Water Vapour Weighted Mean Temperature Model for GPS-Derived Integrated Water Vapour in Peninsular Malaysia

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ABSTRACT:

This paper presents the development of T_M model by using the radiosonde stations from Peninsular Malaysia. Two types of T_M model were developed; site-specific and regional models. The result revealed that the estimation from site-specific model has small improvement compared to the regional model, indicating that the regional model is adequately to use in estimation of GPS-derived IWV over Peninsular Malaysia. Meanwhile, this study found that the diurnal cycle of T_S has influenced the T_M-T_S relationship. The separation between daytime and nighttime observation can improve the relationship of T_M-T_S. However, the impact of diurnal cycle to IWV estimation is less than 1%. The T_M model from Global and Tropic also been evaluated. The Tropic T_M model is superior to be utilized as compared to the Global T_M model.

1. INTRODUCTION

The Global Positioning System (GPS) nominally consists of at least 24 satellites in almost circular orbital planes, with altitudes of about 22,000 kilometres above the Earth's surface. The satellites continuously transmit their signals through the Earth's atmosphere to ground-based receivers and accordingly, the effect of the atmosphere on the propagation of the GPS signal path (or atmospheric delay) provides information about water vapour contents in the atmosphere (Bevis et al., 1992).

The delays were represented as zenith path delay (ZPD) that can be divided into two parts: i) zenith hydrostatic delay (ZHD), which depends only on surface air pressure; and ii) zenith wet delay (ZWD), which is a function of atmospheric water vapour profile (Businger et al., 1996). Information about these delays has enabled the application of GPS for meteorology such as studying diurnal variation in water vapour (see Dai et al., 2002); improving numerical weather prediction (see Gendt et al., 2004) and climate monitoring (see Nilsson and Elgered, 2008). A number of studies have shown that it is offering better spatial distribution, continuous observation, not affected by rainfall and clouds, inexpensive to setup, and a promising tool to complement other remote sensing technique of measuring water vapour content (Ware et al.,2000; Wolfe and Gutman, 2000).

The processes of GPS meteorology, specifically in the estimation of GPS-derived integrated water vapour (IWV) or equivalently precipitable water vapour (PWV), require a fundamental parameter of 'water vapour weighted mean temperature of the atmosphere or TM' since both these IWV and ZWD are interrelated (Wang et al., 2005). A commonly used method to estimate the T_M parameter; (1) to apply a regression function from the relationship of surface air temperature (TS) as described by Musa et al., (2011) and Liou et al., (2001), (2) reanalyses the output from numerical weather prediction model such as Jin et al., (2009) and Heise et al., (2009), (3) estimate by using the Global Pressure and Temperature (GPT) model developed by Boehm et al., (2007) (Yao et al., 2012).

The GPS-derived IWV can be written as (Askne and Nordius, 1987);

$$\mathrm{IWV} = \mathrm{ZWD}/\overline{\mathrm{K}} \tag{1}$$

and,

$$\overline{\mathrm{K}} = \frac{10^6}{R_v\left(\frac{k_3}{T_M} + k_2'\right)} \tag{2}$$

where R_v is the gas constant for water vapour, k_3 and k'_2 are the atmospheric refractivity constants (see Thayer, 1974; Bevis et al., 1994). The T_M in Equation 2 is given by (Wang et al., 2005);

$$T_M = \frac{\int\left(\frac{e}{T}\right)dz}{\int\left(\frac{e}{T^2}\right)dz} \approx \frac{\sum_{i=1}^{N} \frac{e}{T}(h_{i+1} + h_i)}{\sum_{i=1}^{N} \frac{e}{T^2}(h_{i+1} + h_i)} \tag{3}$$

where T is the surface temperature of the radiosonde profile, dz is the function of vertical profile that is defined as the geo-potential height h of radiosonde with respect to vertical profile of the surface pressure layer along the troposphere layer and, e is the surface partial pressure of water vapour that can be defined as;

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$$e = 6.107 \times E^{\frac{a \times T_d}{b + T_d}} \tag{4}$$

where T_d is the dew temperature [a=21.87 and b=265.49 when T_d is below 55°C or a=17.26 and b=237.29, when T_d is above 0°C]. Practically, the weighted T_M parameter can be derived by empirical regression function using the relationship of T_M and T_S;

$$T_M = m \cdot T_S + c \tag{5}$$

where the value of m and c parameters represent the sensitivity of T_M - T_S relationship. Table 1 list several existing T_M models that were developed following equation 5.

