, RMS: 3.79 cm) is comparable to that of the GPT2w model, which is superior to the GZTD model, UNB3 model, and UNB3m model under the same conditions. The feasibility and stability of the model were verified.
3. The accuracy of the R_GZTD model under ECMWF ZTD and radiosonde station data is (bias:0.10 cm, RMS:3.92 cm) and (bias:1.25 cm, RMS:5.35 cm), respectively. Among these models, the R_GZTD model is the optimal model whether on a global scale or in the region, which verifies the feasibility and stability of the model.
4. In the discussion of the model accuracy with the altitude variation characteristics, it is found that the R_GZTD model has an accuracy ratio of more than 12% than the GZTD model in the interval where the elevation is greater than zero. With the increase of the station elevation, the improvement effect of the R_GZTD model is better, which is related to the refined altitude coefficient $\beta$.

In the process of validating the accuracy of the model, it is found that the larger tropospheric delay in the middle and low latitudes, especially in the low latitudes of the Southern Hemisphere, greatly affects the accuracy of the model. Meanwhile, it is found that the accuracy of each model is different under different data sources, so how to eliminate the systematic bias between different data and establish a high-precision tropospheric delay model in the middle and low latitudes still needs further study.

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