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Development of Time-dependent mean Temperature Equations for GPS Meteorology

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ABSTRACT

The mean temperature is one of the key parameters in computing Precipitable Water Vapor (PWV) from Global Positioning System (GPS) measurements and is usually derived as a function of surface temperature through the use of a mean temperature equation (MTE). In this study, two new types of MTEs were developed as functions solely of the observation time so that the mean temperature can be obtained without surface temperature measurements. To validate the new models, we created one-year time series of GPS-derived PWV using the new MTEs and compared them with the radiosonde-observed PWV. The bias and root-mean-square error were on the other of ~1 mm and ~2 mm, respectively.

Keywords: GPS, GPS meteorology, mean temperature equation, precipitable water vapor

1. INTRODUCTION

Global Positioning System (GPS) satellite signals are delayed due to water vapor in the troposphere of the Earth before reaching GPS receivers on the ground. Based on GPS measurements, information on the water vapor distribution in the atmosphere can be obtained by computing tropospheric delays of the GPS signal. GPS meteorology provides the amount of Precipitable Water Vapor (PWV), Slant Wet Delay (SWD) and Zenith Wet Delay (ZWD). Such GPS-based meteorological information, if assimilated as a predicator or a climatic factor in Numerical Weather Prediction (NWP), can be utilized to improve the performance of NWP models (Kuo et al. 1998).

Recently, to improve the accuracy of GPS-derived PWV (this quantity will be referred to as GPS PWV hereafter), a variety of studies are being conducted to develop optimized models for local meteorological conditions. Regional atmospheric model developments for GPS meteorology are usually concerned with a Mean Temperature Equation (MTE) and refraction constants. Especially, the MTE is a key parameter in translating ZWD into PWV. Bevis et al. (1992) suggested that the mean temperature of the atmosphere can be approximated by the surface temperature. The Bevis model (Bevis et al. 1992) was developed using radiosonde measurements taken at 13 sites in North America. Emardson & Derks (2000) developed a model more suited to the climatic conditions of Europe. Liou et al. (2000) developed a local MTE model in addition to monthly MTEs, based on meteorological observations in Taiwan. Woo (2003) and Ha et al. (2006) developed local MTEs based on radiosonde observations in South Korea. All the MTE models mentioned in this paragraph are given as linear functions of the surface temperature and thus temperature-measuring devices should be co-located at the GPS site

In this study, we propose two new types of mean temperature models, in which surface temperature measurements are unnecessary. The novel concepts behind the newly developed MTE models are introduced in the following section and validation results through the error analysis of GPS PWV values obtained with new models are described in Section 3.

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2. TIME-DEPENDENT MEAN TEMPERATURE EQUATIONS

Through the GPS data processing, the amount of the GPS

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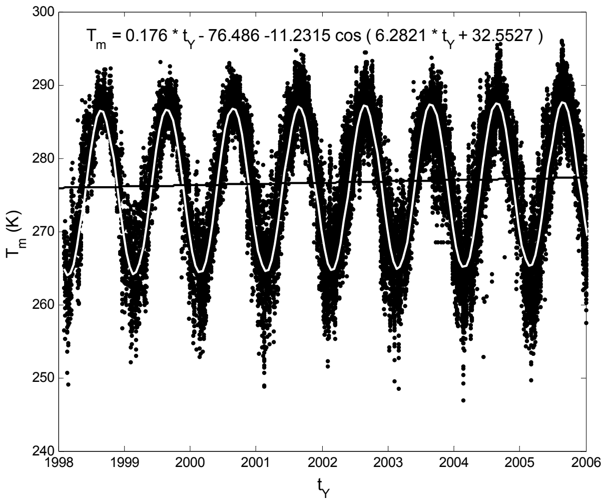

Fig. 1. Mean temperature variations with respect to the observation time in a yearly scale for the years 1998 through 2005.