Table 1. The existing T_M model with the author

T_M model	Equation		Author
Global 1	$T_M = 0.72\ T_S + 70.2$	(6)	Bevis et al., (1992)
Global 2	$T_M = 0.64\ T_S + 86.9$	(7)	Schueler et al., (2001)
Global 3	$T_M = 0.8116\ T_S + 43.69$	(8)	Yao et al., (2014)
Tropic 1	$T_M = 1.07\ T_S - 31.5$	(9)	Liou et al., (2001)
Tropic 2	$T_M = 0.75\ T_S + 62.57$	(10)	Suresh Raju et al., (2007)
Tropic 3	$T_M = 0.84\ T_S + 48.103$	(11)	Wayan et al., (2013)

The Global 1 model has been developed by using radiosonde data covering the America region over 2 year period (1990-1991). The Global 1 model has been widely utilized, especially in GPS-derived IWV such as utilized by Jin et al. (2008); Musa et al., (2011); Xu et al. (2012). However, the Global 1 does not represent the actual climatic condition worldwide. Thus, several efforts have been made to improve the global T_M model such as demonstrated by Global 2 and Global 3. The Global 2 attempted to cover the whole world by using global scale analysis of numerical weather prediction. Meanwhile, Yao et al. (2014) conducted extensive work to adjust the Global 1 model; 135 globally distributed radiosonde stations was utilized spanning 10-year period and Global 3 model was realized.

Ross and Rossenfeld (1997) and Wang et al. (2005) have performed the evaluation study on the Global 1 model. In general, both of them found that the Global 1 model is limited especially in the tropics. Ross and Rossenfeld (1997) found that the Global 1 has a systematic warm bias due to the shorter data period used. Wang et al. (2005) found that Global 1 suffer from the cold bias of 1-6K in the tropics and sub-tropic. Moreover, the Global 1 also suffer from diurnal cycle about 1-4K in morning (00-06 LST) and 3-6 K at night (20-23 LST).

Due to some limitations from these Global models, most of the communities in the tropics have attempted to adapt the Global 1 by using the local or regional radiosonde basis observation to support their regional needs. The Tropic 1 model was developed by using the radiosonde observation at Taipei spanning from year 1988 to 1997. Tropic 2 model was developed to cover the Indian region using data from year 1995 to 1997. Meanwhile, the Tropic 3 model was developed for Western Pacific region (latitude and longitude range 20°N-20°S and 95°E-156°E) from 15 radiosonde stations for whole year 2011. From their results, it was found that the estimation of GPS-derived IWV can be improved by using their own T_M model rather than Global T_M model.

Therefore, this study seeks to attempt an estimation of a T_M parameter for Peninsular Malaysia with a view to utilizing the estimated T_M for GPS-derived IWV estimation.

2. DATA SET: RADIOSONDE AND GPS STATION

The observation from the radiosonde is the primary data for developing the T_M model over Peninsular Malaysia. This radiosonde observation is usually carried out by launching helium gas balloon to the upper atmosphere which allow to measure meteorological parameters. The radiosonde is built by a package meteorological sensor for measuring the pressure, temperature, dew point and geo-potential height (Durre et al., 2006).

In Peninsular Malaysia, there are four well distributed radiosonde stations comprising two on the west coast (Sepang (SPNG) and Bayan Lepas (WMKP)) and two on the east coast (Kota Bahru (WMKC) and Kuantan (WMKD)). These radiosonde stations are named according to the World Meteorological Organization (WMO) radiosonde station identifier. In Malaysia, Malaysian Meteorological Department (MetMalaysia) is the responsible agency to operate the radiosonde launches. The MetMalaysia routinely launch the radiosonde balloon twice daily at 00 and 12 UTC (or 8 am and 8 pm local time).

Three years period of radiosonde data from year 2006-2008 have been acquired from MetMalaysia and has been utilized to estimate T_M parameter, hence, a local T_M model was developed. However, prior to the estimation of the TM parameter, inspection of radiosonde data was conducted to detect missing data and erroneous observations. Thus, the outliers were filtered out and removed from the computation leaving only clean radiosonde data for estimation of the T_M parameter and radiosonde-derived IWV for assessment.

In addition, measurements from four (4) GPS continuously operating reference stations (CORS) which are located nearest to these radiosonde stations were also acquired. These GPS CORS (i.e., Pulau Pinang (USMP), Banting (BTNG), Geting (GETI) and Pekan (PEKN)) are part of the Malaysian Real-Time Kinematic network (MyRTKnet) which is being maintained by the Department of Survey & Mapping Malaysia (DSMM). Only GPS data in year 2008 is available for this study and the ZPD parameter from these stations was estimated according to Musa et al., (2011). Figure 1 shows the spatial location of the radiosonde stations and the GPS CORS, while Table 2 lists the site coordinates of each radiosonde station and the GPS CORS respectively.

