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Establishment of Relationship Between Water-Vapour-Weighted Mean Temperature and Surface Temperature and its Application for Determining Precipitable Water Vapour for India

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ABSTRACT

Atmospheric water vapour plays vital role in weather and climate of the earth. It is also a key parameter for designing the weather model or forecast model for atmospheric extreme events. Accurate measurement of water vapour is essential requirement for any weather model. In this paper, we have derived the local expression for relating water-vapour-weighted mean temperature and surface temperature for different radiosonde sites over the Indian subcontinent. The local expression is used to determine the precipitable water vapour (PWV) over the Indian stations. The study presented here improves the characterization of one crucial element of the hydrologic cycle, the atmospheric water vapour over the Indian subcontinent.

Keywords: *Weighted mean temperature, Surface temperature, Hydrological cycle, Water vapour and GPS meteorology.*

1. Introduction

Atmospheric water vapour plays vital role in weather and climate of the earth. The atmospheric water vapour is also referred to as tropospheric water vapour as the troposphere contains 99% of the water vapour in the atmosphere. The transport of water vapour across the globe acts as driving force for the weather system of earth's atmosphere. The tropospheric water vapour plays crucial role in the earth's weather and climate system. The major part of atmospheric wetness is in the form of water vapour, and this it has crucial impact on the energy balance of atmosphere. If all the water vapour in the air are condensed at particular instant and fall as rain, then the amount would be a depth of only about 2.5-3 cm. This is known as precipitable water. The precipitable water vapour (PWV) is a measure of the total water in vapour form contained in a vertical column of the atmosphere.

The development of GPS satellite system made a drastic change in remote sensing technology. The radio wave propagation through troposphere depends on refractive index of the medium. Apart from atmospheric pressure and temperature, the water vapour content of troposphere also affects the refractive index of the medium. The GPS based remote sensing of troposphere of the earth is popularly known as GPS meteorology. Cheng et al. (2012) and Bevis et al. (1992 a&b) introduced the concept of GPS meteorology in which atmospheric delay in GPS signals could be used for measurement of meteorological parameters. The GPS signal experiences bending as well as retardation while they travel through troposphere. The bending of the GPS signal is due to gradients in the refractive index of the atmosphere. The GPS signal propagates on a curved path instead of the straight line path The difference between the lengths of these two paths is known as the geometrical delay. The waves propagate slower in a troposphere than they would in a vacuum. The required additional time to overcome a given path can also be stated in term of excess path length. The total delay experienced by GPS signal in troposphere is the addition of these two components and can be written as (Rocken et al., 1995).

$$Delay\,\Delta L = \int_C n(s)ds - G \qquad (1)$$

where ΔL is the entire tropospheric delay expressed in form of the equivalent increase in path length, $n(s)$ is the refractive index of the troposphere which varies as a function of location along the curved path *C,* and *G* is the geometrical straight path through the troposphere .The bending component has very insignificant value , about 1cm or less, for paths with elevations greater than about 15^0 . For the GPS signal oriented along the zenith, the delay ΔL is known as zenith total delay (ZTD) and Equation (1) becomes,

$$ZTD = \int_L [n(s) - 1] ds \qquad (2)$$

where ZTD is the total tropospheric delay in the zenith direction. The integral is along the zenith path, and the delay is given in units of s. Equations (1) and (2) are often formulated in terms of atmospheric refractivity *N* rather than the index of refraction, which is defined by,

$$N = 10^6(n-1) \qquad (3)$$

The atmospheric refractivity *N* is fundamental to all theories about radio wave transmission through the neutral atmosphere. The standard mathematical expression for the atmospheric refractivity is (Smith & Weintraub, 1953),

$$N = k_1 \frac{P_d}{T} + k_2 \frac{P_v}{T} + k_3 \frac{P_v}{T^2} \qquad (4)$$

Where *T* is the absolute temperature in Kelvin and P_d and $P_v$are the partial pressures of the dry gases and water vapour respectively, in mbar.

