Journal of Atmospheric and Solar-Terrestrial Physics 107 (2014) 48–53

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Weighted mean temperature model for extra tropical region of India

D. Singh*, J.K. Ghosh, D. Kashyap

Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee 247667, Uttarakhand, India

A R T I C L E I N F O

Article history:
Received 30 December 2011
Received in revised form
6 September 2013
Accepted 28 October 2013
Available online 11 November 2013

Keywords:
Weighted mean temperature
GPS
PWV
Regional
Site specific

A B S T R A C T

The Global Positioning System (GPS) estimates Precipitable Water Vapor (PWV) from Zenith Wet Delay (ZWD) using a key parameter called water vapor weighted mean temperature (T_m) of the atmosphere. However, T_m must be tuned to the specific area and location. Therefore, for estimation of PWV using GPS within the region covered between New Delhi and Srinagar, site specific as well as a regional T_m model has been developed as a function of surface temperature using six years radiosonde data. The result shows that the root mean square error (rmse) of the developed site-specific T_m model is about 3.5 °K at New Delhi and Patiala. However, the rmse of the developed site-specific T_m model at Srinagar is in the range of 4–5.5 °K. It has been found that the site specific T_m model is slightly (0.1–0.5 °K) better than the developed regional T_m model at New Delhi and Patiala, however, the error is more at Srinagar. It finds that the site-specific model is better than the regional and the global model in predicting PWV and provides sub mm accuracy within this region. However, the developed regional model provides the same level of accuracy in estimating PWV and more suitable for this region compared to other regional and global model. The GPS PWV has shown an accuracy of about 6.5 mm using site specific and regional T_m model and found comparatively better than other regional and global T_m model.

1. Introduction

The water vapor content of the atmosphere is the most important parameter in establishing the earth's climate and its short-term changes are an essential piece of information for severe weather forecasting and operational weather prediction (Bevis et al., 1994). It also plays an important role in the atmospheric radiation and the hydrological cycle. Traditionally, the highly variable spatial and temporal distribution of atmospheric water vapor has been essentially determined using a network of balloon–borne radiosonde. The water vapor in the neutral atmosphere is responsible for part of the propagation delay of signals used by GPS. The delay due to water vapor, measured along zenith direction called the Zenith Wet Delay (ZWD). Thus, PWV is directly proportional to the ZWD obtained from ground based GPS receiver. The transform of ZWD estimates into PWV requires the knowledge of the weighted mean temperature of the atmosphere. Since the weighted mean temperature of the atmosphere depends on the vertical profiles of both temperature and water vapor, it should vary in space and time as well as seasonally (Bevis et al., 1992). Most of these weighted mean temperature models are linear models (Bevis et al., 1992; Mendes et al., 2000; Solbrig, 2000; Schueller et al., 2001) based on surface temperature, developed using the altitude profiles of atmospheric water vapor pressure and temperature obtained from different parts of the globe. These global linear models show a variability of about 20% (Bevis et al., 1994). Mendes et al. (2000) evaluated the accuracy of some models (Bevis et al., 1992, 1994; Mendes et al., 2000; Emerdson and Derks, 2000) and concluded that regionally optimized models do not give superior performance compared to the global models. In a study conducted over the Indian subcontinent, Jade et al. (2005) concluded that the most of the weighted mean temperature global models yield almost the same value for Integrated Water Vapor (IWV) for all sites. In an another study Ross and Rosenfeld (1997) after an extensive study on weighted mean temperature based on the meteorological data from 53 global stations concluded that the site specific model would be superior to the geographically and globally invariant model used for weighted mean temperature. However, in the tropics (0–30°N or 0–30°S) the correlation between weighted mean temperature and surface temperature decreases so much that this superiority is not very prominent. This is due to the range of surface temperature variation is rather small. In such cases, regional model is better. A recent study conducted in India on weighted mean temperature models show that the weighted mean temperature model is adequate for the region or station, where the temperature variations are large i.e. at higher latitudes in India (Raju et al., 2007). It is also observed that the station specific weighted mean temperature model is not superior to a region specific model over the tropics. It is also obvious that for a vast country like India

* Corresponding author. Mobile: +91 7579048964.
E-mail address: dinesh1100iitr@gmail.com (D. Singh).

1364-6826/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jastp.2013.10.016

having different climatic condition, a single regional weighted mean temperature model may not be suitable for all sites. The climatic condition is not same in tropical as well as in the extra tropical region of India. The extra tropical region in India shows the large seasonal variation of atmospheric temperature and water vapor content. Therefore, in this study a small region covering between New Delhi and Srinagar is considered, which falls in the extra tropical region. Annual mean PWV is less than 20 mm at Srinagar, which is in mid latitude and shows the large seasonal variation of surface temperature (about 45 °C). Patiala and New Delhi show large seasonal temperature variation (about 40–45 °C). The T_m models show high correlation with T_s and this might be due to the range of T_s variation is large at mid latitude. Though, T_m is not a crucial factor, but it is not negligible especially at mid latitude. Bevis et al. (1994) have shown that the relative error in T_m associates with the relative error in PWV. Ross and Rosenfeld (1997) have also shown that the relative error in T_m corresponds to an absolute error of PWV of 0.1–0.5 mm. The relative estimate of T_m estimated from Bevis et al. (1992) equation is larger at middle and higher latitude. Ross and Rosenfeld (1997) concluded that reduction of relative error of T_m at middle and high latitude could be achieved through the use of site-specific T_m model based on surface temperature. In order to estimate PWV over this region, a regional T_m model has been developed using radiosonde data from three stations available within this region. In addition, site-specific model has also been developed for New Delhi, Patiala and Srinagar.