Table 2. The coordinates of radiosonde stations and GPS CORS, and the different height and distance between radiosonde station and GPS CORS. Different height between GPS and Radiosonde station can affect the T_M if above the 100 m (Wang et al., 2005). There is no height extrapolation applied because of the different in height is below than 100m.

Radiosonde Station	Latitude	Longitude	GPS CORS	Latitude	Longitude	ΔH (m)	ΔD(km)
SPNG	2° 44’	101° 42’	**BTNG**	2° 49’	101° 32’	29.21	12.25
WMKP	5° 18’	100° 16’	**USMP**	5° 21’	100° 18’	8.219	4.4
WMKC	6° 10’	102° 17’	**GETI**	6° 13’	102° 06’	3.181	18.8
WMKD	3° 47’	103° 13’	**PEKN**	3° 29’	103° 23’	4.667	37.79

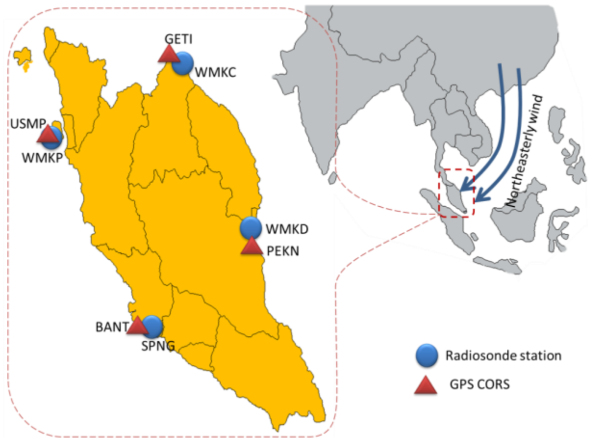

Figure 1. The spatial location of radiosonde station and GPS CORS in Peninsular Malaysia. Right figure shows the northeasterly wind direction flow out from northern hemisphere contribute the variability in T_S at east coast region (Figure is adapted accordingly Tangang et al., (2008)).

3. RESULTS – T_M, T_M-T_S RELATIONSHIP AND DIURNAL CYCLE IN BODY OF TEXT

3.1 Estimation of the T_M Parameter

The filtered and cleaned radiosonde data was used as an input into Equation 3. The result of T_M which covers the period 2006 to 2008 is provided in Table 3. Meanwhile, the statistics of T_S which was measured at ground surface level at radiosonde station is provided in Table 4.

Table 3. The statistical result of T_M for each radiosonde station

Station	Min (K)	Max (K)	Average (K)	Variation (K)
SPNG	283.148	294.153	287.962	1.472
WMKD	283.473	294.647	288.331	1.522
WMKC	283.011	293.122	288.692	1.583
WMKP	283.285	293.998	288.510	1.509

Table 4. The statistical result of T_S for each radiosonde station

Station	Min (K)	Max (K)	Average (K)	Variation (K)
SPNG	293.75	304.55	299	1.894
WMKD	293.55	304.15	298.501	2.013
WMKC	293.122	303.75	299	2.031
WMKP	295.35	303.95	299.56	1.841

The average of T_M over Peninsular Malaysia is almost consistent at all radiosonde stations which range from 287.962K to 288.692K. The annual T_M gradient is very weak which is below 2K. This study found similar result with Ross and Rosenfeld, (1997) which conducted a study on the estimation of T_M parameter over 23-year period observational data from 53 radiosonde stations of global radiosonde network. They found that the T_M at several radiosonde stations close to low-latitude as listed in Table 5 is relatively higher than in Peninsular Malaysia, ranging from about 1-2K. Moreover, Suresh Raju et al., (2007) conducted similar study in Indian region and found that the T_M at near low-latitude region (e.g. Trivandrum (8.5°N), Port Blair (11.6 °N), Bangalore (12.9°N), Kolkata (22.6°N) and Ahmedabad (23.1°N)) fall between 284.1 to 287.8K.

Table 5. Several selected radiosonde stations utilized by Ross and Rosenfeld, (1997). From 53 radiosonde stations, only 5 stations are located near low-latitude. They did not include any radiosonde station located close to equatorial region such as Malaysia.

Location	Latitude °N, Longitude °W	Annual Mean (K)	Variation (K)
Niger	13.5, 357.8	291.61	2.72
Guam	13.5, 215.2	292.74	0.52
Hawaii	19.7, 155.1	289.85	1.11
India	21.1, 280.9	291.92	2.46
Mexico	20.9, 89.7	291.39	1.24
Puerto Rico	18.4, 66.0	291.22	0.89

* Note that, these values have been corrected after the coding error was discovered in the global analysis (Ross and Rosenfeld, 1999).

