Variability of GPS water vapor associated with warming activity in Peninsular Malaysia during the period of 2008–2011
Wayan Suparta, Maszidah Muhammad, Mandeep Singh Jit Singh, Fredolin T. Tangang, Mardina Abdullah and Mohammad Tariqul Islam

ABSTRACT
This study utilizes the precipitable water vapor (PWV) parameter retrieved from ground-based global positioning system (GPS) to detect warming activity in Peninsular Malaysia from 2008 to 2011. Daily average of GPS PWV and surface meteorology data taken from six selected stations over Peninsular Malaysia are analyzed. Prior to warming detection, GPS PWV results are compared with PWV obtained from Radiosonde and found a positive relationship. The daily GPS PWV variability was characterized as high during the inter-monsoon seasons (April-May and October-November) and lower at the beginning, middle and the end of the year. For the monthly variations, GPS PWV increased by about 2.40 mm, which is correlated with an increase in surface temperature of 0.20 °C. We detected variability of PWV with a semiannual variation and the pattern is opposite to the accumulated precipitation, indicating that wet and dry spells coincide with local monsoon and intermonsoon periods. The warming effect in this study was felt over all selected stations with northern parts of Peninsular Malaysia affected significantly. The results imply that GPS is a powerful tool for analysis of warming effects and the mechanism of how it affects the circulation of water vapor is discussed in this study.

Key words | GPS, Peninsular Malaysia, precipitable water vapor, warming activity

INTRODUCTION
Warming activity is an indicator of climate change impact on a particular region. As the warming increases, the impact on socio-economic and political behavior increases and this is seen most keenly in environmental issues, therefore, it has become a major concern for the international community and stake holders during the last few decades. The occurrence of warming can be understood by considering two unbalanced energies. If the balance between the radiation energy from the Sun and the thermal radiation from the Earth and the atmosphere to outer space is disturbed, it can be restored by an increase in the Earth’s surface temperature (Houghton 2009). This occurs when heat is trapped inside the Earth’s atmosphere after the sun’s rays are reflected from the Earth’s surface. The surface of the Earth and the atmosphere heat up, and this causes changes in the climate throughout the world. In the 20th century, studies on global warming and climate change have been attracting a great deal of attention due to its huge impact on human habitats. However, the scope of exploring the impact of warming phenomena and climate change from the perspective of Malaysia is still limited compared with other countries in Asia.

One way to analyze the effects of warming is to study the trend and alterations of Earth’s surface temperature. Meng et al. (2005) and Tangang et al. (2007) show that in every 100 years in Peninsular Malaysia, there is a rise in
The objective of this study is to analyze precipitable water vapor (PWV) variability derived from global positioning system (GPS) to detect the effects of warming activity in Peninsular Malaysia. We used statistical analysis to explain the changes in PWV variation with response to warming activity during the period of 2008–2011. We compare the PWV variability with Radiosonde, or radio sounding (RS), PWV data and their trend with accumulated precipitation taken from NASA’s Tropical Rainfall Measuring Mission (TRMM). The anomaly of PWV trend obtained can be considered for future mitigation of climate change across the country as well as an early warning for stakeholders.

MATERIALS AND METHODS

GPS is a powerful tool and as such has been employed in atmospheric studies, and Bevis et al. (1992) utilised PWV for climate studies. However, this parameter is difficult to characterize in equator regions due to the humidity and irregular weather patterns. For Malaysia, the installation of a GPS receiver by the government is mostly for the purposes of surveying and mapping. This further complicates the study of climate change which requires the installation of a GPS receiver co-located with the meteorological sensors. Indeed, long-term data provided with high temporal and spatial resolution are also limited.

Data and location of the study

Due to the limited access to long-term GPS data over Peninsular Malaysia, we conducted the analysis using 4 years of consecutive data from 2008 to 2011 at six selected GPS stations (BANT, GETI, JHJY, KUAL, PEKN, and USMP). The surface meteorological data (MET) were collected near the GPS station. We used the RS PWV data (WMKC, WMKD, and WMKP) to validate the PWV derived from GPS. Figure 1 shows the locations of the study, which are divided into four regions. GETI, KUAL, and PEKN stations are located on the east coast, while BANT represents the west coast. The northern and southern parts are monitored by USMP and JHJY stations, respectively. JHJY is located in a dense urban environment, while USMP is in Penang Island.

