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ORIGINAL ARTICLE

New versions of the BDS/GNSS zenith tropospheric delay model IGGtrop

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Abstract The initial IGGtrop model proposed for Chinese BDS (BeiDou System) is not very suitable for BDS/GNSS research and application due to its large data volume while it shows a global mean accuracy of 4 cm. New versions of the global zenith tropospheric delay (ZTD) model IGGtrop are developed through further investigation on the spatial and temporal characteristics of global ZTD. From global GNSS ZTD observations and weather reanalysis data, new ZTD characteristics are found and discussed in this study including: small and inconsistent seasonal variation in ZTD between 10°S and 10°N and stable seasonal variation outside; weak zonal variation in ZTD at higher latitudes (north of 60°N and south of 40°S) and at heights above 6 km, etc. Based on these analyses, new versions of IGGtrop, named IGGtrop_r_i ($i = 1, 2, 3$), are established through employing corresponding strategies: using a simple algorithm for equatorial ZTD; generating an adaptive spatial grid with lower resolutions in regions where ZTD varies little; and creating a method for optimized storage of model parameters. Thus, the IGGtrop_r_i ($i = 1, 2, 3$) models require much less parameters than the IGGtrop model, nearly 3.1–21.2 % of that for the IGGtrop model. The three new versions are validated by five years of GNSS-derived ZTDs at 125 IGS sites, and it shows that: IGGtrop_r_1 demonstrates the highest ZTD correction performance, similar to IGGtrop; IGGtrop_r_3 requires the least model parameters; IGGtrop_r_2 is moderate in both zenith delay prediction performance and number of model parameters. For the IGGtrop_r_3 model, the biases at those IGS sites are between −6.4 and 4.3 cm with a mean value of −0.8 cm and RMS errors are between 2.1 and 8.5 cm with a mean value of 4.0 cm. Different BDS and other GNSS users can choose a suitable model according to their application and research requirements.

Keywords Zenith tropospheric delay · IGGtrop model · EGNOS model · UNB model · BDS · GNSS

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1 Introduction

Tropospheric delay is one of the most significant error sources in satellite navigation, and its effect should be properly handled in high-precision GNSS applications (Gao and Chen 2004; Xu 2007). On the other hand, knowledge of the tropospheric delay is essential to determine the precipitable water vapor in the atmosphere (Duan et al. 1996; Liou et al. 2000, 2001). Typically, an empirical model is applied to mitigate the tropospheric delay and therewith to enhance the positioning accuracy. So far, many useful tropospheric delay models have been built including: traditional models such as the Hopfield (1971), Saastamoinen (1972); the UNB models (UNB1 through UNB4) (Collins and Langley 1997, 1998; Leandro et al. 2006, 2008), which are suitable for real-time and kinematic users; and the EGNOS model (Penna et al. 2001; Uemo et al. 2001), which is the WAAS version of UNB3. As latitude-only based models, UNB3 and EGNOS models often cause great prediction biases in some areas where ZTD values deviate significantly from the zonal average (Li et al. 2012); and a few tropospheric delay models which have employed a two-dimensional grid for the regional or global applications to obtain more homogenous performance for different areas (Schüler et al. 2001; Krueger et al. 2004; Leandro et al. 2009; Song et al. 2011; Lagler et al. 2013; Yao et al. 2013; Schüler 2014). Recently, Möller et al. (2013) have explored the potential of improving tropospheric models through considering the tropospheric errors in extreme conditions, derived from NWM (Numerical Weather Model) data.

Based on the detailed time–space ZTD characteristics derived from GNSS ZTD measurements and NWM data, Li et al. (2012) have established a global three-dimensional grid-based ZTD model known as IGGtrop. Using a 3D grid (latitude × longitude × height), the IGGtrop model is able to model the zonal (E–W) as well as the meridional (N–S) variation of ZTD. Hence, it shows better reliability and consistent correction performances around the globe, with a cm-level accuracy in almost every region. The use of vertical grid has also resulted in apparent accuracy improvement for higher elevations, compared to the EGNOS and UNB3m models (Li et al. 2012). In addition, since it was created based on the gridded NCEP (National Centers for Environmental Prediction) reanalysis II data, the computation of the IGGtrop model parameters is relatively simple. Hence, IGGtrop may provide a reference model for the Chinese Beidou Navigation System and other GNSS.