The geographical location has the major influence on the variability of T_S in Peninsular Malaysia. In low latitude region, the sun’s zenith distance remains relatively short throughout the year. Earth’s surface absorbs maximum amount of solar radiation from sun compared to middle and high latitudes. Thus, the T_S remain warmer with values ranging from 298.501 to 299.56K at all radiosonde stations in Peninsular Malaysia with less variation of about 1.841 to 2.031K throughout the year.

3.2 Variability of T_M and T_S

The three years period of radiosonde data (2006-2008) are utilized to observe the variability of T_M-T_S in Peninsular Malaysia. Figures 2 (a-d) show the time series of T_M and T_S at each radiosonde stations.

The time series show that the daily variation of T_M and T_S are low range ≈10K and low variation throughout the year (see Table 3 and 4). The climatic characteristic in low latitude is only wet and dried without appearance of the season changes such as in middle-latitudes. The low-latitude atmosphere is relatively warm to support tropical climate and activities. There is no clear appearance of seasonal cycle trend found at all radiosonde stations.

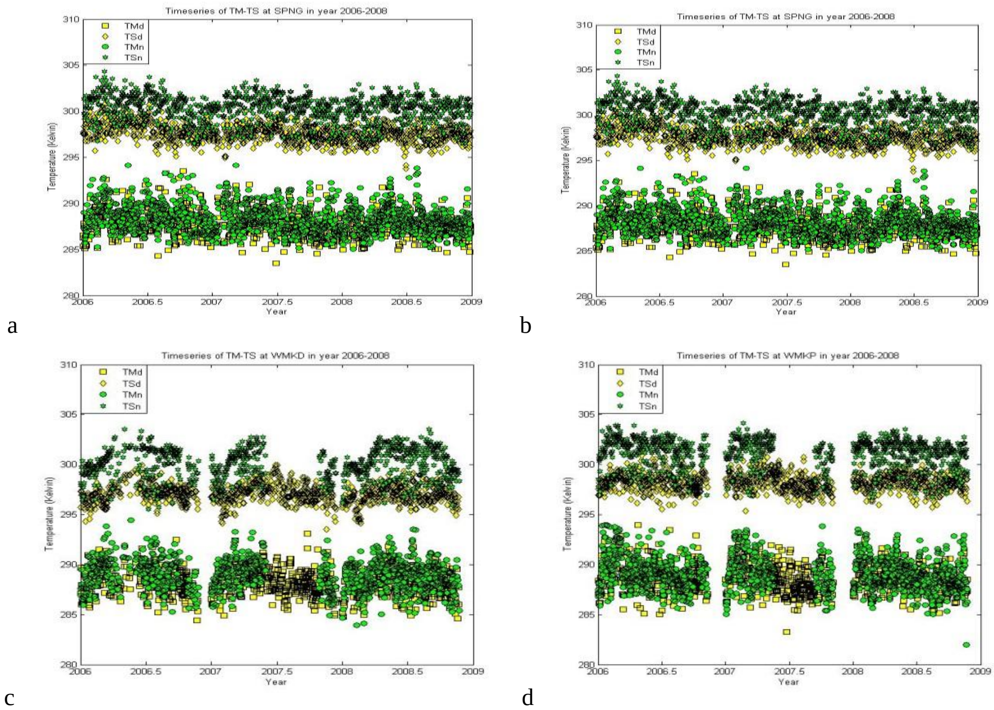

Figure 2. The time-series of T_M and T_S at SPNG (a), WMKC (b), WMKD (c) and WMKP (d). The TS is higher about 10K compared to the T_M. From this figure, it can be clearly seen that observed TS at nighttime is higher than daytime. Meanwhile, no different found in T_M between daytime and nighttime.