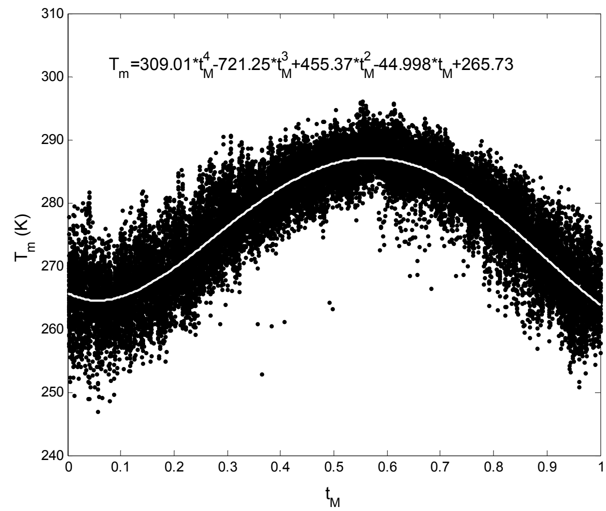

Fig. 2. Mean temperature variations with respect to the observation time in a monthly scale for the years 1998 through 2005.

signal delay caused by water vapor can be obtained as ZWD. Then, the estimated ZWD should be converted to PWV by Eq. (1).

$$PWV = \Pi \cdot ZWD \tag{1}$$

where

$$\Pi = \frac{10^6}{\rho R_v [k_3 / T_m + k_2^{'}]} \tag{2}$$

In Eq. (2), ρ is the density of liquid water (998.00879 kg/m^3), and R_v is the specific gas constant of water vapor (4.615 × 10^2 J/kg·K). k_3 and $k_2^{'}$ are refraction constants and their values are (3.776 ± 0.004)×10^5 K^2/mbar and (17 ± 10) K/mbar, respectively (Davis et al. 1985). T_m is the mean temperature of the atmosphere. The only variable in Eq. (2) is T_m, thus it is a key component in deriving GPS PWV from ZWD estimates. T_m is usually expressed as a function of surface temperature T_s. The most widely used MTE is the Bevis model, which is represented as $T_m = 0.72T_s + 70.2$ (Bevis et al. 1992).

The mean temperature can be obtained from the radiosonde measurement using the observed temperature and the partial pressure of water vapor (Davis et al. 1985). Radiosonde observations used in this study span eight years from 1998 through 2005 and they are taken at seven domestic radiosonde stations in South Korea. Fig. 1 shows the mean temperature variations with respect to the year. The relation between T_m and observation time t_Y (t_Y stands for yearly time scale) was estimated as a sinusoidal function with a linear trend, and the result is depicted in Eq. (3).

$$T_m = 0.176t_Y - 76.486 - 11.2315\cos(6.2821t_Y + 32.5527) \tag{3}$$

The RMS between T_m computed by Eq. (3) and radiosonde observations is 4.2 K. With Eq. (3), one can get the mean temperature just by plugging in the observation time as a yearly time scale.

As another method of deriving time-dependent MTEs, the observed mean temperatures against observation time t_M (t_M stands for monthly time scale) were plotted in Fig. 2. In the figure, the horizontal axis is t_M; 0.0 corresponds to January 1st and 1.0 December 31st. Then the second-, third-, fourth-, and sixth-order polynomials were tried to find out the best fitting function. When the four fitted solutions were compared with radiosonde measurements, the RMS differences were in the range of 4.1-4.7 K. The best agreement was achieved for the fourth-order polynomial and the exact relation is shown in Eq. (4).

$$T_m = 309.01t_M^4 - 721.25t_M^3 + 455.37t_M^2 - 44.998t_M + 265.73 \tag{4}$$

Hereafter, the two MTEs shown in Eqs. (3) and (4) will be referred to as HPt_Y and HPt_M, respectively.

For the error analysis, the mean temperatures observed from radiosondes and those predicted by the Bevis, HPt_Y and HPt_M models are plotted together in Fig. 3. In comparison with the time-dependent MTE models, mean temperature differences of the Bevis model show clear seasonal signals. For the cases of the HPt_Y and HPt_M models, the scatters of mean temperature differences are larger than the Bevis model, with the largest discrepancies periodically