The geographical locations regarding the GPS, MET and RS stations used in this study are compiled in Tables 1 and 2. In this study, the GPS data were supplied by the Department of Survey and Mapping Malaysia (DMSS). The MET data were provided by Malaysian Meteorological Department (MMD), while the RS data were provided by the Department of Atmospheric Sciences, University of Wyoming. The GPS receiver records the data every 15 seconds and spatial resolution for MET data was recorded at hourly intervals, while the RS data were collected twice a day (00:00 UTC and 12:00 UTC), and comprise of temperature, pressure, humidity, wind information and PWV. For studying the irregularity or warming effects, we compared the variability of PWV with monthly precipitation rates taken from NASA’s TRMM website.
To show how Malaysia may be affected by warming activity, the monthly average air temperature from 14 MET sites collected over Peninsular Malaysia is depicted in Figure 2. From that variation, rapid fluctuation of temperature revealed following the monsoon season, the year 2010 was recorded as the warmest period in last 8 years with a peak.

**Table 1 | The geographical location of GPS MET stations over Peninsular Malaysia**

<table>
<thead>
<tr>
<th>GPS</th>
<th>Station ID</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>Height, H&lt;sub&gt;GPS&lt;/sub&gt; (m)</th>
<th>MET</th>
<th>Station ID</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>Height, H&lt;sub&gt;MET&lt;/sub&gt; (m)</th>
<th>Distance GPS-MET station (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BANT</td>
<td>2.82</td>
<td>101.54</td>
<td>8.83</td>
<td></td>
<td>WMKK</td>
<td>3.10</td>
<td>101.60</td>
<td>22.00</td>
<td></td>
<td>24.80</td>
</tr>
<tr>
<td>GETI</td>
<td>6.23</td>
<td>102.11</td>
<td>-0.47</td>
<td></td>
<td>WMKC</td>
<td>6.20</td>
<td>102.30</td>
<td>5.00</td>
<td></td>
<td>35.41</td>
</tr>
<tr>
<td>JHJY</td>
<td>1.53</td>
<td>103.79</td>
<td>39.20</td>
<td></td>
<td>WMKJ</td>
<td>1.60</td>
<td>103.70</td>
<td>37.00</td>
<td></td>
<td>21.20</td>
</tr>
<tr>
<td>KUAL</td>
<td>5.32</td>
<td>103.14</td>
<td>54.99</td>
<td></td>
<td>WMKN</td>
<td>5.40</td>
<td>103.10</td>
<td>6.00</td>
<td></td>
<td>16.54</td>
</tr>
<tr>
<td>PEKN</td>
<td>3.49</td>
<td>103.39</td>
<td>26.03</td>
<td></td>
<td>WMKD</td>
<td>3.80</td>
<td>103.20</td>
<td>17.00</td>
<td></td>
<td>67.20</td>
</tr>
<tr>
<td>USMP</td>
<td>5.36</td>
<td>100.30</td>
<td>19.91</td>
<td></td>
<td>WMKP</td>
<td>5.30</td>
<td>100.30</td>
<td>4.00</td>
<td></td>
<td>11.00</td>
</tr>
</tbody>
</table>

**Figure 1 | Location of GPS receivers and radio sounding stations.**

**Monitoring the trend of water vapor variability**

To show how Malaysia may be affected by warming activity, the monthly average air temperature from 14 MET sites collected over Peninsular Malaysia is depicted in Figure 2. From that variation, rapid fluctuation of temperature revealed following the monsoon season, the year 2010 was recorded as the warmest period in last 8 years with a peak.
between the months of April and May of 2010. On the other hand, the coolest temperature was recorded in December 2010 and January 2011. The surface temperature variation from the figure gives an upward trend with an increment of 0.05 °C per year. Based on this trend, we monitored the warming activity through atmospheric water vapor variability.