Nevertheless, for the IGGtrop model, two main issues remain: (i) comparatively complicated algorithm in the equatorial region, and (ii) a large number of parameters contained in a 3D grid file, which requires extra storage spaces for GNSS receivers. As known, the second problem also exits for some of the 2D grid-based tropospheric models, especially those with high spatial resolutions (Krueger et al. 2004). Therefore, the IGGtrop model needs further improvement to make it more convenient in use. Based on further analysis on ZTD features, this paper aims to build new versions of the IGGtrop models with consistent correction accuracy, by improving the following aspects: (i) simplifying the model algorithm for the equatorial regions, (ii) employing a coarser but more efficient model grid, and (iii) optimizing the storage of the model parameters.

2 IGGtrop global zenith tropospheric delay model

In the establishment of IGGtrop model, global ZTDs are obtained from GNSS ZTD time series of IGS (International GNSS Service) sites (Dow et al. 2009) and NCEP reanalysis II data (Kanamitsu et al. 2002). The following characteristics have been considered:

1. Distinct seasonal cycle of ZTD: In mid and high latitudes, the temporal ZTD variation is dominated by an annual component with generally similar temporal phases for different areas, while it exhibits comparable annual and semi-annual components for the equatorial sites. To tackle such temporal behaviors, IGGtrop employed two methods: (i) for latitudes higher than 15°, the ZTD is modeled by a 1-year period cosine function including two parameters—the annual mean ZTD and amplitude; for regions between 15°S and 15°N, the ZTD is modeled by the summation of 1- and 0.5-year period cosine functions including five parameters—the annual mean ZTD, the amplitude and phase of the annual ZTD component, and the amplitude and phase of the semi-annual ZTD component;
2. Complicated spatial pattern of global ZTD: It is mainly associated with the latitude (solar radiation), while for some regions the situation becomes more complex because of the significant zonal ZTD variations. ZTD variations are tightly related to the global land–sea distributions as well as local topography, and difficult to model. IGGtrop simply employed a 3D grid to simulate the spatial distribution of global ZTD, wherein the zonal distribution is contained. Each grid corresponds to a group of ZTD seasonal parameters mentioned above.

The IGGtrop model was built by few steps: first, design a global 3D grid; then, calculate ZTD time series by its definition from NCEP reanalysis II data and interpolate those ZTD results to the defined spatial grid; and finally, match ZTD time series with a cosine function (mid and high altitudes) or the sum of two cosine functions (equator) to obtain the ZTD seasonal parameters and establish the grid parameter file. The IGGtrop model is able to conveniently provide ZTD correction values without real-time meteorological measurements. More detailed descriptions about model building and getting ZTD estimations from this model are given in Li et al. (2012).

The IGGtrop model has been developed based on a set of 4-year (2006.1–2009.12) NCEP reanalysis II daily average data with a horizontal resolution of 2.5° lat-long and 17 vertical levels from 1,000 to 10 hPa. The 3D grid used in the IGGtrop model is 2.5° × 2.5° × 1 km, which is identical to the NCEP data in horizontal resolution. The GNSS-derived ZTD reference data from 125 global IGS sites during 2001.1–2005.12 were used to validate the IGGtrop model. For each site, mean bias and RMS (root mean square) errors of the IGGtrop model during the entire period were calculated and analyzed. It was found that the global mean bias and RMS error of the IGGtrop model are about −0.8 and 4.0 cm, respectively. The IGGtrop model generally reflects real atmospheric conditions in different regions for its RMS errors only between 2.0 and 8.0 cm for the 125 globally distributed sites, and shows relatively high precision for all the

IGS sites in China region, especially for Lhas which locates at a height of about 3,625 m. It gives significantly better performance than the EGNOS model for the Southern Hemisphere because of the fact that IGGtrop model parameters are derived from the global weather data, while EGNOS only considered the Northern Hemisphere atmosphere. Besides, the IGGtrop model exhibits consistent correction errors at different heights (Li et al. 2012).

3 Strategies and methods for new versions of IGGtrop model

Although the IGGtrop model has achieved relatively high and consistent accuracy, due to its $2.5° \times 2.5° \times 1$ km spatial resolution, it preserves a great number of parameters to cover the global atmosphere, while those parameters require large storage space, which could limit model applications. Therefore, it is necessary to modify the IGGtrop model to meet the requirements of bigger range of users and situations. After further analyses on global ZTD characteristics, we have found that it is possible to modify IGGtrop (i.e., reduce model parameters) while preserving its performance by a better illustration of the ZTD behavior. Similar to our previous study, the study on creating new versions of IGGtrop is also conducted on the basis of the GNSS ZTD measurements from 125 global IGS sites (Dow et al. 2009) and NCEP reanalysis data (Kanamitsu et al. 2002). The GNSS ZTD reference data during 2001–2005 with a temporal resolution of 2 h from those sites are used to validate the new versions of IGGtrop. The locations of all the IGS sites used are plotted as a set of tiny triangles in Fig. 1. The main methods and their subsequent effects on model performance are discussed and demonstrated below.

