A New Technique to Observe ENSO Activity via Ground-Based GPS Receivers

Wayan Suparta, Ahmad Iskandar and Mandeep Singh Jit Singh

Abstract In an attempt to study the effects of global climate change in the tropics for improving global climate model, this paper aims to detect the ENSO events, especially El Nino phase by using ground-based GPS receivers. Precipitable water vapor (PWV) obtained from the Global Positioning System (GPS) Meteorology measurements in line with the sea surface temperature anomaly (SSTa) are used to connect their response to El Niño activity. The data gathered from four selected stations over the Southeast Asia, namely PIMO (Philippines), KUAL (Malaysia), NTUS (Singapore) and BAKO (Indonesia) for the year of 2009/2010 were processed. A strong correlation was observed for PIMO station with a correlation coefficient of −0.90, significantly at the 99 % confidence level. In general, the relationship between GPS PWV and SSTa at all stations on a weekly basis showed with a negative correlation. The negative correlation indicates that during the El Niño event, the PWV variation was in decreased trend. Decreased trend of PWV value is caused by a dry season that affected the GPS signals in the ocean-atmospheric coupling. Based on these promising results, we can propose that the ground-based GPS receiver is capable used to monitor ENSO activity and this is a new prospective method that previously unexplored.

1 Introduction

Global Positioning System (GPS) is satellite constellation of geodetic system that has been employed for determining position on the earth's surface in 3D and time. During its development, GPS technique can be applied to observe the characteristics of the Earth's atmosphere, including weather conditions. The 'weather' here, covering the sun until the surface activities. Bevis et al. [1] was firstly introduced the technique to observe the weather as well as climate by proposing the ground-based GPS and

W. Suparta (✉) · A. Iskandar · M.S.J. Singh
Space Science Centre (ANGKASA), Institute of Climate Change,
Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor Darul Ehsan, Malaysia
e-mail: wayan@ukm.my

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combined with meteorological sensors which are known as the GPS meteorology. GPS meteorology carried to characterize the diversity of climate behavior in the lower atmosphere (the troposphere) and the upper atmosphere layers (Ionosphere) [2]. This can be done by exploiting the delay of GPS satellites in the atmosphere by propagation of electromagnetic signals. The measurements of GPS signals are then used to detect variations that occur in the atmosphere. One major of the atmospheric component caused the signal delay is the precipitable water vapor (PWV).

PWV is a paramount parameter that has crucial roles in the weather and global climate. One of the factors that possibly affecting the PWV variation is due to El Niño-Southern Oscillation (ENSO) phenomenon. ENSO is a complex phenomenon that results from interaction between the ocean and the atmosphere in the tropical Pacific Ocean, which consisted of warm (El Niño) and cool (La Niña) phases. There are some indicators to detect ENSO phenomenon that has been employed, such as sea level pressure anomaly (SLPa), sea surface temperature anomaly (SSTa) and multivariate ENSO index (MEI) and the zonal gradient of precipitation [3–6]. In addition to employ of these parameters, the United States collaborated with the French in 1992 to launch altimetry satellite TOPEX/Poseidon (T/P) for ENSO monitoring [7]. However, the data from this monitoring is still ongoing, which expected for climate research.

Here, GPS measurements through PWV have been employed to study the ENSO activity, where La Niña is one of the phases of ENSO that causes increased of PWV value [8]. The use of this technique is effective-cost and the system no extra maintenance for a longer period, and the data acquired is also useful for space weather studies. Therefore, this study will focus on the analysis of ENSO, especially El Niño phase by using GPS meteorology over the Southeast Asia region. With this technique, an understanding of the characteristics and physical mechanism during El Niño phase can be provided.

2 Methodology

2.1 PWV Retrieved from GPS

The concept of measurements of PWV from GPS technique is depicted in Fig. 1. From the figure, the GPS signal propagate to a receiver on the ground that has been interacting with sea surface of the ocean. When the GPS signal propagates through the Earth's atmosphere, it is affected by the variability of the refractive index of the ionosphere and troposphere. The excess delay of the signal causes bending of the signal, and the total delay along the slant path can be determined [9]. In line with that, the total tropospheric delay (ZTD) in the neutral atmosphere, which comprised the zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD) can be calculated based on the improved Modified Hopfield model [2, 10]. The ZHD was calculated using the Saastamoinen model [11]. A Vienna mapping function (VMF1) was employed to reduce the atmospheric bias in the ZTD estimation [12]. The ZWD was computed by subtracting ZHD from ZTD. The ZWD was then transformed into

