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Empirical T_m modeling in the region of Guangxi

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Abstract: This paper presents three strategies for modeling the regional empirical T_m (the weighted mean temperature of the atmosphere) to obtain more accurate determinations in a regional empirical model that is better adapted to the geographical and climatic characteristics of the applied area. The proposed models utilize data from four radiosonde stations in Guangxi, at Nanning, Guilin, Wuzhou and Baise, over an 11 month period (from Jan. to Nov. of 2011). The experimental results demonstrated the following: (1) there is no significant difference between monthly and annual regression results at each site; (2) it is more reasonable and feasible to use the proposed regional Hybrid model for the area far away from the radiosonde site; (3) from the analysis of the possible temperature conditions, the precision of the proposed regional Hybrid model is higher than that of the well-known Bevis formula and of some other existing models and can reach an accuracy within 1 mm for the GPS-derived PWV estimates for the applied region.

Key words: weighted mean temperature of the atmosphere; linear regression; regional Hybrid model

1 Introduction

Water vapor is a climate variable that plays an important role in atmospheric motion, climate research and operational weather forecasting. Owing to its high variability in space and time, water vapor in the atmosphere is a crucial parameter for the analysis of climatic systems. Compared with conventional meteorological measurements, such as radiosonde, water vapor radiometer and satellite observations, GPS can provide high resolution data in both space and time to estimate near real-time and very accurate PWV in numerical weather prediction (NWP).

Previous studies proved the importance of new strategies for a more effective calculation of GPS PWV using regionally optimized T_m models. Because the well-known Bevis model[1], which was originally deduced for the northern hemisphere, is tuned to a specific area (27°N -65°N), many studies have proposed regionally optimized T_m models for the applied area. For example, to achieve an accurate GPS-derived PWV from T_m, the $T_{m(HK)}$[2] was estimated using radiosonde data from 8-year measurements in Hong Kong, China. They found that the differences between $T_{m(HK)}$ and $T_{m(B)}$ range from 3 K to 8 K. Alternatively, a regionally optimized model ($T_{m(CHN)}$)[3] was proposed for China and has a highly linear relationship with the station heights and can be used across the country. When the station height varies from a few meters to kilometers, the differences between the $T_{m(CHN)}$ and the Bevis model ($T_{m(B)}$) range from -8 K to 10 K. Wang et al[4] proposed the $T_m - T_s$ model, which can be widely used in China and uses data from 83 exchanging sounding stations from the year 2009. Unfortunately, the models deduced in references[3] and [4] are based on the a-

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nalysis of the radiosonde data distributed across the country, which is a very large study area, and other existing site-specific T_m models are far away from Guangxi. Because T_m varies with altitude, season and geographical location, the introduction of errors from other radiosonde data in regionally optimized modeling for a specific region is thus inevitable. Additionally, the precision of regional GPS PWV computed from a site-specific T_m model is needed to perform further investigations. Therefore, analyzing and verifying the feasibility of these models or even building a regional empirical T_m model for the applied region is still necessary.

In this paper, a novel attempt has been made to build regional empirical models deduced from the data from four radiosonde stations in Guangxi, which is located in a low-latitude region. The strategies for monthly, annual and regional analyses are used to build site-specific and regional empirical T_m models.

2 Experimental methods

2.1 Calculation of PWV from GPS measurements

As shown in equation (1), the GPS-derived total zenith path delay (ZPD) contained in a GPS observation can be partitioned into two[1,5]

$$ZPD = \Delta L_h^z M_h(\theta) + \Delta L_w^z M_w(\theta) \quad (1)$$

where ΔL_h^z is the zenith hydrostatic delay (ZHD), ΔL_w^z is the zenith wet delay (ZWD), θ is the satellite elevation angle, M_h is the hydrostatic mapping function and M_w is the wet mapping function. Saastamoinen[6] showed that the ZTD can be expressed as the sum of ZHD and ZWD, the former in millimeters, given by[7]

$$ZHD = (2.2779 \pm 0.0024)P_s/(1 - 0.00266\cos(2\lambda) - 0.00028H \quad (2)$$

where P_s is the total pressure (hPa) at the Earth's surface, λ is the latitude and H is the height above the ellipsoid (in kilometers).