For the analysis, all the data collected were cleaned and the differences in temporal resolution between the data fixed. In this study, the data were sampled into 1 hour temporal resolution. The GPS PWV is computed from both GPS and MET data. The GPS data consist of an observation file (*.o) and a navigation file (*.n) in Receiver Independent Exchange (RINEX) format. MET data together with GPS data for computation of PWV comprise the surface air temperature, \( T (\degree \text{C}) \), surface pressure, \( P (\text{hPa}) \), and relative humidity, \( H (\%) \). As shown in the right hand column of Table 1, most of the meteorological sensors are not co-located at the GPS stations. To obtain accurate measurements of PWV, MET data are interpolated with the position of the GPS receiver using the Equations (1) to (4) as suggested by Klein Baltink et al. (1999),

\[
P_{\text{MSL}} = P_{\text{MET}} / (1 - 0.0000226 H_{\text{MET}})^{5.225} \\
T_{\text{MSL}} = (T_{\text{MET}} + 273.16) + 0.0065 H_{\text{MET}} \\
P_{\text{GPS}} = (1 - 0.0000226 H_{\text{GPS}})^{5.225} \\
T_{\text{GPS}} = (T_{\text{MSL}} - 273.16) - 0.0065 H_{\text{GPS}} T_{\text{GPS}}
\]

where \( P_{\text{MET}}, T_{\text{MET}}, P_{\text{GPS}} \) and \( T_{\text{GPS}} \) are the surface pressure (hPa) and temperature (°C) at MET and GPS stations, respectively. The surface pressure and the temperature at mean sea level (MSL) are represented by \( P_{\text{MSL}} \) and \( T_{\text{MSL}} \). \( H_{\text{MET}} \) and \( H_{\text{GPS}} \) are height above MSL (m) for MET and GPS stations, respectively.

The GPS PWV is computed based on the GPS signal delay information. These signal delays consist of the information from the ionosphere and troposphere layers. The signal delay in the ionosphere can practically be determined by using a dual-frequency receiver. We consider the GPS signal at the neutral atmosphere for determination of zenith total delay, since atmospheric water vapor is distributed in this layer. For this study, Tropospheric Water Vapor program (TroWav) written in MATLAB™.
are used to compute PWV (Suparta 2014), which consists of Zenith Tropospheric Delay (ZTD) information. The ZTD is calculated from the Modified Hopfield model, which is divided into two natural delay components known as Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD). The ZHD is the delay due to the dry gases in the troposphere and the non-dipole component of water vapor refractivity. The Saastamoinen model was used to compute ZHD (Suparta et al. 2008). The Niell mapping function (NMF) is a function used to reduce the dependency of the zenith delay on the satellite elevation angle. The ZWD is the components of dipole moment and dipole orientation of the water refractivity that depends on the humidity content in the troposphere. This delay is calculated from ZHD that is subtracted from ZTD. Moreover, the ZWD is used to estimate the PWV with the conversion factor that varies with the local climate, $\pi(T_m)$ parameter as given by

$$
\pi(T_m) = \left[ \rho_{lw} R_v \left( k_2^2 + k_3 / T_m \right) \right]^{-1} \times 10^6
$$

(5)

where $\rho_{lw}$ and $R_v$ are the density of the liquid water (1,000 kg m$^{-3}$) and specific gas constant for water vapor, respectively. From (5), $k_2$ and $k_3$ are the refraction constants calculated by Bevis et al. (1994). The mean temperature $T_m$ is estimated linearly, $T_m = 70.2 + 0.72(T_s + 273.16)$ and for this work it is calculated using surface temperature ($T_s$) measured at the site. $T_K$ and $T_s$ are in Kelvin and degrees Celsius, respectively.

PWV now can be calculated as given by Bevis et al. (1994)

$$
PWV = \pi(T_m)ZWD_{GPS}
$$

(6)

where $ZWD_{GPS}$ is ZWD value obtained from GPS (ZWD = ZTD – ZHD). Detail computation of PWV from GPS is summarized in Figure 3. Finally, to analyze the warming effect at all the selected stations, we compute the PWV anomaly ($PWV_{anomaly}$). PWV anomaly is an irregular pattern or deviation value of PWV from the normal conditions. We remove the PWV value during the heavy precipitation that was recorded from TRMM to obtain the PWV average during a
quiet day (PWV_{quiet}). Then, an anomaly of PWV at each station is obtained by subtracting the current value of PWV (PWV_{current}) with PWV_{quiet}, with the following equation:

$$PWV_{anomaly} = PWV_{current} - PWV_{quiet}$$  \hspace{1cm} (7)

where all PWV values in Equation (7) are measured in mm. PWV_{quiet} is the PWV value obtained during a ‘normal’ day.