The refraction coefficients k_1 , k_2 and $k_3$were determined empirically and given by the values mention below (Bean, 1966).

k_1=(77.607±0.13)$K\ mbar^{-1} k_2$
=(71.6±8.5) $K\ mbar^{-1}$

k_3= (3.747 ±0.031) X$10^5 K^2 mbar^{-2}$

A more precise expression for refractivity is proposed by Thayer (1974) by considering the non-ideal gaseous behaviour of the atmosphere.

$$N = k_1 \frac{P_d}{T} Z_d^{-1} + k_2 \frac{P_v}{T} Z_v^{-1} + k_3 \frac{P_v}{T^2} Z_v^{-1} \qquad (5)$$

Where $Z_d^{-1}$and Z_v^{-1} are the inverse compressibility factors (corrections for the small departures of the moist atmosphere from an ideal gas) for dry air and water vapour respectively. The first term of the right hand side of the mathematical expression for refractivity (Equation 2) represents contribution due to dry gases. It is usually denoted as dry refractivity N_d. The last two terms represent contribution due to moist air or water vapour. It is denoted as wet refractivity N_w. The total refractivity is represented by

$$N = N_d + N_w \qquad (6)$$

According to the above equations, we can separate the atmospheric delay also into dry or hydrostatic delay and wet delay. So we can write the zenith tropospheric delay (Equation 2) as,

$$ZTD = \int_L [n(s) - 1] ds = 10^6 \int_L N ds = 10^6 \int_L N_h ds + 10^6 \int_L N_w ds = ZHD + ZWD \qquad (7)$$

Where ZHD the zenith is hydrostatic delay and ZWD is the zenith wet delay. The integrated precipitable water vapour (IWV) is defined as:

$$IWV = \int \rho_v\ dz = k\ (ZWD) \qquad (8)$$

Where $\rho_v$the water vapour density in the atmosphere is, $ZWD$is the zenith wet delay, and the “constant” k is given by:

$$\frac{1}{k} = 10^{-6} \left(\frac{k_3}{T_m} + k_2\right) R_v \qquad (9)$$

Here $R_v$is the specific gas constant for water vapour. Using the mathematical expression for mean weighted temperature of the atmosphere T_m

$$T_m = \frac{\int \frac{P_v}{T} dz}{\int \frac{P_v}{T^2} dz} \qquad (10)$$

Bevis et al (1994) derived the relation between mean weighted temperature of the atmosphere T_m and surface temperature T_s is given by,

$$T_m = 70.2 + 072\ T_s \qquad (11)$$

The mean weighted temperature of the atmosphere T_m depends upon surface temperature of the station. The accuracy of PWV measurement depends upon the value of mean weighted temperature of the atmosphere T_m. The Equation (11) is derived by Bevis using data of 13 radiosonde sites of United States of America.

The geographical conditions of radiosonde stations of India will be different from the radiosonde sites used by Bevis. So Equation (11) becomes,