2. Study area and data

The radiosondes data cover the period 2006 to 2010 for New Delhi (28.58N, 77.20N), Patiala (30.33N, 76.46N) and Srinagar (34.08N, 74.83). Only three radiosonde stations are available within this region (28.58° N to 34.08° N). Generally, radiosonde balloons are launched twice a daily and give altitude profiles of pressure, temperature and relative humidity. For estimation of weighted mean temperature (T_m) of the atmosphere using radiosonde data, only those radiosonde data for which the partial water vapor pressure (e) and temperature vertical profiles extending up to 5 km and above have been used for this purpose. The source of radiosonde data is the database of Wyoming University Upper air (Wyoming University Upper air data, 2012). Note that 95% of atmospheric water vapor exists within 5 km from the surface of the earth. The major advantages of radiosonde data are that it provides a good vertical resolution. The degradation of the measurements of relative humidity at high altitude, because of contamination of the sensors is a major disadvantage of the radiosonde. However, the quality of data was controlled through a set of steps, such as elimination of soundings with no surface data recorded; elimination of level within soundings without observations of pressure, temperature, relative humidity and mixing ratio; assurance of most number levels per soundings. The partial water vapor pressure computed from mixing ratio available in the radiosonde data. The radiosonde data also has computed PWV for each epoch called the radiosonde PWV. The radiosonde PWV is the truth-value or reference value. The three stations used in the data analysis are New Delhi, Patiala and Srinagar.

3. Methodology

Exact calculations of T_m require profiles of atmospheric temperature and water vapor pressure from radio soundings. The T_m of the atmosphere is defined and approximated as Davis et al. (1985)

$$T_m = \frac{\sum_{i=1}^{n} \frac{e_i}{T_i} dz_i}{\sum_{i=1}^{n} \frac{e_i}{T_i^2} dz_i} \tag{1}$$

where, n is a number of levels; e_i is the mean partial pressure (in hPa) of water vapor of ith layer; T_i is the mean atmospheric temperature (in Kelvin) of ith layer; dz_i stands for the thickness of ith layer. Askne and Nordius (1987) related PWV and ZWD through a linear relation given as

$$\mathrm{PWV} = \prod \times \mathrm{ZWD} \tag{2}$$

where Π is the proportionality coefficient, which is related to T_m and it is expressed as:

$$\prod{}^{-1} = 10^{-6} \rho R_v [(k_3/T_m) + k'_2] \tag{3}$$

where, ρ is the density of liquid water, R_v is the specific gas constant for water vapor, and k_2' and k_3 are refractivity constants. The above Eq. (1) is used to compute T_m using radiosonde data and considered as the 'true value or reference value' in this study. It will be used for evaluation of accuracy of T_m models in the present study. Since the vertical profiles of e and T that is usually not available at all sites. Therefore, T_m is estimated commonly using empirical linear relationship between surface temperature and estimated T_m for a site or regions. Hence, site-specific T_m models for New Delhi, Patiala and Srinagar have been developed as a function of surface temperature in the present work. Bevis et al. (1992) derived T_m model is $T_m = 70.2 + 0.72 T_s$ and Raju et al. (2007) derived T_m model for Indian region is $T_m = 62.6 + 0.75 T_s$. T_s is the surface temperature in Kelvin.

Note that the ZWD can also be derived from GPS data. However, in this study ZWD is estimated by vertical integration of the wet refractivity values of all vertical layers in the radiosonde data and mathematically written as given below

$$\mathrm{ZWD} \approx 10^{-6} \sum_{i=1}^{n} \frac{N_w^i + N_w^{i+1}}{2} \Delta H_{i+1,i} \tag{4}$$

where N_w: wet refractivity, superscript $i+1$ denotes the nearest upward profile point, i is the current profile point. $\Delta dH_{i+1,i}$ geopotential height difference between the nearest upward and the current profile point i, and n is the total number of profiles available in radiosonde data. The wet refractivity N_w is given by Thayer (1974) is

$$N_w = \left[K'_2 \left(\frac{e}{T} \right) + K_3 \left(\frac{e}{T^2} \right) \right] Z_w^{-1} \tag{5}$$

where $K'_2 = 16.5 \pm 10$ K/mbar, $K_3 = 377{,}600 \pm 3000$ K^2/mbar and Z_w^{-1} is the inverse compressibility and its expression is (Owens, 1967)

$$Z_w^{-1} = 1 + 1650 \left(\frac{e}{T^3} \right) [1 - 0.01317 T_c + 1.75 \times 10^{-4} T_c^2 + 1.44 T_c^3] \tag{6}$$

where T_c is the temperature in Celsius [°C]; T is in Kelvin [°K]; e partial pressure of water vapor in mbar. Finally, ZWD can be estimated from radiosonde data based on Eqs. (4)–(6). The estimated ZWD from radiosonde data based on Eq. (4) will serve as input in the further analysis to estimate PWV using different T_m models.

4. Results

4.1. Development of site specific T_m models for different location

The T_m is estimated based on Eq. (1) for New Delhi, Patiala and Srinagar using three years data of radiosonde (2006–2008) for each location. The site-specific T_m models are developed using linear regression between the estimated T_m and corresponding surface temperature (T_s) of each location. A scatter plot between estimated T_m and T_s of all three locations along with regression line and all statistical parameters are shown in Figs. 1–3.

The developed site specific weighted mean temperature model at New Delhi, Patiala and Srinagar are given sequentially