Development of time-varying global gridded Ts-Tm model for precise GPS-PWV retrieval

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Abstract: Water-vapor-weighted mean temperature, T_m, is the key variable to estimate mapping factor between GPS zenith wet delay (ZWD) and precipitable water vapor (PWV). In near real-time GPS-PWV retrieving, estimating T_m from surface air temperature T_s is a widely used method because of its high temporal resolution and a fair degree of accuracy. Based on the T_m estimates and the extracted T_s parameters at each reanalysis grid node of ERA-Interim data, we analyzed the relationship between Tm and Ts without smoothing of data. The analysis demonstrates that T_s–T_m relationship has significant spatial and temporal variations. Then static and time-varying global gridded T_s–T_m equations were established and evaluated by comparisons with radiosonde data at 758 radiosonde stations in the Integrated Global Radiosonde Archive (IGRA). Results show that our global gridded T_s–T_m equations have prominent advantages over other globally applied models. Large biases of Bevis equation or latitude-related linear model at considerable stations are removed in gridded T_s–T_m estimating models. Multiple statistical tests at 5% significance levels show that time-varying global gridded model is superior to other T_m models at 60.15% radiosonde stations, while the second-best model, GPT2w model, is superior at only 12.7% sites. No model is significantly better at 6.20% sites. GPS-PWV retrievals using different T_m estimates were compared at 74 IGS stations. At most sites, the relative differences of GPS-PWVs are within 1% with the application of time-varying global gridded T_s–T_m equations. Such results are superior to other T_m estimation models. The differences between GPS-PWVs and radiosonde PWVs are influenced by other comprehensive factors instead of a single T_m parameter. However, evident improvements still exist at particular site by using more precise T_s–T_m equations. PWV errors could decrease by more than 30% during wetter seasons.

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1. Introduction

Water vapor is an important trace gas and one of the most variable components in the troposphere. Water vapor's transport, concentration, and phase transition directly involve in atmospheric radiation and the hydrological cycle, leading to its key role in many climate changes and weather processes (Song et al., 2016; Mahoney et al., 2016; Adler et al., 2016). It is always a challenge to measure water vapor content accurately and timely due to its small amount and high spatial-temporal variability. For decades, several methods have been studied , such as radio sounding, water vapor radiometer, sun photometers, GPS and others(Ciesielski et al., 2010; Perez-Ramirez et al., 2014; Li et al., 2016; Campmany et al., 2010; Liu et al., 2013). Compared with traditional water vapor observations, ground-based GPS water vapor measurement has advantages, for example, high accuracy, high spatial-temporal resolution, all-weather availability, and low-cost (Pacione and Vespe, 2008; Haase et al., 2003; Lee et al., 2010; Means, 2013;Lu et al., 2015). Therefore, ground-based GPS water vapor products, mainly including precipitable water vapor(PWV) and slant water vapor(SWV), are widely used in many fields such as real-time vapor monitoring(Karabatic et al., 2011), weather and climate research(Van Baelen and Penide, 2009; Adams et al., 2017), numerical weather prediction (NWP) (Rohm et al., 2014), and so on. However, besides GPS observations, it requires some other kinds of meteorological elements to sense PWV/SWV at each GPS station remotely. Saastamonien model is extensively adopted to compute zenith hydrostatic delay (ZHD), and surface pressure P_s is essential in the model equation (Saastamoinen, 1972). Then zenith wet delay (ZWD) is generated by deducting ZHD from zenith total delay (ZTD)，and ZTD can be directly estimated from precise GPS data processing. Finally, a conversion factor Π, which is used to map ZWD onto PWV, is determined by water-vapor-weighted mean temperature T_m over a GPS station. Mapping function from ZWD to PWV is expressed as(Bevis et al., 1992):

$$PWV = \Pi \cdot ZWD = \Pi \cdot (ZTD - ZHD) \tag{1}$$

and Π is computed using following formula:

$$\Pi = \frac{10^6}{\rho_w R_v \left[(k_3 / T_m) + k_2' \right]} \tag{2}$$

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where ρ_w is the density of liquid water, R_v is the specific gas constant for water vapor, $k_2' = (17 \pm 10) \mathrm{K \cdot mbar^{-1}}$ and

$k_3 = (3.776 \pm 0.014) \times 10^5 \mathrm{K^2 \cdot mbar^{-1}}$ are physical constants (Sheng et al., 2013).

According to previous studies, error in T_m has significant influence upon the retrieval accuracy of PWV. The approximate relationship between the relative error of PWV and T_m is(Wang et al., 2005):

$$\frac{\Delta PWV}{PWV} \approx \frac{T_m + \Delta T_m}{T_m} - 1 = \frac{\Delta T_m}{T_m} \tag{3}$$

There are three main approaches to estimate T_m. They have respective advantages and disadvantages when applying to different applications:

(1) Integral of vertical temperature and humidity profiles are believed to be the most accurate method. The profile data can be extracted from radio sounding or NWP datasets(Wang et al., 2016). However, some inconveniences have to be endured. It usually costs considerable time to acquire NWP data, which is normally released every 6 hours with large volumes. This limits the use of NWP data in near real-time GPS-PWV retrieving. However, another data source, radiosonde data, have low spatial and temporal resolution. At most of the radiosonde sites, sounding balloons are daily cast at 00:00 UTC and 12:00 UTC. Furthermore, lots of GPS stations are not located close enough to any radio sounding site. For these GPS stations, no radiosonde data can be obtained. Therefore such methods are appropriate for climate research or long-term PWV trends study but not meet real-time requirements.

(2) Several global empirical models of T_m are established based on analyses of T_m time series from NWP datasets or other sources (Chen et al., 2014; Yao et al., 2012; Bohm et al., 2015). T_m at any time and any location can be estimated from these models independent of real meteorological observations. But some important real T_m variations, which may be dramatic during some extreme weather events, can be lost without constraints of real data. So these modeled T_m estimates are not accurate enough for high-precise meteorological applications, such as providing GPS-PWV estimates for weather predictions, etc.

(3)Many studies indicated that T_m parameter has relationships with some surface meteorological elements (e.g. surface air temperature T_s). These surface meteorological parameters can be measured accurately and rapidly. T_m then is estimated in real time using these surface measurements. For example, Bevis introduced Bevis T_s-T_m equation, T_m=0.72×T_s+70.2,

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according to analyzing 8712 radiosonde profiles collected at 13 sites in the U.S. over two years(Bevis et al., 1992), and this equation has been widely used in many other studies.

95 　　According to Rohm's research (Rohm et al., 2014), GPS-ZTD can be estimated very precisely by real-time GPS data processing. This means that T_m is a key parameter in near real-time GPS-PWV estimation. On the other hand, method (3) is the most suitable means to estimate T_m in near real-time because of its balance between timeliness and accuracy. However, the relationship between T_m and T_s varies with location and time. Several regional T_s-T_m equations were established using profile data over corresponding fields (Wang et al., 2012). But it is not precise enough to apply the same T_s-T_m model in a vast field,

100 e.g., in Indian region(Singh et al., 2014). Besides this, there are some other vast areas, for example over the oceans, without high-precision specific T_s-T_m equations, and there exist significant differences between the oceanic and terrestrial atmospheric properties. It is necessary to model T_s-T_m relationship over sea region, since several ocean-based GPS meteorology experiments demonstrated the potential of such technique to retrieve PWV over the broad ocean (Rocken et al., 2005;Kealy et al., 2012). A global gridded T_s-T_m model has been established by smoothing T_m data from "GGOS Atmosphere" and T_s data from ECMWF

105 reanalysis data in Lan's study(Lan et al., 2016). The model has relatively lower spatial resolution with 4°×5°, however, its statistic and the estimated T_m residuals due to time variations are not fixed (Yao et al., 2014a).