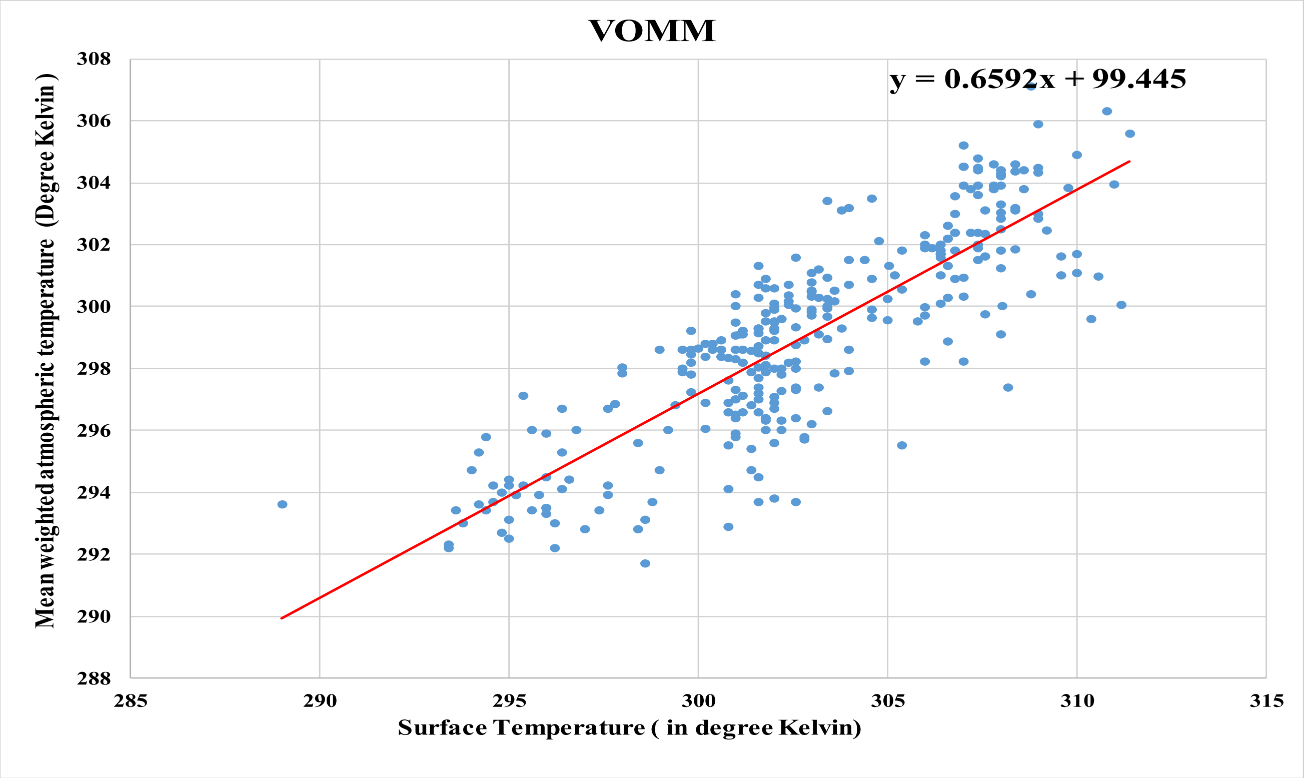

Figure 1: Surface temperature T_s and mean weighted atmospheric temperature T_m at VOMM.