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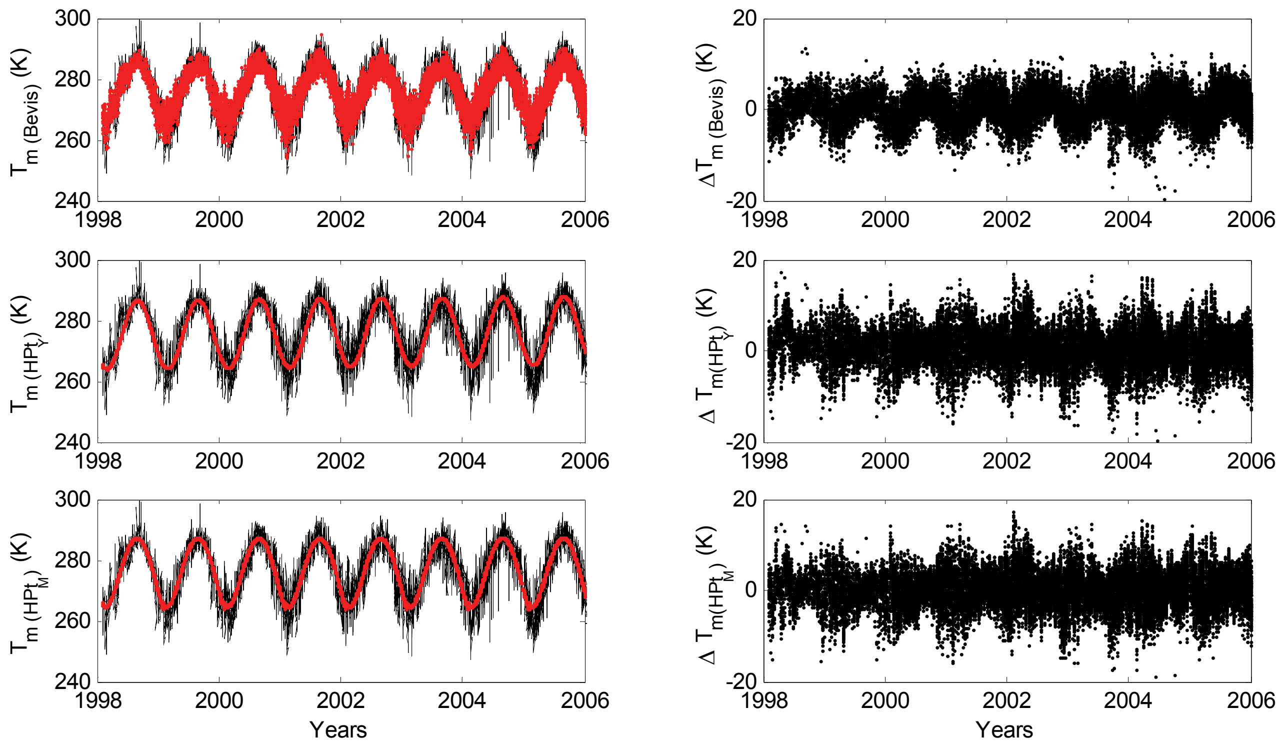

Fig. 3. The left hand sides are mean temperatures observed (black solid line) and calculated (red dots) with each of three MTE models (Bevis, HPt_Y, and HPt_M) during the years 1998 through 2005. The right hand sides are the corresponding differences.

Table 1. The mean, variance, and accumulative T_m error distribution over 10K, 4K, 3K, 2K and 1K differences of the Bevis, HPt_Y, and HPt_M Mean Temperature Equation models with respect to the radiosonde observation.

	Mean	Variance	Error distribution (%)				
	(K)	(K^2)	> 10K	> 4K	> 3K	> 2K	> 1K
Bevis	-0.2	12.0	0.6	31.3	47.4	66.6	88.8
HPt_Y	-0.0	17.5	3.0	37.0	51.9	69.9	89.7
HPt_M	-0.5	16.5	2.6	36.4	51.8	69.6	89.6

happening in the winter months.

The error statistics of the three MTE models with respect to the radiosonde measurements are listed in Table 1. In the table, mean differences are negative, implying that mean temperatures computed by the three MTEs are larger than the radiosonde observation in the average sense. The HPt_Y model has a zero bias, but its variance shows the largest value. In the case of the Bevis model, the variance and accumulated error are the lowest. Also, the Bevis model produces ~5% smaller errors in the range of >4 K differences. Thus we conclude that MTEs as functions of surface temperatures are slightly better than time-dependent ones. However, in the following section, we will show that the performance of the new models is comparable to that of the Bevis model by computing one-year time series of GPS PWV and comparing them with radiosonde-observed PWV.