The GPS-derived PWV can be obtained by subtracting the ZHD from the total ZPD to obtain the ZWD, which is subsequently multiplied by a non-dimensional conversion constant K

$$PWV = K(ZWD) \quad (3)$$

Here,

$$K = 10^6/\rho R_v(k_3/T_m + k'2) \quad (4)$$

where R_v is the specific gas constant for the water vapor, ρ is the density of water $k_2' = 22.1$ K/hPa, $k_3 = 3.739 \times 105$ K^2/hPa and T_m is the weighted mean temperature of the atmosphere[8], which can be defined as

$$T_m = \frac{\int (P_v/T)\,dz}{\int (P_v/T^2)\,dz} \quad (5)$$

where P_v is the partial pressure of water vapor (in millibars) and T is the atmospheric temperature (in degrees Kelvin).

2.2 Site-specific and regional modeling

The deduction of a value of T_m adapted to Guangxi is very important to evaluate the quality of these regional estimations of PWV from GPS. In the estimation of the PWV from the observed ZWD, the best possible accuracy can be achieved if the constant K in equation (3) is estimated for the specific area and season[9]. In practical applications, radiosonde data provide temperature T_i and water vapor pressure $P_{w,j}$ from the surface to different heights, $h_i (i = 0, 1, 2 \cdots, n)$, by a discretized formula (6). T_m can be computed as[10]

$$T_m = \frac{\sum_{i=0}^{i=n-1} \frac{\overline{P}_{w,j}}{\overline{T}_i}(h_{i+1} - h_i)}{\sum_{i=0}^{i=n-1} \frac{\overline{P}_{w,j}}{\overline{T}_i^2(h_{i+1} - h_i)}} \quad (6)$$

where $\overline{P}_{w,j}$ and $\overline{T}_i$ denote the average water vapor pressure and average temperature, respectively, in the atmosphere from h_i to h_{i+1} $\overline{P}_{w,j} = \frac{1}{2}(P_{w,j+1} + P_{w,j})$; $\overline{T}_i = \frac{1}{2}(T_{i+1} + T_i)$.

T_m can be accurately determined using formula (6). However, obtaining radiosonde observations at every GPS station simultaneously is impossible in practical applications. According to Bevis, T_m can be estimated from the surface temperature measurements[1]. The linear regression T_m can be derived from the radiosonde data and the surface temperature data T_s, as given by

$$T_m = a + bT_s \tag{7}$$

The coefficients in the formula (7) have been estimated to minimize the residuals using the method of least squares $\sum_{i}^{n} (a + bT_{s,i} - T_{m,i}) = \min$.

For more accurate estimations of GPS PWV of the applied area, some regionally optimized models that are better adapted to the geographical and climatic characteristics of the specific area have been proposed in China. Table 1 gives a brief outline of the Bevis model and some regionally empirical models in China. Because the heights of the four radiosonde stations are within 200 m, we use $T_m = T_{m(B)} + 5.1$, $h < 200$ m in equation (10) as the regional model in the applied area.

3 Results and discussion

The data from four radiosonde stations collected over an eleven month period (from Jan. to Nov. of 2011) are used to analyze the feasibility of strategies for modeling the regional empirical T_m (the weighted mean temperature of the atmosphere) for the applied area, as well as to perform a comparative study of various T_m models. Figure 1

Table 1 The models for the weighted mean temperature of the atmosphere

Model	Mean temperature
Bevis et al[1,5] Eq. (8)	$T_{m(B)} = 70.2°K + 0.72T_s(°K)$
Wang et al[4] Eq. (9)	$T_{m(CHN1)} = 53.244°K + 0.783T_s(°K)$
Yu and Liu [3] Eq. (10)	$T_{m(CHN2)} = \begin{cases} T_m = T_{m(B)} + 5.1, & h < 200\text{ m} \\ T_m = T_{m(B)} + 3.0, & 200\text{ m} \leqslant h < 500\text{ m} \\ T_m = T_{m(B)} + 2.1, & 500\text{ m} \leqslant h < 1500\text{ m} \\ T_m = T_{m(B)} - 6.6, & h \geqslant 3000\text{ m} \end{cases}$
Chen et al[2] Eq. (11)	$T_{m(HK)} = 106.7°K + 0.605T_s(°K)$