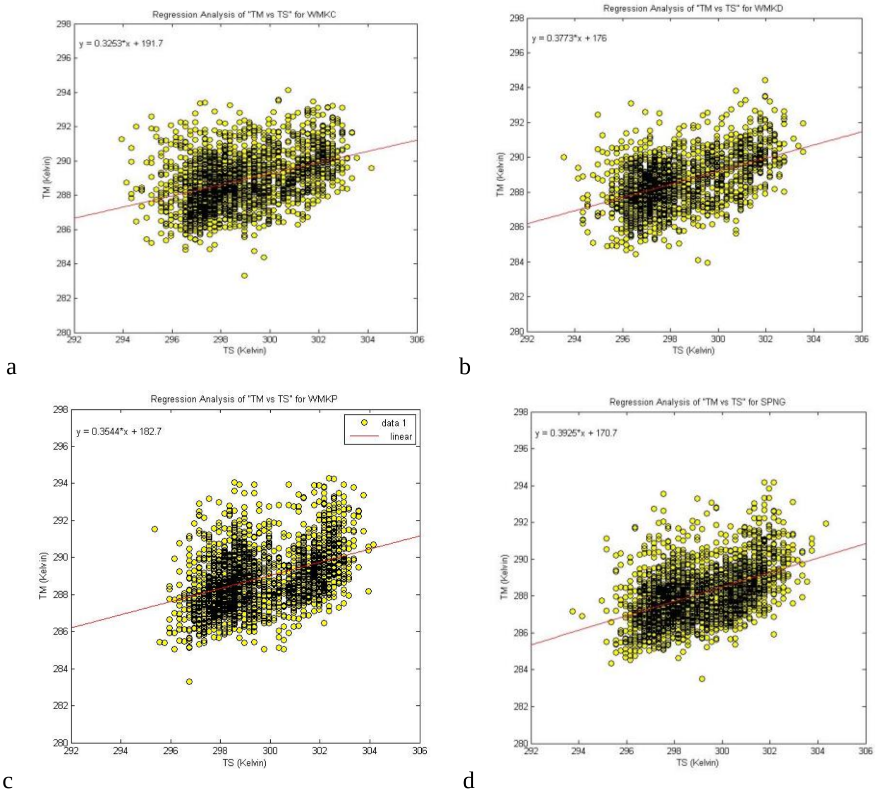

Figure 3. The site-specific T_M model for each radiosonde station in Peninsular Malaysia. Scatter plot T_M against T_S show that the T_M-T_S relationship is <0.4 which indicates weak relationship at all radiosonde stations.

The variability of T_S is influenced by monsoon seasons especially, the northeast monsoon (winter monsoon). This event influences the T_S over the northeast region that can be shown in the scatter plot of Figure 2 (WMKC and WMKD). The T_S is slightly reduced from November until March. During this period, the cold northeasterly wind from the Siberia flow out towards the coastal waters of southern South China Sea and heading to east coast often brings heavy rainfall to this area (see Figure 1; Tangang et al., 2008; Loo et al., 2014).

In addition, the daily variability on T_S occurred between night and daytime. It can clearly be realized the T_Sn (T_S night - observe at 8 pm LST) is higher with about 3K compared to T_Sd (T_S day - measure at 8 am LST). This is because the earth's surface absorbed huge amount of heat from sun in the afternoon (2pm – 4 pm LST) and gradually decreases in the evening (Shinoda, 2005). Meanwhile, the diurnal cycle is very weak about 1K. However, both impacts of monsoon and diurnal cycle is only dominant in T_S and not in the T_M.

3.3 Linear regression analysis for T_M-T_S relationship

The development of T_M model which is based on linear regression analysis of T_M-T_S relationship is essential to allow for the estimation of T_M parameter without depending on the radiosonde data (see Figure 4). Such T_M model can support the estimation of GPS-derived IWV at more frequent up to hourly (as long as the GPS ZPD and T_S are available) intervals. In the linear regression analysis, the T_M is plotted on the y-axis, meanwhile the T_S is plotted on the x-axis. Figures 3 (a-d) shows the scatter plot of T_M against T_S for each radiosonde stations with 3 years data span (2006-2008).

Equations 12-15 are site-specific T_M models developed from the regression analysis for each radiosonde station.

SPNG; $T_M = 0.39T_S + 170.7$ (12)
WMKC; $T_M=0.33T_S +191.7$ (13)
WMKD; $T_M=0.38T_S +176$ (14)
WMKP; $T_M=0.35T_S+182.7$ (15)

Most researchers developed the regional T_M model based on the combination of several observations from radiosonde station within regional scale such as demonstrated by Bevis et al., (1992) in America; Suresh Raju et al., (2007) and Singh et al., (2014) in India. This regional T_M model enables the estimation of GPS-derived IWV at all GPS stations within their region without estimate at every site-specific radiosonde station.