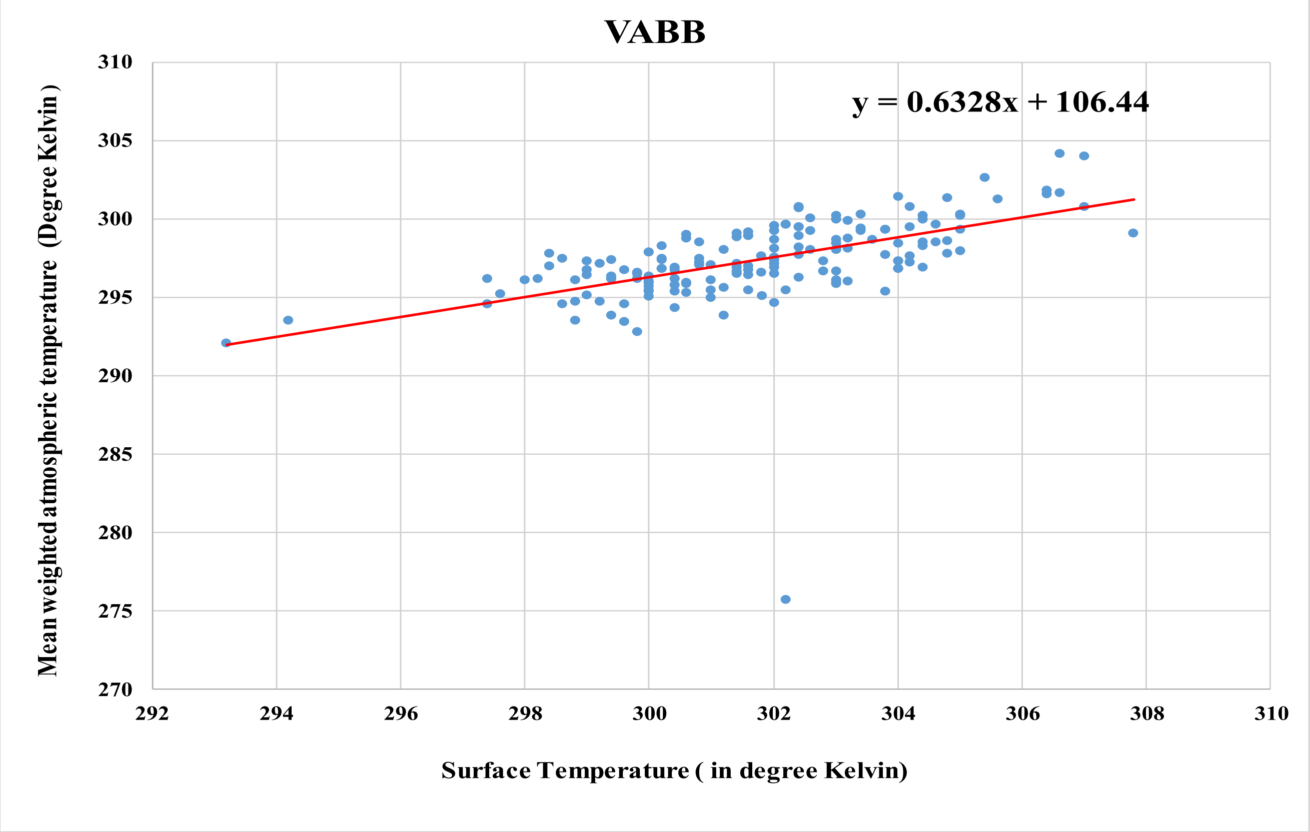

Figure 2: Surface temperature T_s and mean weighted atmospheric temperature T_m at VABB.