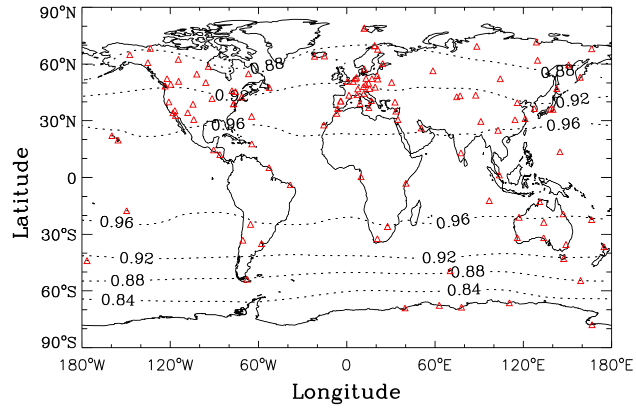

Fig. 1 Spatial distribution of annual mean ZTD value (m) at 7 km height. The *triangles* on the world map represent the locations of the 125 IGS sites used in this study

example, four out of the five IGS sites located within 10°S–10°N show values varying between 0.9 and 2.7 cm, smaller than the corresponding results in the mid-latitudes (about 5 cm on average). The other site Fort (3.88°S, 38.4°W) shows ZTD variation amplitude around 5 cm, but with no obvious semi-annual component. In addition, the seasonal cycles of ZTD at the five sites demonstrate inconsistent trends. It is also revealed that between 10° and 15° latitude on both hemispheres, the temporal characteristics of ZTD are similar to those in the extratropical regions, exhibiting stable and consistent seasonal variation. The IGS sites are relatively sparse in the low latitudes, thus we conduct a similar analysis from NCEP data for this region and it exhibits basically consistent results.

According to the above discussions, a single model parameter is used instead of the original five parameters in 10°S–10°N. Then, the algorithm of IGGtrop is modified as:

$$\mathrm{ZTD}(\varphi,\lambda,h,t)=\begin{cases}\mathrm{meanZTD}(\varphi,\lambda,h)-\mathrm{ampZTD}(\varphi,\lambda,h)\cdot\cos\left(\frac{2\pi}{365.25}(t-D)\right), & |\varphi|\geq 10°\\ \mathrm{meanZTD}(\varphi,\lambda,h), & |\varphi|<10°\end{cases} \quad (1)$$

3.1 Simplification of model algorithm in the equatorial regions

As mentioned above, the IGGtrop model has employed a comparatively more complicated formula to account for the temporal variation of the equatorial ZTD (15°S–15°N), which is the synthesis of two cosine functions with five seasonal parameters. However, it turns out that, for 10°S–10°N, such a five-parameter model exhibits basically no significant accuracy improvement as compared to the model using only the annual mean parameter (representing no seasonal variation). This is probably associated with the relatively weak amplitude of ZTD seasonal variation over this region. For

where (φ, λ, h) is the latitude–longitude–height grid (φ: latitude, λ: longitude, h: height above mean sea level); t is the day of year; meanZTD and ampZTD are the annual mean and seasonal amplitude of ZTD in mm, respectively; D is the phase (corresponding to the day of year when ZTD reaches its minimum), 28 for northern latitudes and 211 for southern latitudes. Equation (1) reduces largely the number of model parameters in the tropics, and also simplifies the computation of ZTD.

Compared to the original model, the modified IGGtrop model using Eq. (1) shows no obvious change in its performance over the equatorial regions. Between 10°S and 10°N, RMS errors are only increased by about −1 to 3 mm for most sites with an exception found at site Fort (1 cm increase in RMS error). Thus, it seems that considering the seasonal variation (annual and semi-annual variation) of equatorial ZTD has limited improvement in model performance. On the contrary, it has resulted in extra complexity for model (considering 5 parameters vs. 1 parameter). Since the equatorial ZTD might mainly depend on local climate conditions, its complicated temporal variation may be better modeled after some thorough investigations using more atmospheric data.