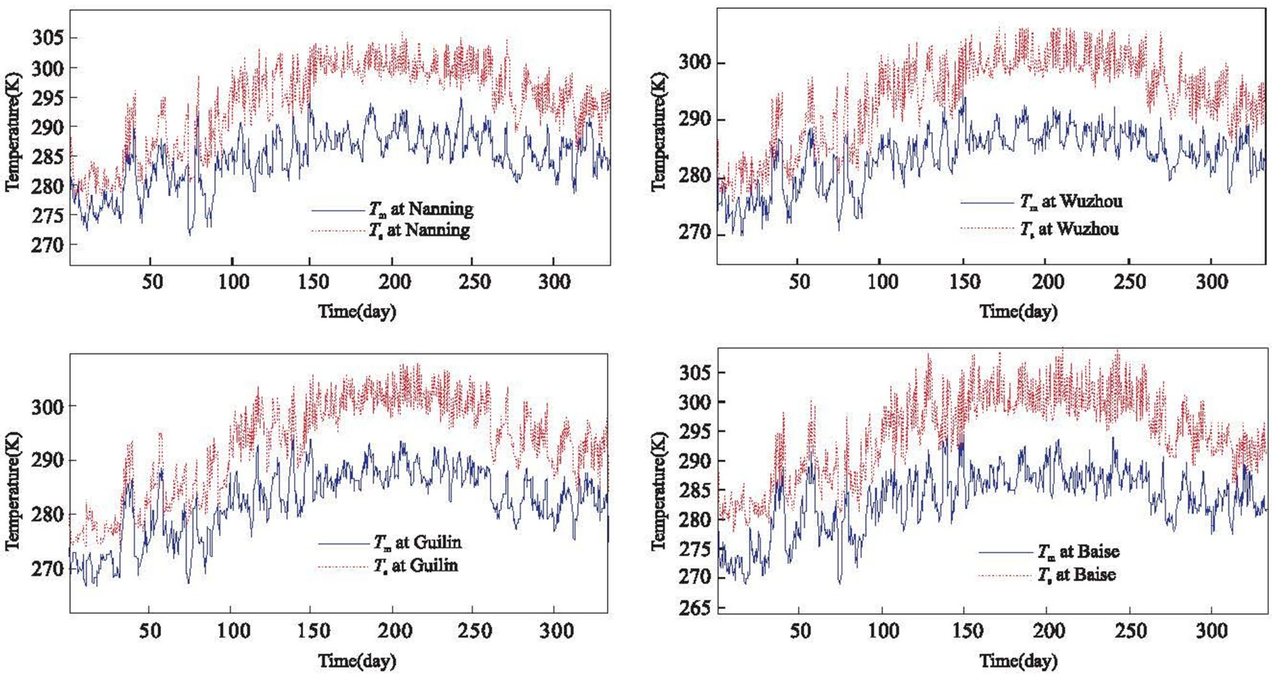

Figure 1 Variations in T_m and T_s with time at the radiosonde stations from the analysis of the data samples

shows the annual variation T_m and T_s with time at four radiosonde stations from the analysis of the data samples. From figure 1, we can see that both T_m and T_s regularly vary with the season and that the maximum and minimum values of T_m and T_s occur in spring and summer, respectively, at the four radiosonde stations. Compared with spring, there is no significant variation in T_m and T_s during the summer. In addition, the T_m values range from approximately 265 K to 305 K in the applied area, corresponding to the dimensionless conversion constant that lies approximately between 0.145 and 0.175[3]. Owing to the T_m and T_s variations with the season, obtaining monthly regression equations is necessary to analyze the seasonal change in T_m.