Table 1. Main differences between T_s-T_m model developed in this study and other global used T_s-T_m models

Strategies \ T_s-T_m Models	Bevis model (Bevis et al., 1992)	Latitude-related linear model (Yao et al., 2014b)	Global-gridded model (Lan et al., 2016)	Time-varying global gridded model (our study)
Applicable Regions	Regional/Global	Global	Global	Global
Data Sources	Radiosonde	T_s from 0.75°×0.75° ERAI, and T_m from 2°×2.5° "GGOS Atmosphere"	T_s from 0.75°×0.75° ERAI, and T_m from 2°×2.5° "GGOS Atmosphere"	T_s and T_m both from 0.75°×0.75° ERAI
Data Processing	Integrate radiosonde profiles	4°×5° Sliding window smooth	4°×5° Sliding window smooth	Integrate ERA-Interim profiles
Variations in model	Static without any variations	Spatial variations depend on only latitude(15° latitude interval), but no temporal variations	4°×5° global gridded, but no temporal variations	0.75°×0.75° global gridded and considering time variations

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The objective of this study is mainly to (1) develop global gridded T_s-T_m models without any spatial smooth of data and assess their precisions, and (2) study the performances of GPS-PWV retrievals using our T_s-T_m models. Table (1) lists the main differences between the T_s-T_m model developed in this study and other global used T_s-T_m models. In section 2, the data sources and T_m determining methods are introduced in detail. Then in section 3, we analyze the T_s-T_m relationships and their variations on a global scale. Global-gridded T_s-T_m estimating models in different forms are established and evaluated in section 4. Section 5 compares different PWV retrievals and section 6 presents conclusions based on our experiments.

2. Data Sources and Methodology of T_m Determination

2.1 T_m Definition

T_m is defined as a function related to temperature and water vapor pressure. It can be approximated as following formula(Bevis et al., 1992):

$$T_m = \frac{\int \frac{e}{T} dz}{\int \frac{e}{T^2} dz} \approx \frac{\sum_{i=1}^{n} \frac{e_i}{T_i} \Delta z_i}{\sum_{i=1}^{n} \frac{e_i}{T_i^2} \Delta z_i} \tag{4}$$

where e and T respectively represent vapor pressure in hPa and temperature in Kelvin, i denotes the ith pressure level and Δz_i is the height difference of ith levels . Vapor pressure e is calculated using equation $e=e_s \times RH$, RH is the relative humidity and saturation vapor pressure e_s can be estimated from temperature observations using Goff-Gratch formula (Sheng et al., 2013). For the ith level, e_i parameter at the middle height is calculated by vertically exponential interpolation of its two neighbor measurement points' water vapor pressure, while the temperature is estimated by linear interpolation. The integral intervals are from earth surface to atmospheric top.

2.2 Data sources and Methodology of T_m Determination

Equation (4) needs temperature, height and relative humidity values of several atmospheric levels through the entire atmosphere. These essential profile data can be obtained from radiosonde or NWP datasets.

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We employed radiosonde data from Integrated Global Radiosonde Archive (IGRA, ftp://ftp.ncdc.noaa.gov/pub/data/igra) to calculate T_m. Version 2.0 of the IGRA-derived sounding parameters provides pressure, geopotential height, temperature, saturation vapor pressure, and relative humidity observations at observed levels. Bias maybe introduced if integrals were terminated at lower levels(Wang et al., 2005), so the integrals were performed up to the topmost valid radiosonde data. According to our quality control processes, some radiosonde profile data were rejected. Surface observation must be available, and top profile level should not be lower than 300 hPa standard level. Furthermore, the level number between surface and the top level should be greater than five to avoid too sparse vertical profile. At most radio sounding stations, sounding balloons are launched every 12 hours, and their ascending paths are assumed to be vertical.

Profile data including same elements are usually provided by NWP products at certain vertical levels. ERA-Interim from ECMWF provides data on a regular 512 longitude by 256 latitude N128 Gaussian grid after the grid transforming performed by NCAR's Data Support Section (DSS). On each grid node of ERA-Interim, temperature, relative humidity and geopotential at 37 isobaric levels from 1000 hPa to 1 hPa can be obtained. Dividing the geopotential by constant gravitational acceleration value ($g \approx 9.80655$ m/s^2), we can determine the geopotential heights of surface and levels. Datasets are available at 00:00, 06:00, 12:00 and 18:00 UTC every day and has been covering a period from 1979.01 to present.

In theory, the computation of equation (4) should be operated through the entire atmosphere, and the geopotential height should be converted to the geometric height. However, vast majority of the water vapor concentrate at the troposphere. Moreover, the geopotential heights of top pressure levels in the two selected reanalysis datasets are around 30~40 km. Geopotential height is very close to geometric height in such height range. According to our computation, relative difference between them is only 0.1%~0.9%. In fact, the height difference Δz can be replaced by geopotential height difference Δh in equation (4), since the division operation can almost eliminate the difference between two different height types. The value change of T_m attributed to height replacement will extremely approximate to zero. For the convenience of calculations, we directly employed geopotential height variable to estimate T_m. In this paper, we denoted the T_m derived from ERA-Interim as T_{m_ERAI}.

At each reanalysis grid node, the computation of equation (4) always starts from surface height to top pressure level. The pressure levels below surface height were rejected in the calculation. T_s is defined as the variable of "temperature at 2 meters

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above ground", and surface water vapor pressure can be derived from "2 meter dewpoint temperature" variable in ERA-Interim. These T_s were also used in the regression analyses between T_m and T_s in the following study.

3. Correlation between Ts and Tm

175　　Many studies have indicated the close relationship between T_s and T_m. However, T_m is also found to be not closely related to T_s in some other regions, e.g., in Indian zone(Raju et al., 2007). Using T_m and T_s generated from global gridded reanalysis data, we are able to study the relationship between T_s and T_m in detail.

　　We first carried on linear regression analyses on the four years long T_s and T_m data generated from point radiosonde data and global gridded ERA-Interim datasets. Analysis results are shown in Fig. (1). Although two datasets have different temporal

180　resolutions (12 hours for radiosonde data and 6 hours for ERA-Interim data) and spatial resolutions, both analyses agree very well with each other. Our analyses also indicate that correlation coefficients between T_s and T_m are generally related to point's latitude as well as other studies(Yao et al., 2014b). Significant positive correlation coefficients can be found in mid- and high-latitudes and reaches the maximum in Polar Regions. Then the correlation coefficients drop dramatically in low latitudes. We further analyzed the main reason for such changes. T_m variable in low latitudes is stable, so it shows independence of other

185　parameters. To study the variations of T_s and T_m, we illustrated denary logarithm values of their standard deviations in figure (2). It is evident that T_m varies much less in low latitudes. Besides latitude-related features, it is worth noting that there are obvious T_s-T_m correlation coefficient differences between lands and oceans. Analyses even demonstrate negative correlation coefficients over certain oceans, e.g., low-latitude Western Pacific, Bay of Bengal or Arabian Sea. It may be mainly attributed to the different thermodynamic properties of the underlying surface, including the transfer of water latent heat, the different

190　specific heat capacities, etc. These properties influence the T_s greatly, leading to the significantly smaller variations of T_s over the seas than over the lands. Unreliable regression analysis results may be derived by both the T_s and T_m with small variations. In figure (3), scatter plots of T_s and T_m from ERA-Interim at two locations N 0.35° E 180.00° and N 70.53° E 180.00° are given. Compared with the other point, the T_s-T_m relationship at the point near the equator, as the blue dots show, is quiet obscure since the whole variation ranges of T_s and T_m are both below 10 K. The linear regression result, as the magenta line shows,