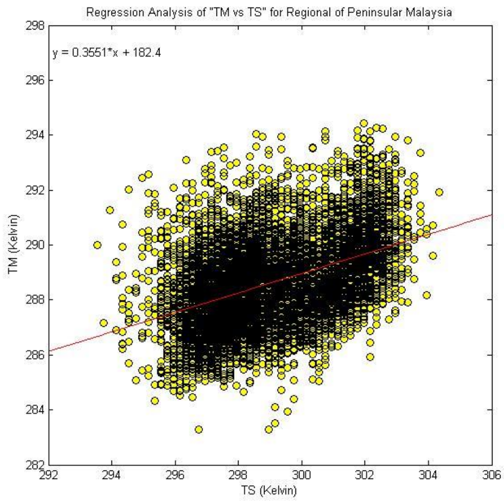

Figure 4. Regional T_M model is developed by combining all the radiosonde stations over Peninsular Malaysia to form a single equation of linear regression analysis.

In this study, Equation 16 is developed for regional model.

$$\text{Regional; } T_M=0.36T_S+182.4 \quad (16)$$

It was revealed that the regression slope and intercept of regression analysis at all radiosonde station in Peninsular Malaysia are between the range of 0.2941 to 0.3759 and 175.6 to 200.4, respectively. This indicates that the relationship of T_M-T_S in Peninsular Malaysia has weak correlation. Similar result was found by Ross and Rossenfeld, (1997) in which all tropical radiosonde stations showed weak correlation of about less than 0.5. For further understanding, this study attempts to investigate the cause of weak correlation of T_M-T_S relationship in Peninsular Malaysia.

3.4 Influence of diurnal cycle in T_M-T_S relationship

According to the Figure 2, the variability of T_M-T_S is influenced by the diurnal cycle of T_M-T_S. The magnitude of diurnal cycle on T_M and T_S is different; it is smaller on T_M than T_S. Nevertheless, the variation of T_S especially, its large variability contributes weak correlation to the T_M-T_S relationship. To investigate it, this study designed the temporal analysis for T_M-T_S relationship. Two types of linear regression were developed based on observation epochs (i.e. daytime and nighttime observation). Table 6 depicts two epochs of T_M model; daytime and nighttime T_M model. The impact of these T_M models on GPS-derived IWV was assessed in Section 4.

Table 6. The daytime and nighttime T_M models have been developed for each radiosonde station. From temporal analysis, it was found that the relationship of T_M-T_S is always higher; >0.5 for the night observation. Meanwhile, the spatial location also indicates that the T_M-T_S daytime has weak relationship at east coast compared to the west coast.

Radiosonde Station	Daytime model	Nighttime model
SPNG	$T_M =0.51T_S+136.2$ (17)	$T_M =0.66T_S +91.8$ (21)
WMKC	$T_M =0.23T_S +220.5$ (18)	$T_M =0.51T_S +135.6$ (22)
WMKD	$T_M =0.34T_S +186.6$ (19)	$T_M =0.62T_S +101.6$ (23)
WMKP	$T_M =0.49T_S +143.8$ (20)	$T_M =0.64T_S +96.9$ (24)

The result shown that serious problem on the relationship T_M-T_S is due to the diurnal cycle of T_S. The variability of T_S influenced the sensitivity of T_M-T_S relationship. The relationship of T_M-T_S has improved for the nighttime observation from weak correlation (0.3) to moderate correlation (>0.5). However, in the daytime observation, the strength of T_M-T_S relationship is improved only at west coast radiosonde stations (SPNG and WMKP), without any improvement noticed at the east coast stations (WMKC and WMKD). Thus, the geographical aspect should be considered in T_M-T_S relationship.

4. ASSESSMENT

This assessment was conducted to validate the accuracy of T_M model in Peninsular Malaysia. Only four GPS stations located nearest to the radiosonde stations were utilized in the assessment. One year period of data span which is in whole year 2008 has been processed to estimate the ZPD parameter. This ZPD was processed along with various types of T_M model to obtain GPS-derived IWV. Meanwhile, the radiosonde data in year 2008 from all radiosonde stations were also utilized to benchmark the estimation of GPS-derived IWV along with the T_M model.

Three (3) cases study has been proposed to evaluate the impact of T_M model in GPS-derived IWV estimation. In this assessment, the result of GPS-derived IWV will be assessed with the radiosonde-derived IWV.

Case 1: Available T_M models
Case 2: Site-specific versus Regional T_M models
Case 3: Site-specific versus Daytime versus Nighttime T_M models

The root mean square error (RMSE) analysis technique has been implemented to assess the accuracy of T_M model. This RMSE analysis is utilized to indicate the closeness of the estimation of GPS-derived IWV to the radiosonde-derived IWV. Lower value of RMSE indicates the most accurate GPS-derived IWV to the radiosonde measurement, while higher RMSE suggest otherwise. Equation 25 describes the RMSE equation.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(x_{GPS,i} - x_{radiosonde,i})^2}{n}} \quad (25)$$

where X_{GPS} is the estimation of GPS-derived IWV with the T_M model and $X_{radiosonde}$ is the radiosonde-derived IWV.