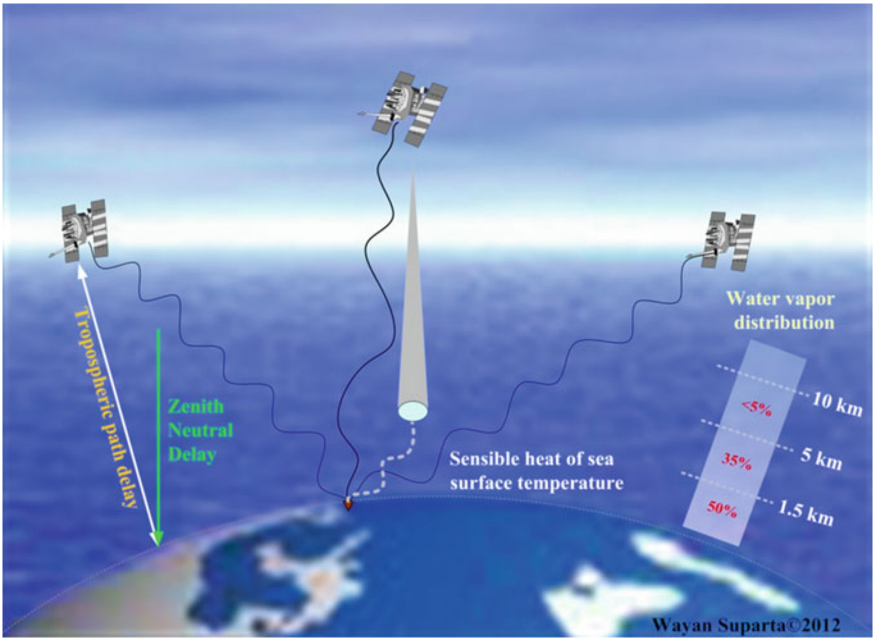

Fig. 1 Propagation of GPS signals to a receiver on the ground that covers the sea surface temperature influences adopted from Suparta et al. [8]

an estimate PWV by employing the surface temperature measured at a particular site. The PWV total (in mm) from a receiver position to the top of the atmosphere can be calculated. Detailed of PWV determination from GPS observations for this work can be found in the paper of Suparta et al. [2] and Suparta [13].

To calculate the PWV, the GPS data is combined with meteorological data (pressure (P in mbar), temperature (T in °C) and relative humidity (H in percent)). The meteorological data obtained from the meteorology station should be collocated with the GPS station to obtain optimum accuracy of vertical water vapor. For the meteorological data that was not collocated with GPS station, interpolation of the meteorological data into the GPS station will be conducted by using the formula, as proposed by Klein Balting et al. [14]. The total PWV was estimated using the formula proposed by Bevis et al. [15]:

$$PWV = \pi(T_m)ZWD \tag{1}$$

where $\pi(T_m)$ is the conversion factor that varies with local climate (e.g., geographical condition, season and weather) and dependent on a weighted mean temperature(T_m), ZWD is Zenith Wet Delay derived from GPS observations. Based on the above formula, T_m is crucial parameter in the estimation of PWV value, and for the Western Pacific region with latitude range 20°N–20°S and longitude 95°E–156°E, the T_m was obtained as [16]

$$T_m = 0.83663\,T_s + 48.103 \quad (2)$$

where T_m is in Kelvin and T_s is the surface temperature (in Kelvin). Note that the empiric T_m equation was obtained by a regression linear method for 15 selected radiosonde stations over the Western Pacific.

2.2 Data and Location

The GPS and meteorological data for this study were gathered from four selected stations over the Southeast Asia region. El Niño phase that occurred in 2009/2010 is selected, and the data was processed to verify the response of GPS PWV on ENSO phenomenon. The GPS station consists of the Philippine Island Manila Observatory (PIMO), Kuala Terengganu (KUAL), Nanyang Technological University Singapore (NTUS) and Bakosurtanal (BAKO). For the four selected stations, PIMO is located at Quezon City of Metro Manila, Philippines, while KUAL station is located on the East Coast of Peninsular Malaysia. Meanwhile, the NTUS station is located in the south-western part of Singapore, near the Jurong West Extension area, and slightly moved downward, BAKO is located in Cibinong, West Java, Indonesia. For the meteorological station, the data is collected from Manila airport weather station (Philippines), Kuala Terengganu (Malaysia), Nanyang Technological University (Singapore), and Soekarno-Hatta (Indonesia). The GPS data from KUAL station was obtained from the Department of Survey and Mapping Malaysia (DSMM), while another station was downloaded from the Scripps Orbit and Permanent Array Center (SOPAC) website. All the GPS data were supplied with resolution of a 30 s interval. The meteorological data were downloaded from the Weather Underground website.

The location of the study is depicted in Fig. 2. The specific of geographical coordinates for GPS stations and instruments set up of the GPS receivers is shown in Table 1, while the specific of geographical coordinates of meteorology station is compiled in Table 2. To relate the ENSO activity with PWV response, SSTa Oceanic Niño Index (ONI) in pathways of Niño 3.4 and Niño 4 regions is employed. The SSTa data were obtained from the National Oceanic and Atmospheric Administration (NOAA) which provided weekly.