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also makes less sense with low T_s-T_m correlation coefficient of only -0.0893. Besides complicated spatial variations, researches

have revealed that T_s-T_m relationships also have temporal variations(Wang et al., 2005). So a good T_s-T_m model should take

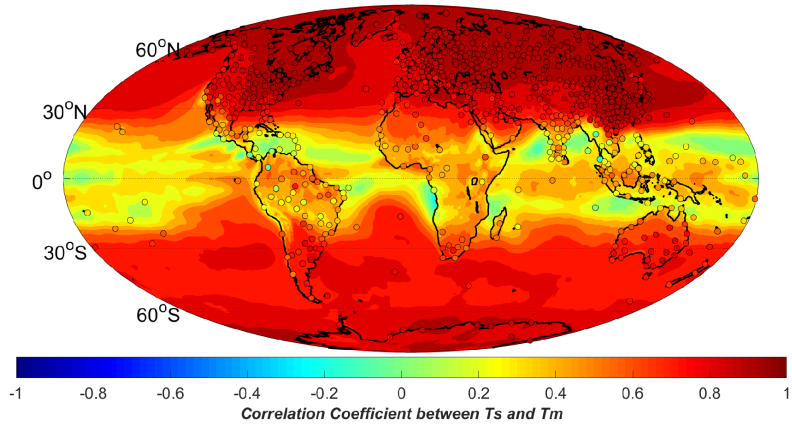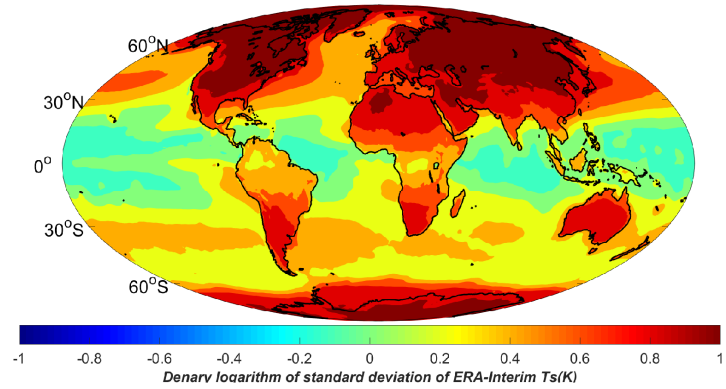200 both spatial and temporal variations into consideration, which is the main work in the following sections.

Figure 1: Correlation coefficients between T_s and T_m generated from radiosonde data (dots) and ERA-Interim reanalysis datasets (color-filled contours) over a period of 4 years from 2009 to 2012.

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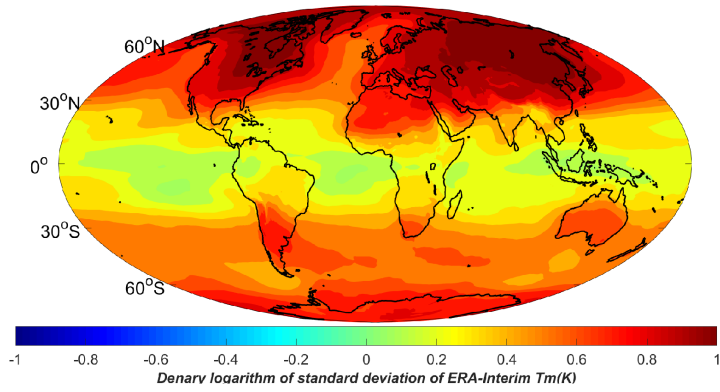
Figure 2: Denary logarithm of standard deviation of (top) T_s and (bottom) T_m generated from ERA-Interim over a period of 4 years from 2009 to 2012. Temperature unit is Kelvin.
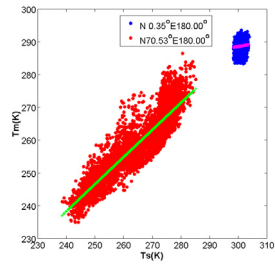

Figure 3: T_s-T_m scatter plots at two locations: (blue dots) N 0.35° E 180.00° and (red dots) N 70.53° E 180.00°, the magenta and green lines are their linear fitting curves. Temperature unit is Kelvin.

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4. Developments of Global-gridded T_s-T_m models

Since T_s -T_m relationship has complicated spatial variations, it is necessary to establish detailed global gridded T_s -T_m estimating equations for precise GPS-PWV remote sensing. In this section, static and time-varying global gridded T_s -T_m models are established and assessed.

215 **4.1 Static global-gridded T_s-T_m model**

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Linear formulas including T_s and T_m, which is expressed as $T_m = a \times T_s + b$, are adopted in most studies, such as Bevis equation. Based on the T_s and T_m products from ERA-Interim, we performed linear fittings of T_s versus T_m on each grid point. Then slope constant (a) and intercept constant (b) of each linear expression and fitting RMSEs were calculated and contoured in figure (4). The a and b values are related to the point's latitude as well as its underlying surface. Constant a value varies from 0.6 to 0.8 when constant b about 100~50 over most continents in northern mid-high latitudes. The constants in Bevis equation, which are 0.72 and 70.2 respectively, are within such value ranges. Constant a is smaller (about 0.5~0.7) over lands in the southern mid-high latitudes. Especially, there are acute value changes of constant a and b from lands to seas in mid-high latitudes. The reason is the different variation features of T_s and T_m between seas and lands, which can be seen in figure (2). In low latitudes, a value is smaller than other regions whether over lands or oceans because of the low T_s and T_m variations. Fitting RMSEs are within 2~4 K over mid-high latitude lands, and relatively lower values over the seas or low latitude areas. The reason for the low RMSEs over the oceans around the equator is just the smaller fluctuations of T_m. Attributed to no spatial or temporal smooth of any data in our study, the precision and resolution of our static model, with no RMSE larger than 4.5 K, is clearly better than previous studies (Lan et al., 2016).
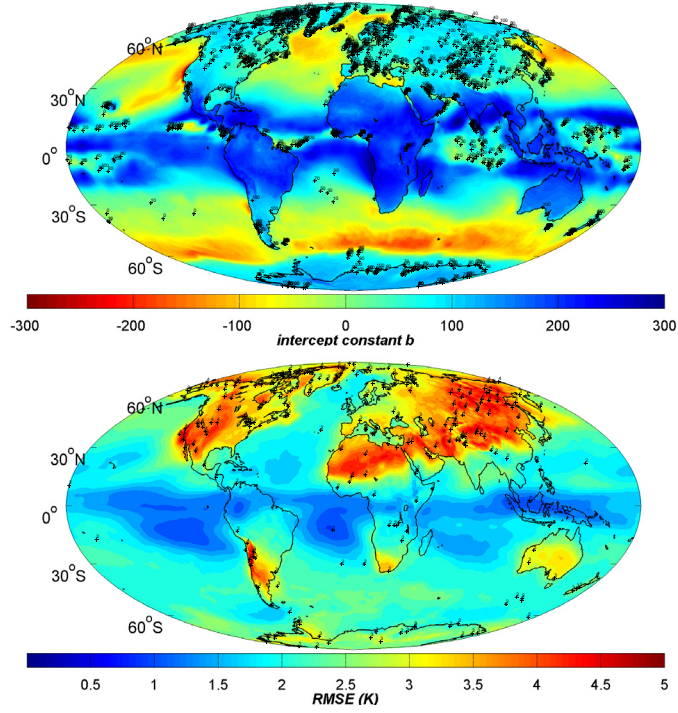

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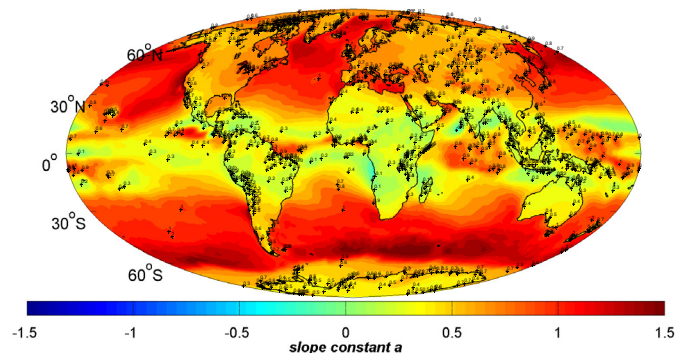
Figure 4: Distribution of (top) slope constant *a*, (middle) intercept constant *b*, and (bottom) RMSE of static linear T_s-T_m equations at ERA-Interim grid nodes. The numbers in figures are contour values. Temperature unit is Kelvin.