4.1 Case 1: Available T_M model

This study investigates the performance of available T_M parameter in Peninsular Malaysia. The entire T_M models listed earlier in Table 1 were applied to estimate GPS-derived IWV at all GPS stations. The result for the Case 1 is listed in Table 7.

Table 7: Statistical analysis of GPS station using available T_M model from Table 1

GPS station	Global 1 (kg/m^2)	Global 2 (kg/m^2)	Global 3 (kg/m^2)	Tropic 1 (kg/m^2)	Tropic 2 (kg/m^2)	Tropic 3 (kg/m^2)
BTNG	3.010	3.624	2.984	2.860	2.937	3.079
GETI	3.972	4.666	3.940	3.745	3.861	3.239
PEKN	3.058	3.745	3.026	2.861	2.861	2.894
USMP	1.151	2.457	1.072	0.607	0.908	1.341

Results and discussion of Case 1:

In general, the estimation of GPS-derived IWV is superior by using Tropic model rather than Global model. The Tropic model improved about 1% - 2% from Global model. The Global model could be problematic due to several reasons;

1. The warm temperature, low pressure gradient and high abundant of water vapour in low latitude is inadequately considered to reflect the tropical climatic condition.
2. The sparse selection of radiosonde in low-latitude region in Global model is bias to utilize because the sparse interpolation is not representative of the actual water vapour condition.
3. Single equation of Global model consists of cold bias that is contributed from middle and high latitudes to be utilized in low-latitude region. This study found that, the Global 1 and 3 contribute about 6K, meanwhile the Global model 2 contributes about 10K.

In comparison of Global model;

The Global 3 has slightly improvement for low-latitude region. This is because more radiosonde stations from the tropical region have been selected and were included to fit the global model. In contrast, the Global 1 is suit for middle latitude because the coverage of radiosonde station ranges between 27°N-65°N in Northern America (Yao et al., 2012). Nonetheless, the Global 2 utilized the numerical weather model and reanalysis data to develop the global model. However, less accurate numerical weather model contribute uncertainty to T_M estimation (Wang et al., 2005).

In comparison of Tropic Model,

The Tropic 1 is most suited to employ in Peninsular Malaysia. It was developed the T_M model by utilizing about 10 years periods of radiosonde observations in Taipei. Meanwhile, one year radiosonde observation from Tropic 3 overestimated the T_M parameter at about 10 K. This indicates that the short period of observation utilized to develop the T_M model is not suitable because it may consist of systemic bias (Ross and Rossenfeld, 1997).

4.2 Case 2: Site-specific versus regional T_M models

Few studies demonstrated that the site-specific T_M model is greater than the regional T_M model (Liou et al., 2001; Suresh Raju et al., 2007; Singh et al., 2014). The site-specific T_M model is accurately tuned to site-specific weather condition at single GPS station only which is in contrast to regional T_M model that take account of the variability of weather over a large coverage area. Thus, the site-specific T_M model should give better result compared to regional T_M model (Bevis et al., 1992).

However, to develop the site-specific T_M model at each GPS station is likely complicated, especially if there are hundreds to thousands of GPS station within the area. The simple practice is to develop the regional T_M model which is based on the combination of several radiosonde observations within the desire coverage area. This regional T_M model allows the estimation of GPS-derived IWV at entire GPS station within the coverage area of radiosonde observation.

Thus, the purpose of the Case 2 is to determine the preferred T_M model between regional and site-specific. To realize this, the regional T_M model that has been developed in Equation 16 was used to estimate GPS-derived IWV at the entire GPS stations. Meanwhile, for site-specific, the site-specific T_M model was utilized to estimate GPS-derived IWV at the specific location of GPS station in relation to the nearest radiosonde station as listed in Table 2. The result from the Case 2 is shown in Table 8.

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Table 8: Comparison between regional and site-specific T_M model. The RMSE from both models have no significant difference.