As mentioned in the analysis above, both equation (9) and equation (10) are models based on the radiosonde data distributed over a large study area. Because the weighted mean temperature of the atmosphere varies with altitude, season and geographical location and due to the irregular and uneven distribution of the radiosonde stations, we proposed three strategies to build a regionally optimized model that is better adapted to the applied area: (1) the monthly regression equations are estimated to analyze the seasonal change in T_m at each radiosonde site; (2) the annual regression equations are estimated to perform a comparative study between the monthly and annual regression results; and (3) the regional regression equations are estimated for a more accurate estimation of the GPS PWV in the area lacking radiosonde observations and to perform a comparative study with other existing regional T_m models. Tables 2 to 4 are the results of the linear regressions using these three strategies. The root mean square (RMS), mean absolute error (MAE), and maximum

Table 2 Monthly analysis of coefficients and from the radiosonde data

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Annual
Nanning	A	148.99	66.71	72.37	213.28	86.19	160.95	117.93	101.43	126.19	96.44	190.77	116.90
	B	0.45	0.75	0.72	0.24	0.67	0.42	0.57	0.62	0.54	0.64	0.32	0.57
	RMS	1.71	1.72	3.60	2.13	2.54	1.35	1.86	1.82	1.80	1.68	2.65	2.35
	MAE	1.43	1.38	2.90	1.64	1.93	1.11	1.61	1.44	1.39	1.30	2.07	2.04
	MIN	-4.69	-4.05	-5.63	-4.94	-8.48	-2.86	-3.42	-7.28	-5.54	-4.14	-4.86	-9.31
	MAX	3.23	5.73	11.40	5.58	3.77	3.56	4.00	3.06	4.37	3.56	6.98	9.78
Guilin	a	223.49	12.93	133.72	176.71	54.43	140.96	151.72	181.06	78.70	99.20	116.38	90.47
	b	0.17	0.93	0.50	0.36	0.78	0.48	0.45	0.35	0.69	0.62	0.57	0.65
	RMS	1.79	2.28	3.05	2.88	2.89	1.34	1.82	1.96	1.47	1.59	2.33	2.51
	MAE	1.54	1.82	2.41	2.11	2.17	1.13	1.57	1.67	1.27	1..23	1.93	2.03
	MIN	-2.98	-5.77	-5.73	7.49	-8.06	-3.57	-3.21	-4.74	-2.26	-3.63	-4.96	-8.15
	MAX	3.54	4.74	7.43	8.58	5.32	2.39	3.24	3.92	3.36	3.81	4.94	10.75
Wuzhou	a	169.42	53.94	76.51	189.27	89.27	144.49	112.31	176.68	135.70	135.56	152.04	109.02
	b	0.38	0.79	0.70	0.32	0.66	0.47	0.58	0.37	0.50	0.50	0.45	0.59
	RMS	2.12	2 .00	3.05	1.94	2.56	1.42	1.51	1.59	1.53	1.43	2.52	2.20
	MAE	1.70	1.58	2.41	1.58	2.04	1.09	1.23	1.22	1.24	1.13	2.07	1.70
	MIN	-4.41	-4.14	-6.06	-3.29	-6.36	-4.77	-3.12	-5.36	-3.25	-4.14	-4.86	-6.90
	MAX	4.90	5.79	8.34	6.08	3.12	2.37	-3.77	3.23	3.89	3.57	4.30	8.29
Baise	a	89.60	22.91	57.31	147.69	122.94	148.51	156.77	161.55	152.05	71.98	169.64	89.58
	b	0.65	0.89	0.77	0.46	0.55	0.46	0.44	0.42	0.45	0.72	0.39	0.66
	RMS	1.82	2.68	2.94	2.05	3.19	1.21	1.81	1.60	1.79	1.67	2.44	2.51
	MAE	1.36	2.19	2.38	1.63	2.62	0.91	1.56	1.27	1.50	1.40	1.98	2.11
	MIN	-4.32	-6.27	5.88	-4.60	-7.97	-3.04	-3.76	-4.22	-3.77	-3.66	-5.45	-8.02
	MAX	4.92	5.34	8.40	6.30	4.60	3.50	3.83	2.94	3.97	2.97	5.72	9.05

Table 3 Comparison of the annual regional model and the site models

	Nanning	Guilin	Wuzhou	Baise	Hybrid	Bevis
A	116.90	90.47	109.02	89.58	100.16	70.20
B	0.57	0.65	0.59	0.66	0.62	0.72
RMS	2.35	2.51	2.20	2.51	2.53	3.09
RMS (Hybrid to Site)	2.65	2.60	2.22	2.62		
RMS (Site to Site)	3.19		2.68	2.52		
RMS (Bevis to Site)	3.79	2.81	2.97	2.69		