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4.2 Time-varying global-gridded T_s-T_m model

T_s-T_m relationship has time variations which should also be considered in precise T_s-T_m model. Therefore a time-varying equation is applied for T_s-T_m regression at each grid node:

$$T_m = a \times T_s + b + m_1 \boldsymbol{cos}\left(\frac{doy}{365.25} \cdot 2\pi\right) + m_2 \boldsymbol{sin}\left(\frac{doy}{365.25} \cdot 2\pi\right) + n_1 \boldsymbol{cos}\left(\frac{doy}{365.25} \cdot 4\pi\right) +$$
$$n_2 \boldsymbol{sin}\left(\frac{doy}{365.25} \cdot 4\pi\right) + p_1 \boldsymbol{cos}\left(\frac{hr}{24} \cdot 2\pi\right) + p_2 \boldsymbol{sin}\left(\frac{hr}{24} \cdot 2\pi\right) \tag{5}$$

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240   where *doy* represents the observed day of year and *hr* is the observed hour in UTC time; (m_1, m_2), (n_1, n_2) and (p_1, p_2) are the fitting coefficients of formula items to reflect amplitudes of annual, semiannual and diurnal variations in our T_s-T_m models.

Our regression indicated that the static terms in equation (5), which are determined by coefficients *a* and *b*, are similar to the static models in section 4.1 expect a little difference over some oceans. Besides *a* and *b*, we also illustrated the amplitudes of annual, semiannual, and diurnal terms. We can see that there are large annual variations (amplitude > 5 K) in the vast regions
245   from Tibet to North Africa, and some places in Siberia and Chile, while diurnal variations (amplitude > 3 K) mainly occurs in mid-latitude lands such Northeast Asia or North America. Semiannual variations, however, are small in most areas expect some high-latitudes (amplitude > 3 K). All variations are smaller over the seas due to the slower temperature changes over waters than lands. By using time-varying T_s-T_m models the estimated T_m's RMSEs, which are also contoured in figure (5), dropped significantly in the regions with large annual or diurnal variations.
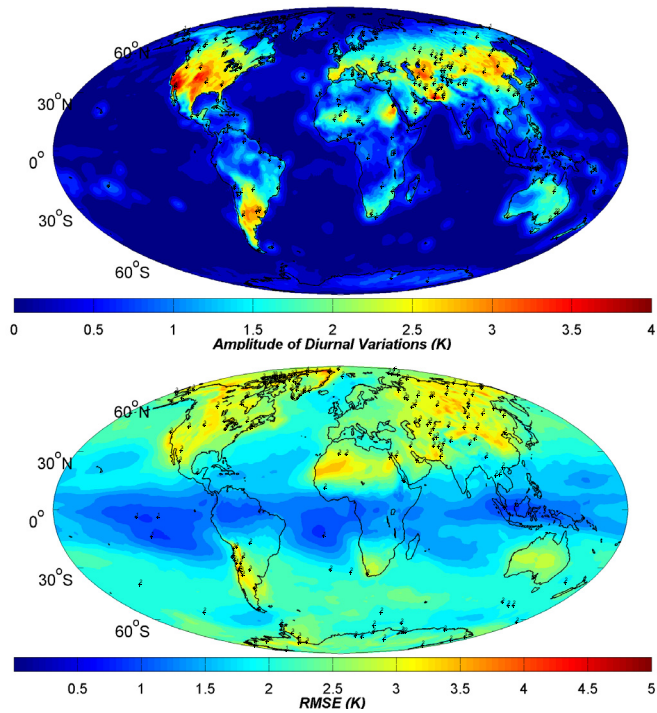

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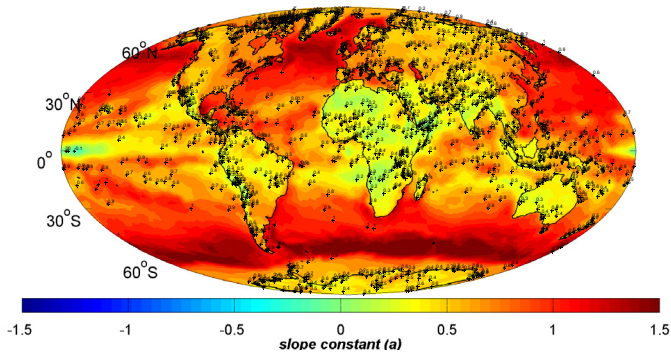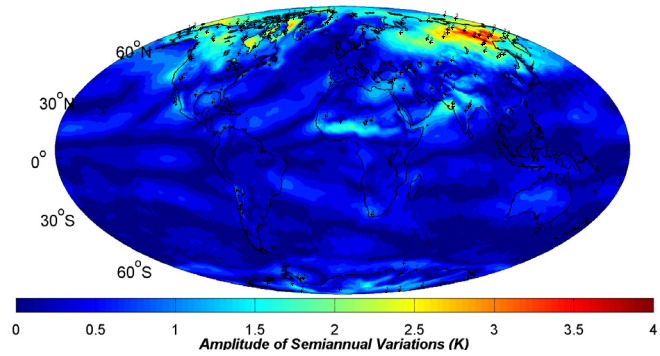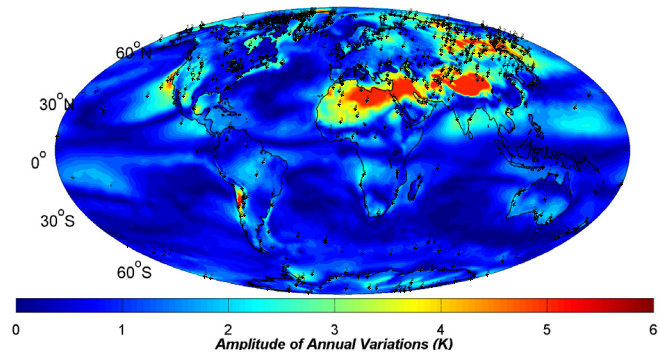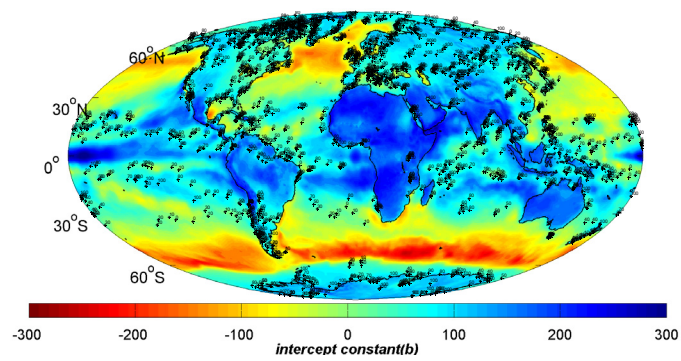
Figure 5: （top）slope constant *a*, (second) intercept constant *b*, amplitudes of T_m (third) annual, (forth) semiannual and (fifth)diurnal terms in our time-varying global gridded T_s -T_m models, and (bottom) the model estimated T_m 's RMSE distribution. The numbers in figures are contour values. Temperature unit is Kelvin.