3.2 Vertical grid with uneven resolution

In the IGGtrop model, the vertical variation of ZTD is represented by a regular vertical grid with a spacing of 1 km, extending from 0 up to 25 km over the earth surface. However, ZTD does not decrease linearly with increasing elevation, and it exhibits stronger variation with respect to height in lower atmosphere than in higher atmosphere. The vertical resolution of NCEP data that was used to establish IGGtrop varies normally between 0.5 and 1.2 km below 6 km and between 1.5 and 3 km above 6 km, according to its fixed pressure levels. In view of this, we redesign the vertical grid of IGGtrop with its spacing being increased to 2 km for regions above 6 km. Hence, the modified vertical grid with 16 levels (named Hlevel) is [0, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24] km. We have investigated the differences in ZTD estimations of the IGGtrop model using the raw vertical grid and the new vertical grid. It is found that at those omitted vertical levels, i.e., 7, 9, 11, 13, 15, 17, 19, 21, and 23 km, the differences are always within 1 mm. Thus, such modification in vertical grid basically causes negligible change in the ZTD estimation of the IGGtrop model.

3.3 Horizontal grid with adaptive resolution

It is found that the horizontal grid (with the same resolution with NCEP data) used by IGGtrop may contain a lot of redundant information for ZTD modeling. In fact, the horizontal distribution of global ZTD can be well dealt by a coarser grid instead of the one used in IGGtrop. Building a more efficient horizontal grid for IGGtrop is crucial for model improvement and is expected to reduce the number of model parameters more significantly than the other methods. Based on a further study, we have found several strategies in this aspect as detailed in the following.

(a) 1D horizontal grid for regions above 6 km:
As mentioned in the previous section, apart from its meridional structure, global ZTD also shows obvious zonal variation because of the climate difference caused by uneven distributions of land, sea, and mountains. Hence, in IGGtrop, a latitude–longitude grid has been employed for ZTD prediction in different regions. However, such geographical impact on climate tends to decay with increasing height, and it is noted that statistics derived from NCEP data exhibit fundamentally little zonal difference in ZTD for regions above 6 km. The spatial distribution of annual mean ZTD at 7 km height is shown in Fig. 1. This indicates that a latitude-based grid will be adequate in higher atmosphere.

(b) Low resolution horizontal grid for areas of high latitude:
Figure 2 of Li et al. (2012) gives the horizontal structure of global ZTD at mean sea level, and it shows that ZTD demonstrates obviously smaller zonal difference in higher latitudes than in lower latitude. In addition, the circle of latitude becomes shorter while latitude increases. Thus, a new horizontal grid with larger spacing in longitude or even a latitude-based grid is suitable for high-latitude regions.

(c) A coarser horizontal grid for the globe:
For the IGGtrop model, a more efficient global horizontal grid can be also obtained simply by changing the original grid spacing and checking its influence on model result. Such modifications include lowering the original resolution in longitude or in the two horizontal directions around the globe, and so on.

Based on the above discussions, four specific methods are determined to create a new horizontal grid: (i) a latitude-(only) based grid with a spacing of 2.5° for regions above 6 km; (ii) a latitude-(only) based grid with a spacing of 2.5° for latitudes north of 60°N and south of 40°S; (iii) a global latitude–longitude grid with 2.5° × 5.0° resolution; (iv) a global latitude–longitude grid with 5.0° × 5.0° resolution. These four methods about horizontal grid, i, ii, iii, and iv, will be labeled as P1, P2, P3, and P4 in the following discussion, respectively. When a 2D horizontal grid is transformed to a 1D grid, the original model parameters for the same latitude are averaged to get the new parameter values. Those four methods can be applied separately or combined together, which will lead to a more significant reduction in model parameters.

The effect of the above described modification in horizontal grid on ZTD prediction performance is demonstrated by a detailed comparison of bias and RMS errors between the modified models and IGGtrop. As shown previously, the modifications in vertical grid and model algorithm for the equatorial regions both cause little change in model performance. Hence, for simplifying our analysis, some methods are applied together. To facilitate discussion, each method is assigned a short name: ‘E’ refers to the simple algorithm for the equatorial regions; ‘H’ refers to the modification in vertical grid; and ‘P1’, ‘P2’, ‘P3’, and ‘P4’ have been mentioned earlier. The combination of different methods is represented

Table 1 General statistics of zenith tropospheric delay estimation errors for the IGGtrop model and its new versions during the period 2001–2005