3. VALIDATION OF THE NEW MODELS

For validation of the HPt_Y and HPt_M model, PWV estimates were obtained based on GPS and radiosonde measurements taken at the Sokcho weather station for one year from March 1, 2008 to February 28, 2009. The Sokcho weather station located in the eastern Korea has a permanent GPS site and conducts radiosonde observations twice a day at 00:00 and 12:00 UTC. Thus, it is a perfect site to check the performance of GPS PWV against the radiosonde measurement. For the GPS data processing, GIPSY-OASIS II developed by Jet Propulsion Laboratory (JPL) was used (Webb & Zumberge 1993). The 24-hour GPS data were processed with the standard precise point positioning technique by utilizing the JPL-provided precise orbit and clock solutions (Zumberge et al. 1997). The analysis results are shown in Fig. 4, where PWV values at 00:00 and 12:00 UTC are shown.

Fig. 4a depicts GPS PWV computed with the Bevis model, together with radiosonde PWV. Even though radiosonde and GPS PWV show the same tendency, most of the radiosonde PWV values are slightly larger than GPS estimates as can be seen in Fig 4b. Fig. 4b shows PWV differences between GPS PWV obtained with three MTE models and radiosonde

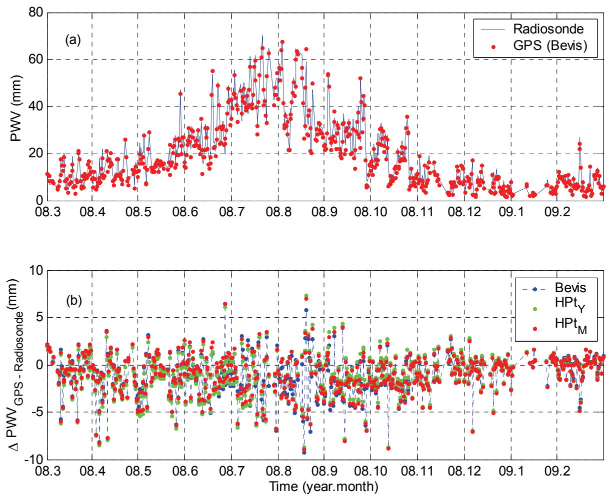

Fig. 4. (a) Radiosonde PWV (blue solid line) and GPS PWV (red dots) using the Bevis model at the Sokcho weather station from March 1, 2008 to February 28, 2009, (b) PWV differences between radiosonde PWV and GPS PWV values obtained with three different MTE models.

PWV. From Fig. 4b, one can find that the differences are very similar regardless of the choice of the MTE model, and most of the differences are lying in the range of ±0.5 mm.

The biases between radiosonde PWV with GPS PWV, which were computed with three different MTE models, are almost at the same level. The biases for the Bevis, HPt_Y and HPt_M models are -1.0 mm, -1.0 mm, and -1.1 mm, respectively. The RMS values of GPS PWV computed with the Bevis, HPt_Y and HPt_M models are 2.4 mm, 2.3 mm, and 2.4 mm, respectively. In addition to these results, we found that the RMS and bias errors obtained in this test are comparable to previous studies of validating GPS PWV with radiosonde PWV (e.g., Liou et al. 2000, Niell et al. 2001). Thus we conclude that one can replace the linear regression type MTE, which is a function of the surface temperature, with the time-dependent one without losing the accuracy and precision of GPS PWV.

4. CONCLUSIONS

Local MTE models (HPt_Y and HPt_M) as functions of the observation time were developed using the eight-year-long radiosonde measurements collected at seven radiosonde sites in South Korea. The accuracies of local models and the Bevis model were analyzed with radiosonde observations assumed as the truth. The errors of the Bevis model showed seasonal signals with high errors in the summer and winter seasons. For the HPt_M and HPt_Y models, the errors were higher only during the winter months. For validation of the newly developed models, we compared radiosonde PWV and GPS PWV for one year. Radiosonde PWV and GPS PWV computed with three MTE models show similar trends, and the biases are ~1 mm. Also the RMS values were almost the same at ~2 mm. This result indicates that, if a locally optimized time-dependent MTE is available, it is possible to obtain accurate and precise PWV without surface temperature measurements.

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