4.3 Assessments of T_s-T_m models

In order to assess the T_s-T_m model's precisions further using other independent data sources, we generated T_m and T_s from radiosonde data at 758 radiosonde stations in the year 2016. These data are not assimilated into 2009~2012 ERA-Interim datasets. As a result, we can regard them as independent data to our model. At each radiosonde site, different T_s-T_m models were employed to calculate T_m. In contrast, we also estimated T_m using GPT2w model (Bohm et al., 2015), which is a global gridded T_m empirical model independent of surface meteorological observation data. Then these calculated T_m will be evaluated

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by comparisons with the radiosonde's integrated T_m values (denoted as T_{m_RS}) twice a day.

The model estimated T_m are denoted as T_{m_Bevis}, T_{m_LatR}, T_{m_static}, $T_{m\_varying}$, and T_{m_GPT2w} respectively from Bevis equation, Yao's latitude-related model, our static global gridded model, time-varying global gridded model, and GPT2w model. When global gridded models are employed, there is a problem that a radiosonde station may not be located at a grid node. Therefore, the coefficients in T_s-T_m equations at radiosonde site's location should be horizontally interpolated from neighboring grids. The interpolation formula is expressed as (Jade and Vijayan, 2008):

$$C_{site} = \sum_{i=1}^{4} w^i C_{grid}^i \tag{6}$$

C_{site} and C_{site}^i respectively represent the coefficients in T_s-T_m equations at radiosonde site location and its neighboring grids. w^i is the interpolation coefficients, which is determined using equation:

$$w^i = \frac{\left(R\psi^i \right)^{-\lambda}}{\sum_{j=1}^{4} \left(R\psi^j \right)^{-\lambda}} \tag{7}$$

where R=6378.17 km is the mean radius of the earth, λ is the scale factor which equals one in our study, and ψ^i is the angular distance between the ith grid node and the station's position. ψ^i is computed using following formula related to latitude φ and longitude θ:

$$\cos\psi_i = \sin\varphi_i \cdot \sin\varphi + \cos\varphi_i \cdot \cos\varphi \cdot \cos\left(\theta_i - \theta \right) \tag{8}$$

Considering the reanalysis grids are definite, and every radiosonde site is in situ, we can compute these interpolation coefficients in Eq. (6) for all radiosonde stations. Then these coefficients are stored as constants to avoid reduplicate calculation.

Taking T_{m_RS} as reference values, we calculated the bias and root mean square error (RMSE) of T_{m_Bevis}, T_{m_LatR}, T_{m_static}, $T_{m\_varying}$, and T_{m_GPT2w} at each radiosonde site and illustrated them in figure (6). Obviously, Bevis equation has bad precisions in many regions with absolute bias and RMSE larger than 5 K. T_{m_LatR} can reduce estimated biases in many regions, but the

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RMSEs remain large. And there still exist large biases at quite a few radiosonde stations, e.g. in Africa or West Asia. T_{m_static} and T_{m_GPT2w} can remove large T_m biases at most of the radiosonde stations. $T_{m\_varying}$ performs significantly better all over the world, especially in the Middle East area, North America and Siberia region, etc.

Detailed statistics of the bias's and RMSE's distributions of different models are shown in figure (7) and table (2). At over 96% radiosonde stations, biases of $T_{m\_varying}$ are within -3~3 K and large positive biases (>3K) nearly disappear, while there are significant large ones in T_{m_Bevis} and T_{m_LatR}. Improvements in RMSEs are more evident, $T_{m\_varying}$'s RMSEs are smaller than 4 K at over 90% radiosonde sites while few sites (<1%) have RMSEs larger than 5 K, which is clearly better than other models. In T_{m_Bevis} and T_{m_LatR}, there are more than 17% radiosonde sites have RMSE larger than 5 K. The overall performance of T_{m_GPT2w} is very close to T_{m_Bevis} except that its absolute bias is smaller than other T_s-T_m models.
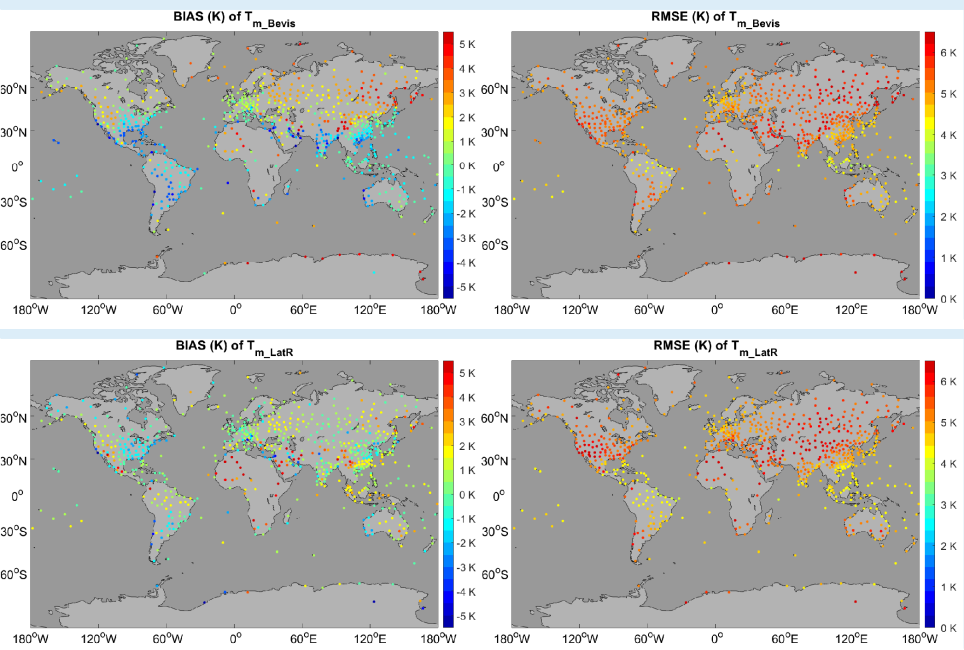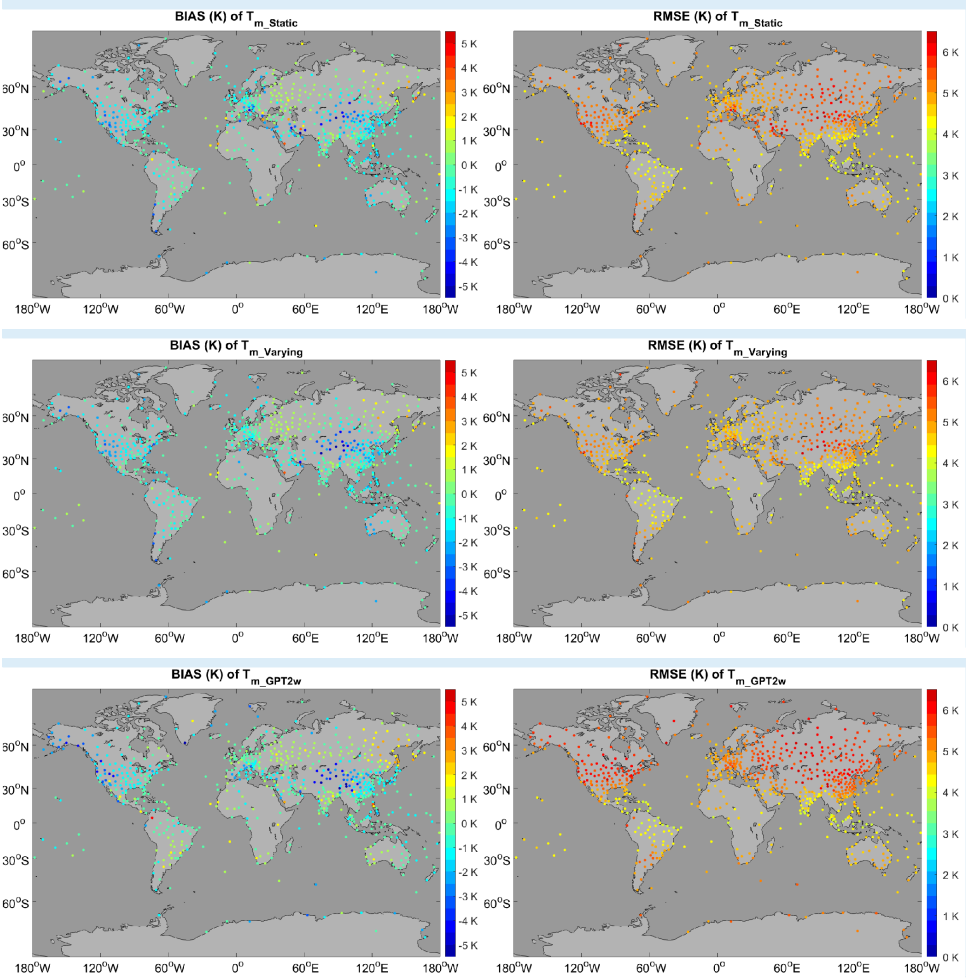
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Figure 6: (left) bias and (right) RMSE of estimated T_m using T_s–T_m equations from (top) Bevis equation, (second) Yao's latitude-related model, (third) static global gridded model, (forth) time-varying global gridded model and (bottom) GPT2w model at each radiosonde station comparing with radiosonde data of the year 2016. Temperature unit is Kelvin.