	IGGtrop	E+H+P1	E+H+P1+P2	E+H+P1+P3	E+H+P1+P4	E+H+P1+P2+P3	E+H+P1+P2+P4
Bias	−0.8	−0.8	−0.8	−0.9	−0.9	−0.8	−0.8
	[−5.8, 2.7]	[−5.8, 2.7]	[−5.8, 4.3]	[−5.8, 2.7]	[−6.4, 2.8]	[−5.8, 4.3]	[−6.4, 4.3]
RMS	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	[2.1, 7.9]	[2.1, 8.0]	[2.1, 8.0]	[2.1, 8.0]	[2.1, 8.5]	[2.1, 8.0]	[2.1, 8.5]

Values in brackets show the minima and maxima of both bias and RMS values for all 125 IGS sites (all values in cm)

by '+' symbol. Since method 'P1' only relates to the model structure above 6 km and it does not influence the correction effectiveness of IGGtrop for all the IGS sites used in this study which are all situated below 4 km, the following discussion will be mainly focused on the other three methods in terms of horizontal grid, i.e., P2 through P4 and their combinations.

Table 1 shows the general statistical results of ZTD prediction performance for six new versions of IGGtrop models that are established through modifying original IGGtrop using the corresponding combined methods listed in the table. Those new models are similar with IGGtrop on their global mean performance, while some new models demonstrate slight extensions in the range of bias and RMS error values for the 125 global IGS sites. For example, for the model using E+H+P1+P2, the global maximum bias is increased from 2.7 to 4.3 cm. This is because of the additional error found in south polar region which is due to the latitude-(only) based horizontal grid used for this region in the model. The land–sea distribution in the Antarctic leads to stronger ZTD spatial variation than in the Arctic. In this study, there are 16 IGS sites north of 60°N, and 10 sites south of 40°S. For the model using E+H+P1+P4, the global minimum bias is decreased from −5.8 to −6.4 cm and the maximum RMS error is increased from 7.9 to 8.5 cm. Combined effects are also seen in Table 1 when different modifications on horizontal grid—P2, P3, and P4—are applied together.

To give a more detailed result of biases and RMS errors for the 125 sites, Fig. 2 shows the histograms of bias and RMS values for IGGtrop and three of its new versions, which are represented by different colors and line styles. It can be noted that new models show basically similar error distributions with IGGtrop, especially for RMS error. Since most of the bias values are within ±3 cm and RMS values within 8 cm, the three new models have generally consistent ZTD correction performance in different regions. Figure 3 gives the statistical result of ZTD estimation errors from IGGtrop and its new versions for different height bands. In Fig. 3, it is found that the coarser horizontal grid used in the new models leads to slight accuracy degradation at elevations above 1.0 km. Figure 4 shows the differences in ZTD prediction errors between IGGtrop and four of its new versions for each IGS site. For most sites, the differences in RMS errors are

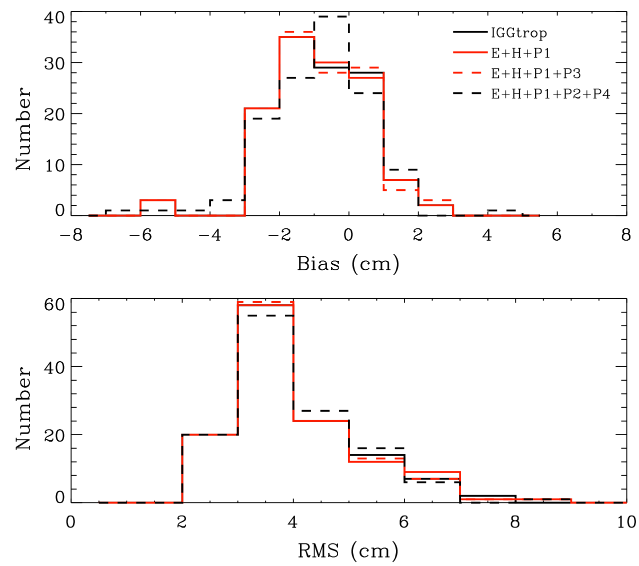

Fig. 2 Histograms of zenith tropospheric delay estimation errors for the IGGtrop model and three new versions

within 1 cm, while the differences in biases show slightly larger values. The model obtained using E+H+P1 method exhibits almost negligible difference in ZTD corrections as compared to IGGtrop outside the equatorial zone. Difference in RMS error as large as about 2 cm is only found in the Antarctic, which is attributed to ignoring the zonal ZTD variation in this region. Since there are fewer sites located in higher elevation or latitudes, more statistics are needed in the future.