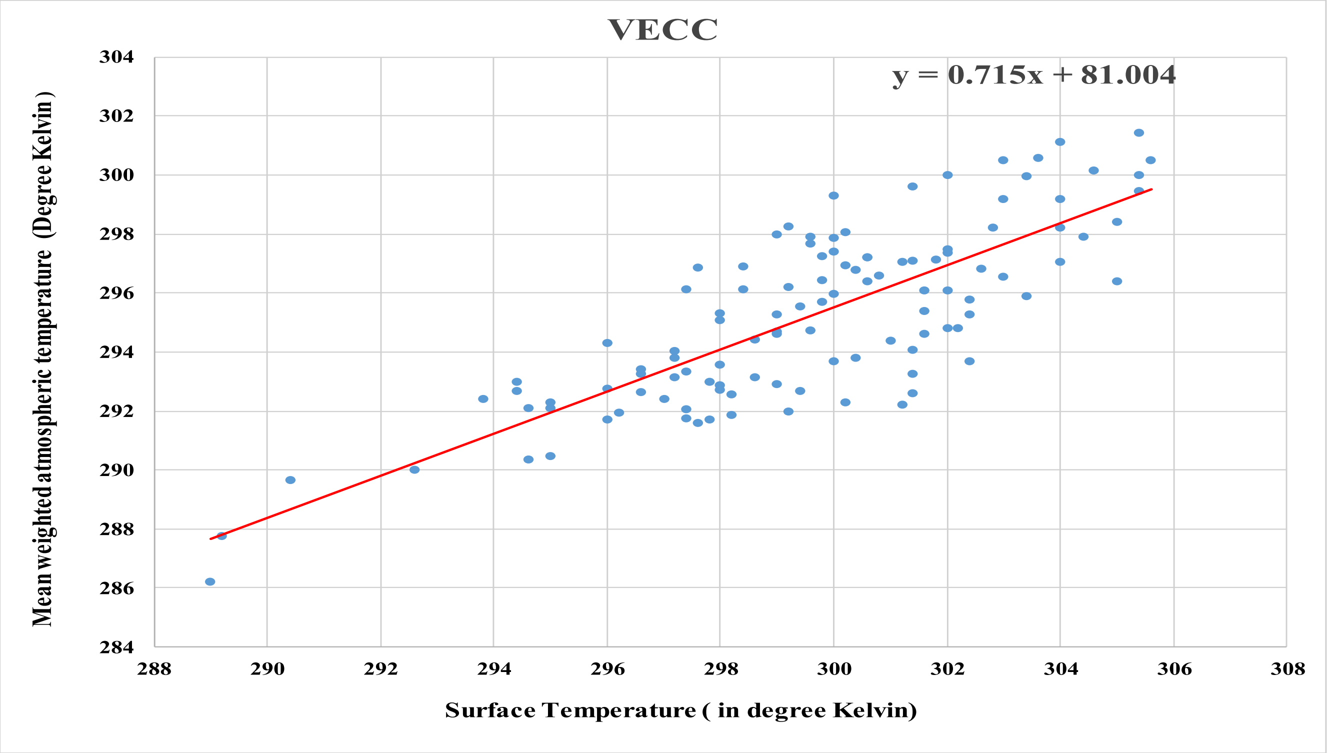

Figure 3: Surface temperature T_s and mean weighted atmospheric temperature T_m at VECC.