**RESULTS AND DISCUSSION**

**GPS PWV validation**

In order to validate the GPS PWV, data from three selected GPS stations (GETI, PEKN, and USMP) near the three selected RS sites for DJF 2010/2011 (December 2010, January 2011, and February 2011) were analyzed in daily average. The selection of this period was due to continuous availability of data (GPS, MET and RS). Figure 4 shows the comparison of GPS PWV compared to the measured RS PWV. GETI & WMKC show a strong correlation. PEKN & WMKD give a moderate correlation, while USMP & WMKP show a low correlation. The correlation value between GPS PWV and RS PWV is compiled in Table 3. As shown in the table, GETI & WMKC give a high value in mean difference between both data ($\Delta_{GPS\&RS}$). Both PEKN & WMKD and USMP & WMKP show almost similar results in their $\Delta_{GPS\&RS}$.

From Figure 4 and Table 3, the GPS PWV agreed very well with RS PWV and displays the potential to measure PWV as well as monitoring the warming activity. The difference values between both techniques are possibly due to the GPS stations not being co-located with the RS stations. As can be seen on the right hand column of Table 3, the difference in height ($\Delta H_{GPS\&RS}$) between GPS and RS varied from 3.83 to 15.91 m. This difference coincidently corresponded with the correlation of PWV between GPS and RS, where the higher the position of the station, the lower the correlation. This indicates that the altitude of the station is very important because it has affected the variability of pressure and temperature. In the range of that altitude difference, many events from unknown meteorological parameters, especially the winds and the atmospheric pressure, can influence the coordinates of the system. For example, the vertical profile of a balloon can move away from the launching point with extreme weather events.

**Analysis of GPS PWV variation**

Figure 5 shows the variation of GPS PWV at four representing regions with southern (Figure 5(a)), western (Figure 5(b)), northern (Figure 5(c)) and eastern (Figure 5(d)) parts. At all the regions, maximum value of PWV was found to be at the end of April or at the beginning of May, and the minimum value is at the beginning of

![Figure 4](https://iwaponline.com/jwcc/article-pdf/7/1/240/374047/jwc0070240.pdf)
January. The trends of PWV pattern at six GPS stations are consistent throughout the 4 years under observation. Several peaks are also seen in the time series of PWV with values at all stations ranging between 35 and 55 mm. The northern part of Peninsular Malaysia recorded the highest PWV level with an average of 46.56 mm followed by the western, eastern and southern parts with an average of 46.25 mm, 45.46 mm and 45.23 mm, respectively. Note that there were no GPS data available in May and November of 2011. We also received the significant impact of GPS PWV over Peninsular Malaysia at the end of 2008 until the beginning of 2009 as indicated by dashed circle line ‘anomaly case’, which dropped below 40 mm.

Table 3 | Comparison of PWV values from GPS and RS measurements

<table>
<thead>
<tr>
<th>GPS &amp; RS station ID</th>
<th>Number of sample, N</th>
<th>Correlation coefficient, r</th>
<th>Mean difference, ΔGPS&amp;RS (mm)</th>
<th>Shortest distance (km)</th>
<th>Altitude difference, ΔHGPS&amp;RS (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GETI &amp; WMKC</td>
<td>90</td>
<td>0.70</td>
<td>10.31</td>
<td>33.87</td>
<td>3.83</td>
</tr>
<tr>
<td>PEKN &amp; WMKD</td>
<td>90</td>
<td>0.52</td>
<td>8.17</td>
<td>63.16</td>
<td>10.00</td>
</tr>
<tr>
<td>USMP &amp; WMKP</td>
<td>90</td>
<td>0.40</td>
<td>8.88</td>
<td>13.33</td>
<td>15.91</td>
</tr>
</tbody>
</table>

Figure 5 | Daily average of GPS PWV variation for the station at (a) southern, (b) western, (c) northern, and (d) eastern parts on Peninsular Malaysia from 2008 to 2011.
Table 4 compiles the mean value of PWV and STD for the region as defined. As shown in the table, KUAL station shows more than a 5% increment and decrement in annual PWV average, while in the other five stations the increment was less than 5%. Small changes can be seen at JHJY with annual mean and STD less than 1% and 15%, respectively. For the year 2008 and 2009, at KUAL unlike the other stations the increment of STD was more than 40% while the others are less than 20%. From a PWV and STD point of view, the southern part is seen to be more stable than the other parts. The western and northern parts give similar increment or decrement. However, the PWV values in the eastern part (KUAL) are more dynamic from year to year, especially across 2009 and 2010, where PWV variations showed flutter within a large range from 35 to 55 mm compared with GETI and PEKN.