Figure 5 shows biases and RMS errors of IGGtrop and its new versions for the six IGS sites in China. Compared to IGGtrop, four of new models show lower accuracy at sites Kunm and Urum, where the RMS errors are increased by a few millimeters. This is consistent with the previous analysis that increasing the horizontal spacing of grid leads to accuracy degradation at higher elevations because these two sites are both located above 1.0 km.

3.4 Efficient storage of model parameters

For IGGtrop, all the model parameters have been preserved in a grid parameter file. In this file, parameters such as annual

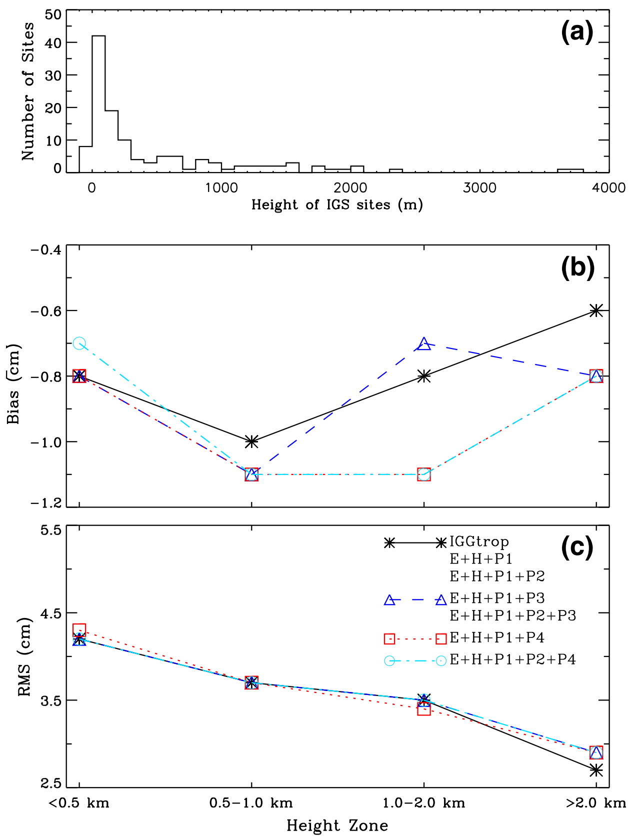

Fig. 3 **a** Histogram of the heights of the 125 IGS sites used in this study; **b**, **c** the mean bias and RMS errors in four height bands for the IGGtrop model and its new versions, respectively. From the lowest band to the highest one, there are 86, 18, 16, and 5 IGS sites, respectively

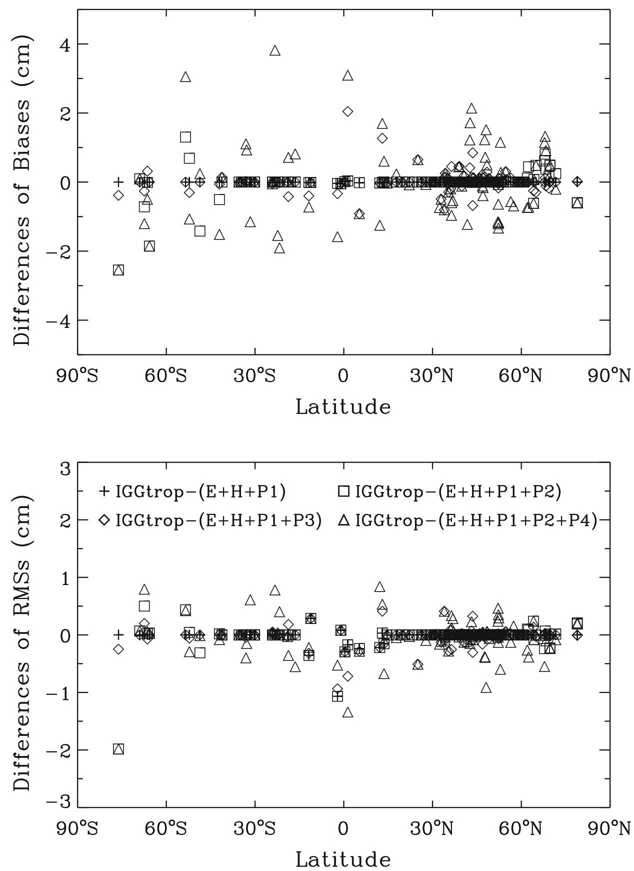

Fig. 4 Differences in bias and RMS values between the IGGtrop model and four of its new versions for each IGS site