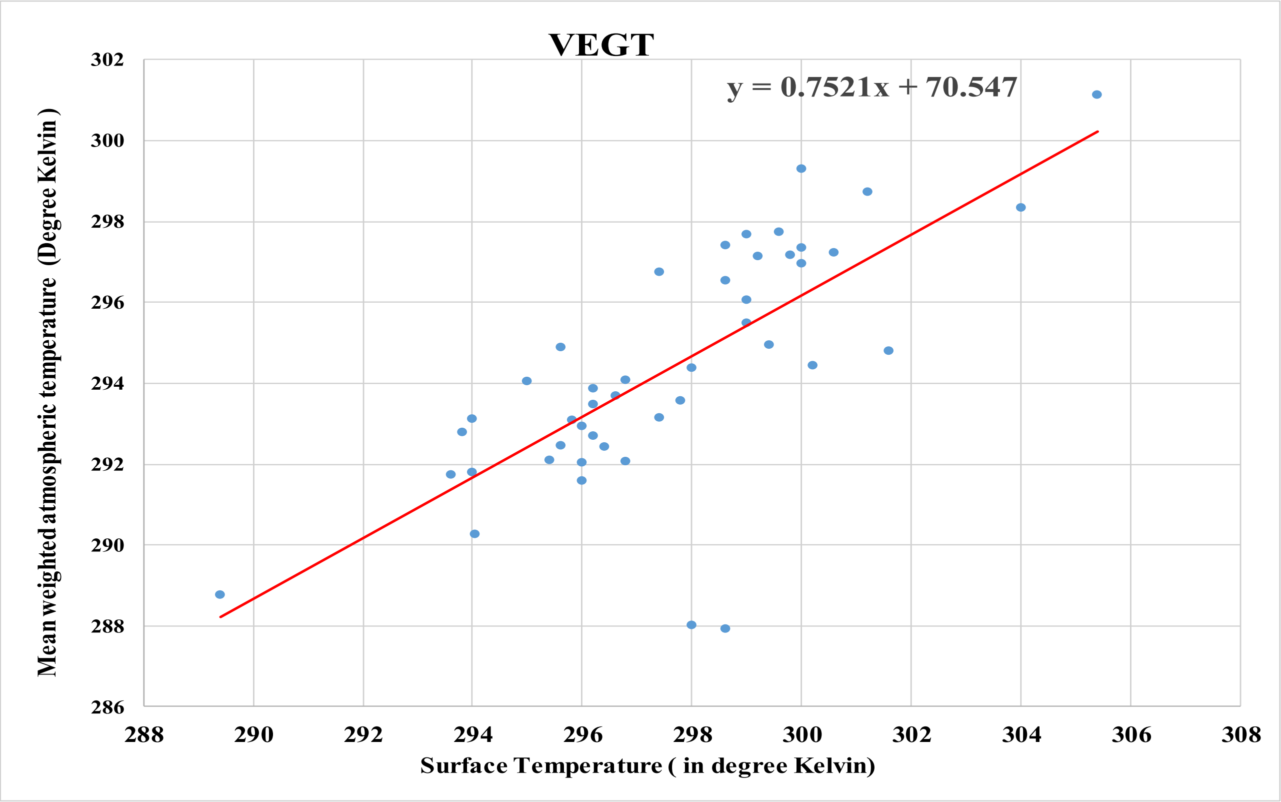

Figure 4: Surface temperature T_s& mean weighted atmospheric temperature T_m at VEGT.

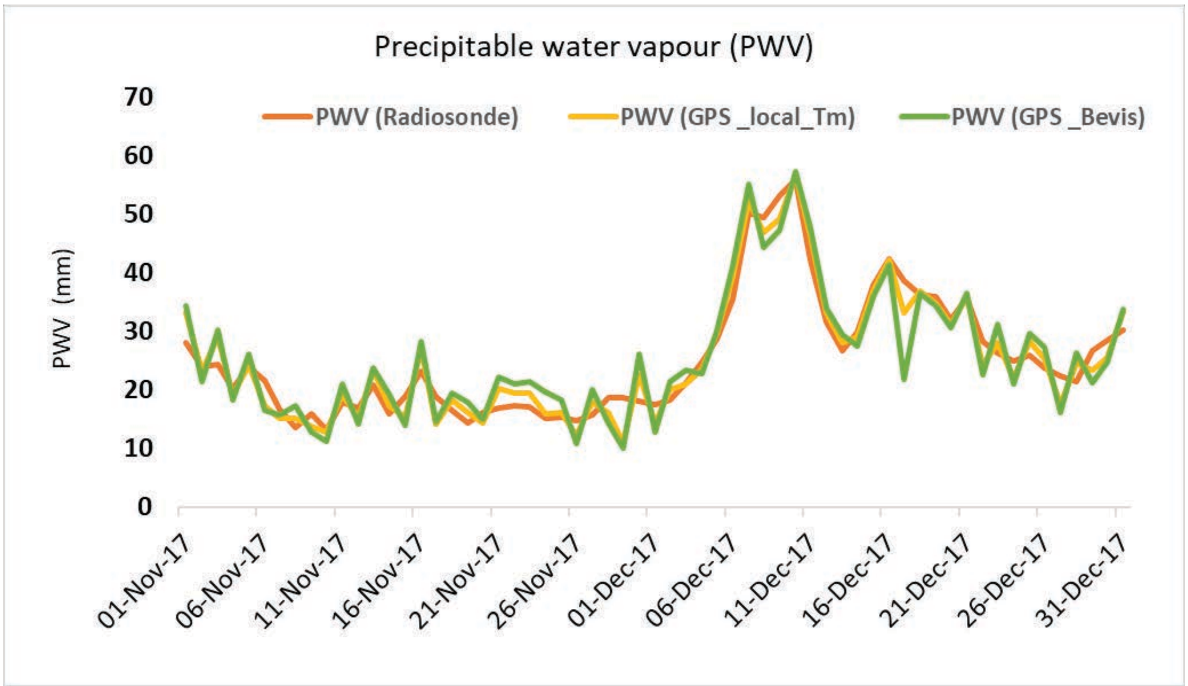

Figure 5: Comparison of Precipitable Water Vapour (PWV) at Mumba (VABB).

inappropriate at all the locations other than USA. The expression for T_m derived using radiosonde data and geographical conditions of Indian subcontinent will be more appropriate and will result in accurate PWV over the station. In this paper the Equation (11) is modified according to Indian geographical conditions.