GPS station	Regional (kg/m^2)	Site-Specific (kg/m^2)	Difference (kg/m^2)
BTNG	2.887	2.972	-0.085
GETI	3.720	3.691	0.029
PEKN	2.890	2.878	0.012
USMP	0.631	0.615	0.016

Result and discussion from Case 2:

1. The range of RMSE in regional model is from 0.631 kg/m^2 at USMP to 3.720 kg/m^2 at GETI. While for site-specific model the range is from 0.615 kg/m^2 at USMP to 3.691 kg/m^2 at GETI.
2. The USMP has smaller RMSE which is 0.6 kg/m^2. Meanwhile, the GETI station suffers large uncertainty of about 3.691 to 3.720 kg/m^2 in GPS-derived IWV estimation.
3. The distance between GPS and radiosonde stations influence the accuracy of IWV. This study found that the large distance between GPS and the radiosonde stations degraded the accuracy of GPS-derived IWV estimation. The variability of moisture in tropical region is high. The condition of moisture at two different locations could be vary largely if they are far apart. In this study, the distance of USMP is relatively closer to the corresponding radiosonde station (WMKP) compared to other GPS stations. This explains why the USMP has smaller RMSE compared to the rest stations.
4. Site-specific model has slightly reduced the residual of IWV at all GPS stations except BANT. Nevertheless, the improvement from site-specific model is less significant as shown in Table 8.
5. The use of regional model is adequate to support the estimation of GPS-derived IWV at entire GPS station in Peninsular Malaysia. Thus, it is not necessary to develop site-specific model at every GPS station.

4.3 Case 3: Site-specific versus daytime versus nighttime T_M Models

The effect of different T_S in diurnal has influenced the T_M-T_S relationship as discuss in Section 3.4. This study also investigated the effect of diurnal variability on the GPS-derived IWV estimates over Peninsular Malaysia. In order to investigate this effect, this study has separately used the temporal T_M model (daytime and nighttime). For the daytime, the estimation of GPS-derived IWV was achieved by utilizing the daytime T_M model, while the nighttime case was by utilizing the nighttime T_M model. The result for the daytime and nighttime are listed in Table 9 and Table 10, respectively.

Table 9: Comparison between regional, site-specific and daytime T_M models during daytime observation. The RMSE is slightly reduced by using daytime T_M model.

GPS station	Regional (kg/m^2)	Site-Specific (kg/m^2)	Daytime (kg/m^2)
BTNG	3.107	3.109	2.893
GETI	3.422	3.381	3.396
PEKN	2.709	2.705	2.705
USMP	0.561	0.545	0.502

Table 10: Comparison between regional, site-specific and nighttime T_M models during nighttime observation. The RMSE is slightly reduced by using nighttime T_M model.

GPS station	Regional (kg/m^2)	Site-Specific (kg/m^2)	Nighttime (kg/m^2)
BTNG	3.157	3.340	2.924
GETI	3.100	3.073	3.108
PEKN	3.067	3.047	3.064
USMP	0.697	0.681	0.690

Result and discussion of Case 3:

1. In overall, the diurnal effect contributed uncertainty of about 1%-2% to the entire GPS-derived IWV in Peninsular Malaysia. There is less significant improvement found by utilizing the daytime and nighttime T_M models separately.
2. The RMSE in nighttime is higher compared to daytime, this is probably influenced by warm bias (Wang et al., 2005). This diurnal cycle on IWV needed further investigation to reduce the impact of diurnal cycle especially during nighttime.
3. The different of diurnal cycle of T_M is about 1K which contributed about 1%-2% uncertainty to GPS-derived IWV. The effect of diurnal cycle is not critical to GPS meteorological application. Thus, few authors have combined the daytime and nighttime observations to develop a single T_M model such as demonstrated by Klein Baltink et al., (2000). However, the impact of diurnal cycle might be significant for the study of diurnal cycle of IWV such as demonstrated by Morland et al., (2009) and Ortiz de Galisteo et al., (2011).

5. CONCLUSION

Accurate information about atmospheric water vapour is essential for operational weather forecast and climate monitoring especially for tropical communities where large amount of water vapour can be observed. As demonstrated by numerous researchers, the GPS meteorology is capable of estimating the integrated column of water vapour. However, the accuracy of the estimation from GPS meteorology is interrelated to the accuracy of T_M model which depends on local spatio-temporal resolution. For improving the estimation of GPS-derived IWV, this study estimates the T_M parameter from four radiosonde stations in Peninsular Malaysia over 2006 to 2008 and hence, develops the T_M model based on the relationship of T_M parameter with respect to T_S over Peninsular Malaysia. The T_M and T_S are found to be warm throughout the year with values ranging from about 288-289K and 298-299K respectively as well as small variation of about 1-2K. This study developed two types of T_M models which are site-specific and regional T_M model based on the linear regression analysis. It was found that, weak correlation of relationship between T_M-T_S is due to the diurnal cycle of T_S. By separating daytime and nighttime observation, the T_M-T_S relationship was improved from weak (<0.5) to moderate (> 0.5 to 0.6). However, impact of diurnal cycle in IWV is very small and less significant. This study also investigated the use of T_M model from Global and Tropic model. The Tropic model was found to be superior for use in Peninsular Malaysia compared to the Global model.

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