mean ZTD, annual and semi-annual amplitudes are stored as float point data, and each parameter occupies 4 bytes of receiver's memory. To save the storage space, we now attempt to convert the original data type of those three parameters into integer data, which occupy only 2 bytes. It is simply achieved by increasing the three parameters (unit:mm) by a factor of ten and then rounding the results. Since the global ZTDs derived from NCEP data show annual means within 2,700 mm and seasonal amplitudes less than 300 mm, 2-byte integers (ranging in value from −32,768 through 32,767) are enough to accommodate these parameters. For each of the three parameters mentioned above, data type conversion can cause a truncation error of about 0.05 mm, and together they will lead to a ZTD error of 0.15 mm at most, according to the ZTD algorithm of the IGGtrop model (Li et al. 2012). This error is much lower than the average RMS error of the IGGtrop model, as well as the uncertainty of GNSS-derived ZTD. Analysis also reveals that the models using new parameter storage method produce the same results with the corresponding ones with float-type parameters.

4 The IGGtrop_r_i ($i = 1, 2, 3$) models

After various modification methods are analyzed in Sect. 3, we finally recommend three new versions of IGGtrop model for BDS/GNSS users, which are, respectively, named IGGtrop_r_1, IGGtrop_r_2, and IGGtrop_r_3. They are established by modifying IGGtrop using combined methods E+H+P1, E+H+P1+P3, and E+H+P1+P2+P4, respectively, together with the new storage method for grid parameters.

Here, we give a brief description on the procedures of these three new versions, i.e., the IGGtrop_r_i ($i = 1, 2, 3$) models. First, define a 3D grid with a horizontal resolution of 2.5° × 2.5° and 16 vertical levels (Hlevel). Then, built the IGGtrop model based on the defined grid from multi-year NWM data (e.g., NCEP reanalysis II data between 2006 and 2009). Finally, derive grid parameters for the IGGtrop_r_i ($i = 1, 2, 3$) models according to the corresponding methods mentioned above, respectively, and convert all the model parameters into integers and form the final grid parameter files for the three models.

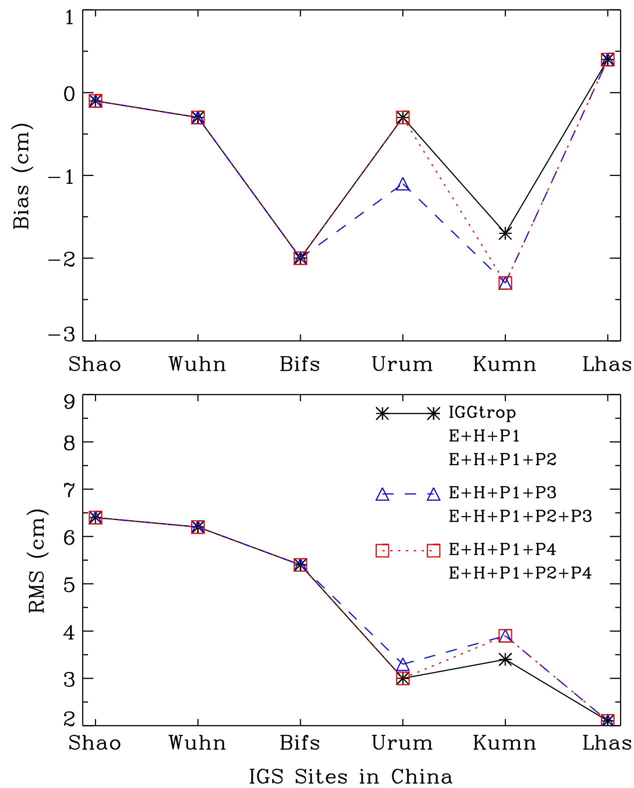

Fig. 5 Statistics of zenith tropospheric delay estimation errors for the IGGtrop model and its new versions at six IGS sites in China. The coordinates of the six sites are listed as follows: Shao (31.1°N, 121.2°E, 22.0m), Wuhn (30.5°N, 114.4°E, 26.3m), Bjfs (39.6°N, 115.9°E, 87.4m), Urum (43.6°N, 87.6°E, 856.1m), Kumn (25.0°N, 102.8°E, 2023.0m), Lhas (29.7°N, 91.1°E, 3624.7m)