2. Data and Methodology

Bevis et al. (1994) derived the relation between mean weighted temperature of the atmosphere T_m and surface temperature T_s. In statistics, linear regression is a linear approach to modelling the relationship between a scalar response and one or more explanatory variables. The case of one explanatory variable is called simple linear regression. For more than one explanatory variable, the process is called multiple linear regression .The relation between mean weighted temperature of the atmosphere T_m and surface temperature T_s are determined for selected radiosonde sites of India using linear regression model for the radio sounding observations for upper air. The daily radiosonde soundings are obtained for selected locations. The geographical locations of selected radiosonde stations are described in Table 1.

Table 1. Geographical locations of selected radiosonde stations in India.

Station Code	Geographical location
VOMM (Chennai)	13.0827° N, 80.2707° E
VABB (Mumbai)	19.0760° N, 72.8777° E
VECC (Kolkata)	22.5726° N, 88.3639° E
VEGT (Guwahati)	26.1445° N, 91.7362° E

The obtained radiosonde observations are processed for linear regression analysis between surface temperature and water-vapour-weighted mean temperature. Similar analysis is repeated for all the selected radiosonde sites. The Precipitable Water Vapour (PWV) is derived for Mumbai (VABB) using Equation (8). We derived the PWV using both the values of T_m i.e the value of T_m using the relation provided by Bevies (Bevis et al., 1994) and relation obtained in Table 2. These values are compared with values obtained by radio sounding data for the same station. The accuracy of both the methods are also determined by Root Mean Square Error (RMSE) and Mean Square Error (MSE) analysis

3. Results

The relation between mean weighted temperature of the atmosphere T_m and surface temperature T_s is

Table 2. The expression obtained for mean weighted atmospheric temperature T_m at different locations.

Station Code	Geographical location	Expression for Surface temperature T_s and mean weighted atmospheric temperature T_m
VOMM (Chennai)	**13.0827° N, 80.2707° E**	$T_m = 99.4 + 0.65\ T_s$
VABB (Mumbai)	**19.0760° N, 72.8777° E**	$T_m = 106.4 + 0.63\ T_s$
VECC (Kolkata)	**22.5726° N, 88.3639° E**	$T_m = 81.0 + 0.71\ T_s$
VEGT (Guwahati)	**26.1445° N, 91.7362° E**	$T_m = 70.0 + 0.75\ T_s$

determined for selected radiosonde sites of India using linear regression model for the radio sounding observations for upper air. The obtained results are shown in Figures 1 to 4. They represent the linear relationship between T_m and T_s at Chennai (VOMM), Mumbai (VABB), Kolkata (VECC) and Guwahati (VEGT) respectively. The expression obtained for mean weighted atmospheric temperature T_m at different locations are described in Table 2. The PWV derived for Mumbai (VABB) using Equation (8) is shown in Figure 5. It shows the values of PWV derived using radiosonde data, using local relation for T_m and using Bevis relation for T_m. When we examine Figure 5, we observe that the yellow line (Gps_local) is always closer to the orange line (PWV_radiosonde) in comparison with the green line (GPs_Bevis). Here, we consider PWV value derived from radio sounding data as standard value. The deviations in GPS_local derived PWV values from the corresponding standard values are less as compared to GPS_Bevis derived PWV values. The same is reflected in the error analysis given in Table 3. Thus it can be inferred that the accuracy increases when we use the local relation in the measurement of PWV.

Table 3. RSME & MSE analysis.

Station Code VABB (Mumbai)	**RSME (mm)**	**MSE (mm^2)**
PWV using Local relation	2.8	7.5
PWV using Bevis relation	4.5	23.8

4. Conclusions

The relationship between water-vapour-weighted mean temperature T_m and surface temperature T_s is established in this study. It implies that the T_m is dependent on geographical location of the observation site. Usually PWV is determined using T_m. For accurate measurement of PWV, it is desirable to have accurate value of T_m. The results obtained in this study can be applicable for precise measurement of PWV at respective radiosonde sites. Precise measurement of PWV will improve the weather model and forecast of extreme weather events.

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