From the figure, one could see that the possibilities of differences in PWV content in the observed region are due to topographic and local terrain features factors, which result in different evaporation rates. More than that, stations in the northern and western parts, which lie between 13 and 15 km from the coast, are more influenced by the Strait of Malacca and the urban city, while the stations located in the eastern part situated a distance less than 9 km from the South China Sea (SCS) have less precipitation. On the other hand, the southern part which is located away from the ocean (more than 45 km), receives a lower PWV compared with the western and eastern parts. The evaporation process of the ocean is probably higher than in mainland, where the sun via outgoing longwave radiation (OLR) has a significant influence (e.g., Hall & Manabe 2000).

Investigation of warming effect

Figure 6(a) shows the monthly average of GPS PWV at six selected stations for a 4-year period of observation. Three significant maximum peaks and four minimum peaks were observed. In general, the PWV variation looks like an m-pattern for every year or semiannual cycle, which indicates the PWV is increased during the first (April–May) and the second (October–November) inter-monsoons. All the stations showed a similar pattern of PWV as the average. However, the KUAL PWV pattern initially deviates when compared with the PWV pattern at another station, but then immediately becomes synchronized again during the year 2009. Overall, the trend of GPS PWV is increased by 0.6 mm per year with an average PWV of 45.75 mm. PEKN was shown to be 1.92% higher than the PWV average, followed by USMP and BANT, and the lowest is KUAL. The mean PWV at KUAL is 44.79 mm, which is 2.30% lower than the PWV average.

To clarify the information of PWV affected by the warming activity, monthly accumulated precipitation from TRMM with same period as in Figure 6(a) is plotted in Figure 6(b). The maximum and the minimum peaks of this parameter are opposite to those of GPS PWV. Moreover, accumulated precipitation in November and December of every year in the eastern part is observed to be high, while the other parts were lower at about 500 mm. As seen in the figure, average accumulated precipitation for the 4 years of observation is 248.48 mm, with the minimum and the maximum values of 45.43 mm and 643.22 mm, respectively. Although the variability of accumulated precipitation is opposite to that of PWV, their trend is increasing by 11.76 mm per

<table>
<thead>
<tr>
<th>Region</th>
<th>GPS Station</th>
<th>Mean (mm) 2008</th>
<th>Mean (mm) 2009</th>
<th>Mean (mm) 2010</th>
<th>Mean (mm) 2011</th>
<th>STD (mm) 2008</th>
<th>STD (mm) 2009</th>
<th>STD (mm) 2010</th>
<th>STD (mm) 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern</td>
<td>JHJY</td>
<td>45.01</td>
<td>45.46</td>
<td>45.33</td>
<td>45.10</td>
<td>1.91</td>
<td>2.17</td>
<td>1.86</td>
<td>1.95</td>
</tr>
<tr>
<td>Western</td>
<td>BANT</td>
<td>44.85</td>
<td>45.58</td>
<td>47.72</td>
<td>46.86</td>
<td>2.24</td>
<td>2.14</td>
<td>2.23</td>
<td>1.57</td>
</tr>
<tr>
<td>Northern</td>
<td>USMP</td>
<td>45.91</td>
<td>46.12</td>
<td>47.55</td>
<td>46.64</td>
<td>2.73</td>
<td>2.84</td>
<td>2.60</td>
<td>2.17</td>
</tr>
<tr>
<td>Eastern</td>
<td>GETI</td>
<td>44.57</td>
<td>44.96</td>
<td>45.66</td>
<td>44.82</td>
<td>2.22</td>
<td>2.75</td>
<td>2.22</td>
<td>2.34</td>
</tr>
<tr>
<td></td>
<td>KUAL</td>
<td>41.70</td>
<td>45.03</td>
<td>45.76</td>
<td>46.68</td>
<td>1.79</td>
<td>3.12</td>
<td>2.51</td>
<td>2.32</td>
</tr>
<tr>
<td></td>
<td>PEKN</td>
<td>46.60</td>
<td>46.31</td>
<td>47.28</td>
<td>46.23</td>
<td>2.04</td>
<td>2.17</td>
<td>2.18</td>
<td>2.65</td>
</tr>
</tbody>
</table>
year. Referring to Figure 6, both trend GPS PWV and accumulated precipitation for the period of study are increased by 2.40 mm and 47.04 mm, respectively. Both parameters bring lower PWV to this region when precipitation is high. Based on these figures, the precipitation was higher every year at November and PWV is lower in the next month. The high of this precipitation is due to the beginning of the Northeast monsoon and much of the water vapor content in this season is precipitated as rain. On the other hand, the Northeast monsoon brings cool temperatures and water vapor is cumulated and forms cloud, then is transformed to raindrops. The PWV on the next month will be lower when heavy rain falls. This phenomenon affected the east coast of Peninsular Malaysia, where the eastern stations (GETI, KUAL and PEKN) showed high accumulations of precipitation.