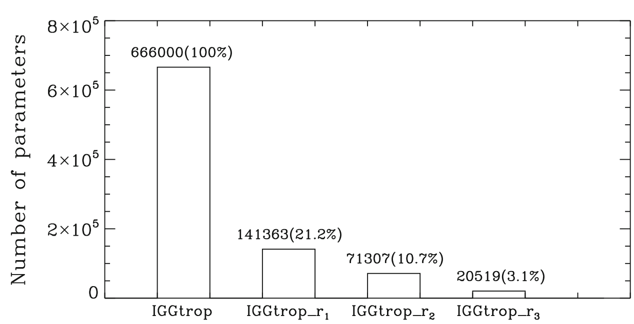

Fig. 6 Comparison of numbers of parameters between the IGGtrop and IGGtrop_r_i ($i = 1, 2, 3$) models. *Numbers in the bracket* represent the ratios of new versions to the raw IGGtrop model

To illustrate the effect of those modification methods on model parameters, Fig. 6 gives a comparison of total numbers of parameters between IGGtrop and IGGtrop_r_i ($i = 1, 2, 3$). There are noticeable reductions in the number of parameters, especially for IGGtrop_r_3. Overall speaking, all the three new versions are capable of maintaining the general application performance of IGGtrop, but they also show different characteristics: for most places, IGGtrop_r_1 provides nearly identical ZTD corrections compared to the original IGGtrop model, with a parameter set about one-fifth the size of that of IGGtrop; IGGtrop_r_2 shows slightly higher errors at higher elevations compared to IGGtrop, with a parameter set about one-tenth the size of that of IGGtrop; and IGGtrop_r_3 is the most efficient model with a parameter set only 3 % the size of that of IGGtrop and has lower precision for some parts of equatorial and south polar regions compared to IGGtrop. The grid parameter files of the three recommend models occupy 276, 139, and 40 KB of memory, respectively. Their features ensure that the IGGtrop_r_i ($i = 1, 2, 3$) models could meet different levels of application requirements.

5 Conclusions

A comprehensive study is conducted on how to develop a series of new global ZTD models IGGtrop_r_i ($i = 1, 2, 3$) which are more efficient and convenient for BDS/GNSS users. It is accomplished by applying a simpler algorithm for the estimation of equatorial ZTD, an adaptive spatial grid, and an improved storage method for model grid parameters.

The primary strategy is to develop an efficient spatial grid with optimized irregular resolutions, which are determined by regional spatial ZTD variation in different areas. Analyses indicate that: ignoring the zonal variation of ZTD in high latitudes only leads to larger prediction errors in the Antarctic; doubling the spacing of horizontal grid does not change the general precision, while it lowers the model accuracy at higher elevation sites and slightly increases the range of global errors.

Three new versions of IGGtrop model, called IGGtrop_r_1, IGGtrop_r_2, and IGGtrop_r_3, based on different combinations of modification methods, have been recommended for BDS/GNSS applications. They are able to provide similar ZTD prediction results compared to IGGtrop with much fewer model parameters, about 21.2, 10.7, and 3.1 % of IGGtrop, respectively. IGGtrop_r_1 demonstrates performance very close to the level of the original IGGtrop except for some places near the equator, thus it can be applied instead of IGGtrop for GNSS users outside those regions. IGGtrop_r_2 is characterized by moderate performance and moderate number of model parameters. From IGGtrop_r_1 to IGGtrop_r_3, the global mean ZTD errors have little change, while the ranges of biases and RMS errors both show slight increase. The global mean bias and RMS error for IGGtrop_r_3 are about −0.8 and 4.0 cm, respectively. And the corresponding biases for different regions are between −6.4 and 4.3 cm, and RMS errors are between 2.1 and 8.5 cm.

The grid parameter files of the IGGtrop_r_i ($i = 1, 2, 3$) models, which store model parameters in integer type, take up memory space of 276, 139, and 40 KB, respectively. BDS/GNSS users are provided multiple options to choose the most suitable model of IGGtrop_r_i ($i = 1, 2, 3$) according to their demands. After the improvements in this research, the IGGtrop and its new versions together are expected to be applied more friendly and extensively in Chinese BDS and other GNSS. In addition, most methods proposed in this study to improve the ZTD estimation efficiency of the IGGtrop model are based on further knowledge of ZTD behavior, therefore we believe that they might be also useful for other similar grid-based tropospheric models.

The future work will deal with the validation of the IGGtrop and IGGtrop_r_i ($i = 1, 2, 3$) models for higher regions, i.e., above 4 km, through airborne experiment or other atmospheric observations. Since IGS sites usually locate on the Earth's surface, such statistics are not available in this study.

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