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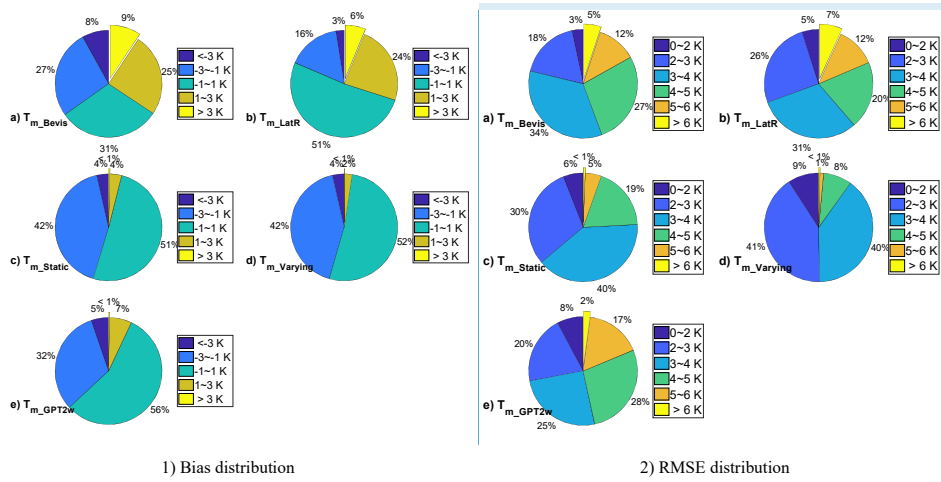
1) Bias distribution   2) RMSE distribution

Figure 7: (left) bias's and (right) RMSE's distributions of T_{m_Bevis}, T_{m_LatR}, T_{m_static}, $T_{m\_varying}$ and T_{m_GPT2w} compared with respect to radiosonde data at 758 stations in 2016. Temperature unit is Kelvin.

Table 2: Statistics of T_m estimates from different T_s-T_m models and GPT2w model comparing with radiosonde T_m derivations

Statistics	T_{m_Bevis}	T_{m_LatR}	T_{m_static}	$T_{m\_varying}$	T_{m_GPT2w}
Average value of absolute T_m bias (K)	1.90	1.31	1.17	1.13	-0.74
Average value of T_m RMSE (K)	3.95	3.83	3.37	3.02	3.83
Average relative RMSE of T_m (%)	1.44	1.39	1.23	1.10	1.40
Max Relative RMSE of mean T_m (%)	3.69	4.26	2.57	2.40	4.31
% of sites with T_m RMSE < 4 K	55.67	61.35	75.86	90.11	53.43
% of sites with T_m Relative RMSE less than 1.5%	59.50	64.78	77.70	88.92	56.60

To verify the superior T_m estimation model at each radiosonde site, we employed the following statistical tests under the assumption of normal distribution of estimated T_m's error:

(1) Firstly, Brown-Forsythe's tests(Brown and Forsythe, 1974) of equality of variances were carried out at each site for estimated T_m errors from two different models, e.g., model A and B. The purpose of this step is to determine that whether there is significant variance difference between two T_m results. If the test rejects the null hypothesis at 5% significance level that the errors of model A and B have the same variance, the model with smaller sample variance is regarded as the better one. However,

18

if the test doesn't reject the homogeneity of variances, analysis of variance (ANOVA) is performed in the next step.

(2) ANOVA is a technique to analyze the differences among group means(Hogg, 1987). It evaluates the null hypothesis that the samples all have the same mean against the alternative that the means are not the same. If the null hypothesis is rejected at 5% significance level, the T_m sample with smaller absolute mean value is believed to be better. Otherwise, we think that two models perform almost the same at this radiosonde site.

(3) After multiple tests and comparisons, the best model at each radiosonde stations may be determined. However, at some sites no superior model can be confirmed. So all models are believed to have equivalent performances.

Finally, we counted the number of sites at which each T_m model respectively performed superiorly, and the results are given in table (3). The time-varying global gridded model is superior to others at 456 radiosonde stations (60.16% of all sites), while the second-best estimations, T_{m_GPT2w}, is superior at only 12.66% sites.

Table 3: Number of radiosonde sites at which the five global applied T_m estimation models respectively perform superiorly

Superior model	None	T_{m_Bevis}	T_{m_LatR}	T_{m_static}	$T_{m\_varying}$	T_{m_GPT2w}
Number of sites	47	48	70	41	456	96

In figure (8)，T_m series at IGRA station NO.62378 (N 29.8628° E 31.3492°) are given. We can see that large negative biases (< -5 K) between T_{m_Bevis} (or T_{m_LatR}) and T_{m_RS} exist, while T_{m_static} performs only slightly better from July to October. But $T_{m\_varying}$ and T_{m_GPT2w} can eliminate most of the seasonal errors. Different properties of T_m series appear at another IGRA station NO.40841 (N 30.2500° E 56.9667°). Some observation data are missing, but we can still see that there are large positive differences (> 5 K) between T_{m_Bevis} (or T_{m_LatR}) and T_{m_RS} through the year. T_{m_static}'s biases are much smaller but still have some big errors in many months. The $T_{m\_varying}$, however, performs as well as at NO.62378 IGRA station, with small biases and good capturing of T_m's variations. Both time series of T_{m_GPT2w} are smooth so they cannot capture the large fluctuations of T_m time series leading to T_{m_GPT2w}'s worse accuracy than $T_{m\_varying}$.

On the other hand, even $T_{m\_varying}$ also have large differences from T_{m_RS} at a few IGRA stations, especially in Central Asia. It is because that our fitting analyses were based on the T_m values derived from reanalysis datasets, and reanalysis T_m did not agree well with radiosonde data at these IGRA sites during specific seasons. Improvements on reanalysis data in these regions should be performed in future.