Comparing the variation of surface temperature in Figure 2, their maximum peak for MAM (March, April, and May) of 2010 was similar to that of PWV in Figure 6(a). During this period, the trend of surface temperature and GPS PWV increased about 0.18% per year and 1.35% per year, respectively. In addition, the average PWV always drastically dropped in DJF months every year with the exception of DJF 2009/2010 when the drop was smaller. This behavior gives the warmest year for this study. As the climate warms, the temperature in the atmosphere is higher, and relative humidity is opposite to that of temperature pattern, hence PWV is expected to naturally increase (Trenberth 2011). In other words, a warmer atmosphere will hold more moisture than colder air. This clarifies the Clausius-Clapeyron equation for the relationship between temperature and water vapor changes.

Looking at the warming impacts, the PWV variations in Figure 6(a) are split into three cases to obtain PWV anomaly (see Equation (7)). By removing the PWV values identified during the three cases of heaviest precipitation in Figure 6(b), we obtained a PWV average during quiet day (PWV\textsubscript{quiet}) of 44.70 mm, which is 2.35% less than the PWV average over all the periods. Figure 7 shows the PWV anomaly which covered three cases of warming impacts during the period of 2008–2011. For Case 1, three stations (JHJY, PEKN and USMP) experienced warmer temperatures compared to the other three stations. KUAL showed the weakest warming with a PWV 2.54 mm lower than BANT and GETI stations (moderate warming). The low PWV value at KUAL in 2008 coincides with low pressure which occurred along the east coast during this period.
coast of Peninsular Malaysia and which influences the GPS station located on the hilltop of Bukit Pak Apil, Kuala Terengganu. During Case 2 and Case 3, all stations showed warming with an increasing trend. However, PEKN showed a small decrement in PWV (1.04%) from Case 1 to Case 2, but it increased 1.39 mm (42%) in Case 3. From this figure, JHJY, PEKN and USMP were warmer at overall periods, even though JHJY showed slower changes in PWV anomaly than the other stations. On the other hand during this study period, BANT and USMP in the west coast and northern part, respectively, are the stations most affected by the warming activity, in which PWV increased more than 3.50 mm. In short, from the trend of PWV compared to surface temperature and the warming effects obtained, all stations are experiencing warming, which indicates that PWV can be proposed as a climate parameter for studying the global warming phenomena.

CONCLUSIONS AND FUTURE WORK

This paper has shown the potential use of GPS PWV to detect warming activity in Peninsular Malaysia for the period of 2008–2011. The PWV trend in this region is in agreement with the surface temperature trend, and its natural variability was significantly dominated by the annual cycle. We found that the PWV variation is in opposite pattern to the distribution of accumulated precipitation. At the six selected stations, the northern part of Peninsular Malaysia is observed warmer, and the eastern part faced heavy rainfall during the monsoon. However, PEKN and USMP are consistently the warmest stations recorded in this study. JHJY and GETI experienced moderate warming, and KUAL the weakest. In conclusion, the results show that the warming activity has a high impact on our climate patterns with an annual cycle noted at all the stations in Peninsular Malaysia, mostly due to summer and winter monsoons. These results imply that GPS PWV with high temporal and spatial resolution is a reliable parameter to be used for studying these warming effects.

From 4 years of analysis, the trend of warming activity detected from PWV variability significant affects the region. Although the trend of surface temperature for the 8-year observation showed a smaller increase (0.05 °C per year), almost all the regions in Peninsular Malaysia are affected by global warming. To clearly measure the warming long-term effect, good quality GPS and MET data should be provided with complete time series. The comparison of warming effects in other places in Southeast Asia is also important to observe a regional pattern. The effect of warming, which can aid the
forecast model, will be studied in future work by providing long-term data for detailed analysis.

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