Table 4 The differences between the regional Hybrid model and other models

Surface temprature (℃)	-5	0	5	10	15	20	25	30	35	40
Hybrid -Wang (K)	2.83	2.01	1.19	0.36	-0.46	-1.28	-2.10	-2.92	-3.75	-4.57
Hybrid -Yu (K)	-0.99	-1.47	-1.96	-2.44	-2.92	-3.40	-3.88	-4.37	-4.85	-5.33
Hybrid -Bevis (K)	4.11	3.63	3.14	2.66	2.18	1.70	1.22	0.73	0.25	-0.23
Hybrid -Guilin (K)	1.38	1.22	1.07	0.91	0.76	0.60	0.45	0.29	0.14	-0.02
Hybrid -Nanning (K)	-2.53	-2.26	-2.00	-1.73	-1.47	-1.20	-0.94	-0.67	-0.41	-0.14
Hybrid -Wuzhou (K)	-0.90	-0.75	-0.61	-0.46	-0.31	-0.16	-0.01	0.14	0.29	0.43
Hybrid -Baise (K)	1.59	1.43	1.26	1.09	0.92	0.76	0.59	0.42	0.25	0.09

(MAX) and minimum (MIN) errors are used to assess the precision of the linear regression equations. These linear regression equations are named the Site model and the Hybrid model.

The analysis of coefficients *a* and *b* from the monthly radiosonde data is shown in table 2. Coefficients *a* and *b* vary by month, and the RMS values in March are the highest at Nanning, Guilin and Wuzhou. In addition, the regional Hybrid model provides the same level of accuracy as the monthly regression equations. The RMS and MAE values of all annual linear regression equations are less than 3 K, which corresponds to an error of less than 1 mm in the GPS-derived PWV[10]. It can be concluded that there is no need to build monthly T_m models and that the annual linear regression equations can be used for all eleven months.

In table 3, the precision of the annual linear regression equations using radiosonde data in the applied area are equivalent, and the RMS values are less than 3 K. The situation is different when applying the Bevis model, for which the RMS values can reach 3.79 K when fitting the radiosonde data at Nanning; the RMS fitting for all of the radiosonde data observed at all of the radiosonde stations is 3.09 K. We chose the annual linear regression equations of Guilin to fit the three other radiosonde data sets to analyze the precision of the site-specific T_m used in other radiosonde stations. The table shows that the precisions are lower than that of the regional Hybrid model when fitting the radiosonde data from Nanning and Wuzhou. Hence, we conclude that the Hybrid model can be used to achieve an accuracy within 1 mm in the GPS-derived PWV estimates for the applied region, whereas the Site models cannot be used; furthermore, the precision of the regional models that are based on the data from the area surrounding the site is higher than that of the Bevis model.

To further assess the precision of different T_m models for the applied region, we chose the Hybrid model as the regional T_m model to perform a comparative study of the various T_m models. The extreme maximum and minimum temperatures generally range from 36℃ to 42℃ and from minus 6℃ to 0℃, respectively, in Guangxi over the studied years. The differences between the Hybrid model and other models are shown in table 4. The differences between the Hybrid model and the Bevis model, between the Hybrid model and the Wang model and between the Hybrid model and the Yu model range from 0.13 K to 3.57 K, −2.40 K to 3.28 K and −4.96 K to −1.53 K, respectively, when the surface temperature ranges from −5℃ to 40℃. Thus, we can further conclude that to estimate GPS PWV with an accuracy of 1 mm in all seasons in the applied region, the Bevis model, Wang model, Yu model and one Site model are not appropriate for the applied region, whereas the differences between the Hybrid model and the four Site models are less than 3 K for all possible temperatures in the applied area.

4 Conclusions

The results of this comparative study of different regional T_m models in the region of Guangxi indicate that building a monthly T_m model is not necessary and that the precision of the proposed regional Hybrid empirical T_m model is higher than that of the Bevis model and other existing models. In addition, the proposed regional Hybrid empirical T_m model can provide an accuracy of 1 mm in the GPS PWV estimations in all seasons for the applied area. Although the well-known Bevis model is a simple and acceptable choice for many regional studies and many regional empirical T_m models deduced using radiosonde station data in China, a regional empirical model that is better adapted to the geographical and climatic characteristics of a specific region is still necessary for more accurate determinations.

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