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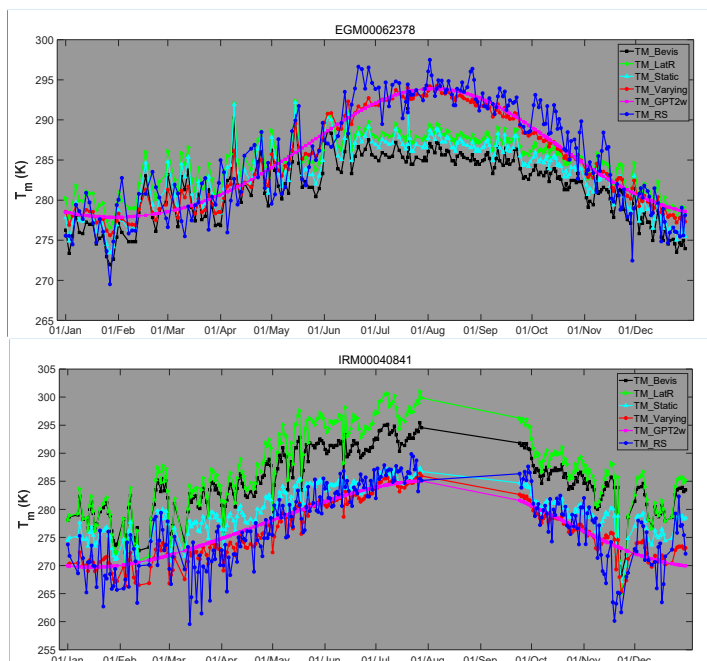
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Figure 8: T_m series of T_{m_Bevis}, T_{m_LatR}, T_{m_static}, $T_{m\_varying}$, T_{m_GPT2w} and T_{m_RS} at (top) EGM00062378 and (bottom) IRM00040841 IGRA sites. Temperature unit is Kelvin.

5. GPS-PWV retrieving experiments

GPS-PWV has different error sources with different properties, including GPS ZWD error, surface temperature and pressure measurement errors, T_m estimation error (Ning et al., 2016), and etc. It is complicated to evaluate GPS-PWV uncertainty due to the lack of collaborated additional independent techniques to monitor water vapor at GPS site. Therefore several experiments were carried out to investigate GPS-PWV precisions carefully.

5.1 Impact of T_m estimation

In order to study the actual impacts of T_m on GPS-PWV retrievals, we firstly downloaded GPS ZTD products (Byun and

20

370 Bar-Sever, 2009) at several IGS sites in the year 2016 from CDDIS FTP address (ftp://cddis.gsfc.nasa.gov/pub/gps/products/troposphere/zpd). These selected GPS sites were equipped with meteorological sensors so surface pressure and temperature measurements could be obtained. $ZHDs$ were calculated using surface pressures and Saastamonien model. It is deducted from $ZTDs$ to obtain $ZWDs$. Then T_m was generated through six approaches: the first five T_m series were T_{m_Bevis}, T_{m_LatR}, T_{m_static}, $T_{m\_varying}$, and T_{m_GPT2w}. The sixth T_m were integrated from ERA-Interim

375 profiles and interpolated to GPS site locations(Wang et al., 2016; Jiang et al., 2016). Finally, GPS-PWVs were generated from ZWD and six different T_m estimates. We denoted these GPS-PWV sets as PWV_{BTm}, PWV_{LTm}, PWV_{STm}, PWV_{VTm}, PWV_{GTm}, and PWV_{ETm}. The only differences between these GPS-PWVs are the T_m estimates, so the impacts of other errors could be excluded.

The T_m from ERA-Interim is believed to be the most accurate, so we regarded the PWV_{ETm} as reference values to assess

380 other PWVs. Finally, PWVs at 74 IGS sites, which have over one hundred compared points, were obtained. The relative RMSEs of PWV_{BTm}, PWV_{LTm}, PWV_{STm}, PWV_{VTm} and PWV_{GTm} at these selected stations were calculated and illustrated in figure (9), and detailed statistics are given in table (4). Mean relative error of all sites drops from 1.18% of PWV_{BTm} to 0.91% of PWV_{VTm}. Obviously at most sites, PWV_{VTm}, which have minim relative errors, is prior to other PWV retrievals. At 55 sites PWV_{STm} and PWV_{VTm} obtain relative RMSE smaller than 1.0%, while at only 28 sites of PWV_{BTm}, 31 sites of PWV_{LTm} and 22

385 sites of PWV_{GTm} perform similarly. Some relative RMSEs were remarkably reduced. For example, at ALIC site which located in Australia with mean PWV of about 23 mm, the relative RMSE dropped from 1.97% of PWV_{BTm} to 1.10% of PWV_{VTm}. The time series of relative differences of PWV_{BTm}, PWV_{LTm}, PWV_{STm} PWV_{VTm}, and PWV_{GTm} at ALIC station are given in figure (10). Obviously, PWV_{BTm} and PWV_{LTm} have bigger relative errors through the year while PWV differences are significantly larger only in summer season. It is attributed to the wetter atmosphere in summer than in winter. PWV_{STm} eliminates those

390 large differences but still retain some residual errors, which are removed more than 1.0 mm in PWV_{VTm} further. PWV_{GTM} has some large errors during the period from May to July. All these results demonstrate that our time-varying global gridded has precision advantages.

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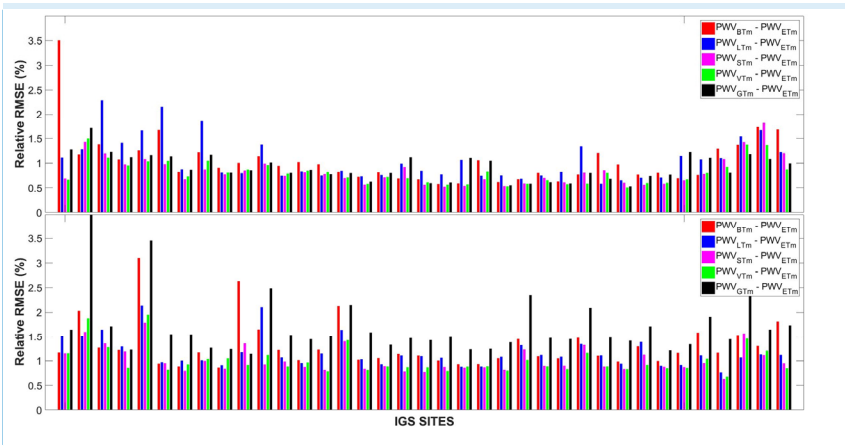
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Figure 9: Relative RMSEs of PWV$_{BTm}$, PWV$_{STm}$, PWV$_{VTm}$ and PWV$_{GTm}$ compared with PWV$_{ETm}$ at 74 IGS stations in the year 2016
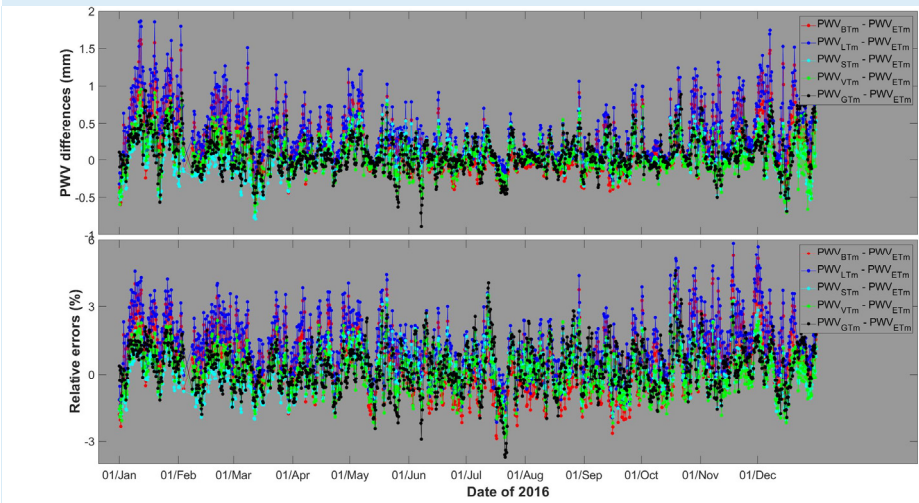

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Figure 10: (top) PWV differences and (bottom) relative differences of PWV$_{BTm}$, PWV$_{LTm}$, PWV$_{STm}$, PWV$_{VTM}$ and PWV$_{GTm}$ compared with PWV$_{ETm}$ at ALIC station in the year 2016. PWV unit is mm.

22

Table 4: Statistics about relative errors of different PWV retrievals

Statistics	PWV_{BTm}	PWV_{LTm}	PWV_{STm}	PWV_{VTm}	PWV_{GPT2w}
Mean relative RMSE of all sites	1.18%	1.12%	0.93%	0.91%	1.32%
Number of sites with relative errors < 1.0%	28	31	55	55	22

5.2 Comparisons between GPS-PWVs and radiosonde PWVs

Among our selected 74 IGS sites, there are only 11 sites located within 5 km to nearby IGRA radiosonde stations. At these common stations, we generated PWVs from radiosonde data (PWV_{RS}) by adjusting sounding profiles to the heights of IGS sites. It worth noticing that geoid undulation corrections should be carried out on each IGS site's geoid height (Jiang et al., 2016). Then we compared PWV_{BTm}, PWV_{LTm}, PWV_{STm}, PWV_{VTm}, PWV_{GTm} and PWV_{ETm} with PWV_{RS}. Figure (11) shows the statistics. The RMSEs of GPS-PWVs are around 1~5 mm. Comparisons indicate that at most selected sites the RMSEs of different GPS-PWV retrievals are very close (differences ≤ 0.2 mm) regardless of the T_m sources applied. This means that other errors (e.g. ZTD estimation errors or sounding sensors errors) instead of T_m occupied the differences between GPS-PWVs and radiosonde PWVs. However, we still found obvious gaps between PWVs at NRIL (N 88.3598° E 69.3618°, 4.1km to nearby radiosonde NO.23078 sites). RMSEs decrease from 2.29 mm of PWV_{BTm} to 1.84mm of PWV_{VTm} and 1.42 mm of PWV_{ETm}. As shown in figure (12), the large PWV differences mainly appeared from May to September. During such five months, mean GPS-PWV differences to PWV_{RS} decreased by over 30% from 2.52 mm of PWV_{BTm} to 1.67 mm of PWV_{VTm}. The accuracy of PWV_{GTm} is close to PWV_{VTm} at this site, and it indicates that the spatiotemporal variations of T_m are also modeled very well by GPT2w model.
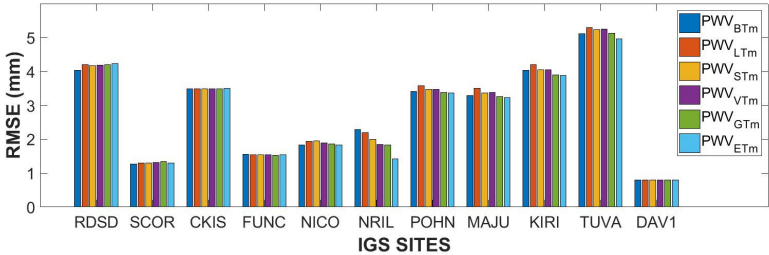
Figure 11: RMSEs of PWV$_{BTm}$, PWV$_{STm}$, PWV$_{VTm}$, PWV$_{GTm}$ and PWV$_{ETm}$ compared with PWV$_{RS}$ at 11 IGS stations in 2016. PWV unit is mm.
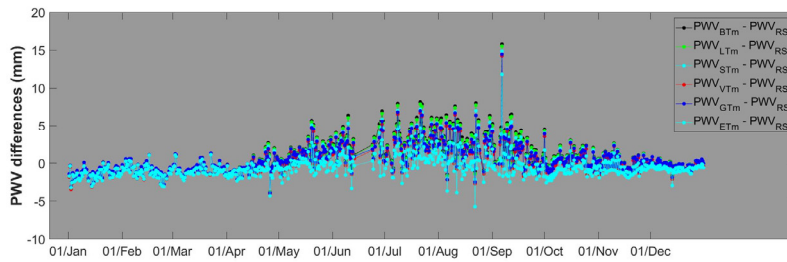
430 **Figure 12: PWV differences of PWV$_{BTm}$, PWV$_{LTm}$, PWV$_{STm}$, PWV$_{VTm}$, PWV$_{GTm}$ and PWV$_{ETm}$ compared with PWV$_{RS}$ at NIRL station in the year 2016. PWV unit is mm.**

6. Summary and conclusion

In this study, we estimated T_m using temperature and humidity profile data from IGRA radiosonde data and ERA-Interim reanalysis datasets over a four-years-long period from the year 2009 to 2012. T_s were also extracted from the two data sets.

435 Then we analyzed the relationship between T_s and T_m at each reanalysis grid node and radiosonde station. Analyses indicated that: (1) T_m has a stronger relationship with T_s in mid-high latitudes than in low latitudes; (2) T_s-T_m correlation coefficients are higher over lands than over oceans in low latitudes; (3) the T_s-T_m relationship's variation properties is much more complicated rather than only dependence on point's latitude, and (4) the T_s-T_m relation has strong annual, semiannual, and diurnal variations in many areas.

Using global gridded ERA-Interim datasets from 2009 to 2012, we developed static and time-varying global gridded T_s-

440 T_m models. Annual, semiannual, and diurnal variations in T_s-T_m relationship are considered in a time-varying model. Then we evaluated T_m results from different T_s-T_m models and GPT2w model by comparing them with radiosonde data in 2016. Results demonstrate that time-varying global gridded T_s-T_m model has a significant global precision advantage over other global applied models. Average T_m RMSE reduces by about 1 K. The proportion of sites with small biases and RMSEs increases

445 significantly. At over 90% radiosonde sites, time-varying global gridded model has RMSE smaller than 4 K, and the RMSEs

24

larger than 5 K nearly disappear. On the other hand, there are more than 17% radiosonde sites have RMSEs larger than 5 K in Bevis or latitude-related models. Multiple statistical tests at 5% significance level verify the significant superiority of the new time-varying model at more than 60% of radiosonde sites. Analyses at specific stations also demonstrate that time-varying global model can eliminate large errors in estimated T_m series.

More precise T_s-T_m models also have positive impacts on GPS-PWV retrievals. Regarding the GPS-PWVs using ERA-Interim T_m estimates as references, relative errors of GPS-PWV using time-varying global gridded T_s-T_m models are within 1.0% at more than 74% IGS sites, which is better than other models. The differences between GPS-PWVs and radiosonde PWVs are around 1~5 mm and mainly influenced by comprehensive error sources rather than single T_m. But at some special sites, such differences could decrease by more than 30% in wetter conditions.

According to our experiments, we are confident that the time-varying global gridded T_s-T_m models presented here will help us to retrieve GPS PWV more precisely, and to study precise PWV variations in high temporal resolution as well as T_s observations. Matlab array file consisting of global gridded coefficients in our model, as well as Matlab codes to interpolate coefficients at any given location, are provided as the supplement of this study. It could be useful for researchers and applicants in relevant fields.

Data sets

Radiosonde data: ftp://ftp.ncdc.noaa.gov/pub/data/igra

ERA-Interim Project: https://doi.org/10.5065/D6CR5RD9

GPS-ZTD Product: ftp://cddis.gsfc.nasa.gov/pub/gps/products/troposphere/zpd

Our model Supplement: https://www.atmos-meas-tech-discuss.net/amt-2018-67/amt-2018-67-supplement.zip

Competing interests

The authors declare that they have no conflict of interest.

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