2.3 Data Processing

To process and analyze all the parameters, a tropospheric water vapor program (*TroWav*) developed by Suparta et al. [2, 12], Suparta [13] was employed. The algorithms of the *TroWav* include satellite elevation angle, the ZTD, the ZHD, the ZWD and mapping function calculations. Figure 3 shows the flowchart of PWV determination. Then to study the relationship between GPS PWV and ENSO activity uses the correlative analysis. All the data are analyzed on a weekly basis

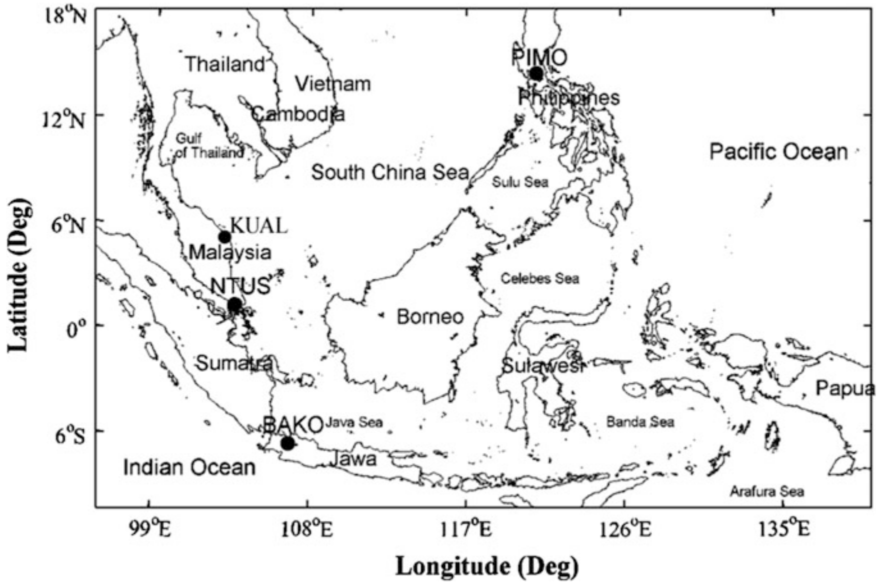

Fig. 2 Location of the study

Table 1 Geographical coordinates and instruments set up of GPS receivers

Station (country)	Latitude (degree)	Longitude (degree)	Height (m)	Type of GPS receivers
PIMO (Philippines)	14.64N	121.08E	95.53	ASHTECH UZ-12
KUAL (Malaysia)	5.32N	103.14E	55.00	Trimble NetR5
NTUS (Singapore)	1.35N	103.68E	75.38	LEICA GRX1200GGPRO
BAKO (Indonesia)	6.49S	106.85E	158.20	LEICA GRX1200+GNSS

Table 2 Geographical coordinates of meteorological stations

Station (country)	Latitude (degree)	Longitude (degree)	Elevation (m)
Manila (Philippines)	14.50N	121.00E	21.00
Kuala Terengganu (Malaysia)	5.30N	103.10E	9.00
NTUS (Singapore)	1.35N	103.68E	75.38
Soekarno-Hatta (Indonesia)	6.10S	106.70E	8.00

because the SSTa data only available on a weekly. The weekly data processing is based on the GPS week from daily data. In the figure, GPS data for KUAL are available in binary format (*.dat), consisting of *.nav and *.obs. To translate, repair and testing the GPS data uses a Translate/Edit/Quality Check (TEQC) routine developed by UNAVCO (http://www.unavco.org/). The TEQC routine can convert *.dat file into the Receiver Independent Exchange Format (RINEX) files. Then split

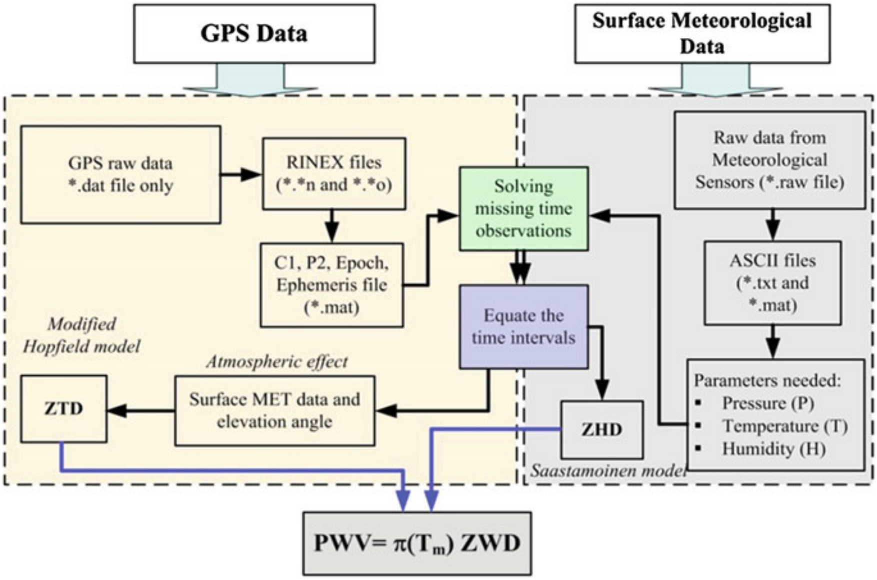

Fig. 3 Flowchart of PWV estimation adopted from Suparta et al. [8]

into individual files (L1, L2, C1, P2, epo, eph) for easy processing using Matlab™ program. For another station, all the RINEX observation file uses hatanaka (d-file) format and processed with 30 s interval (Fig. 4).

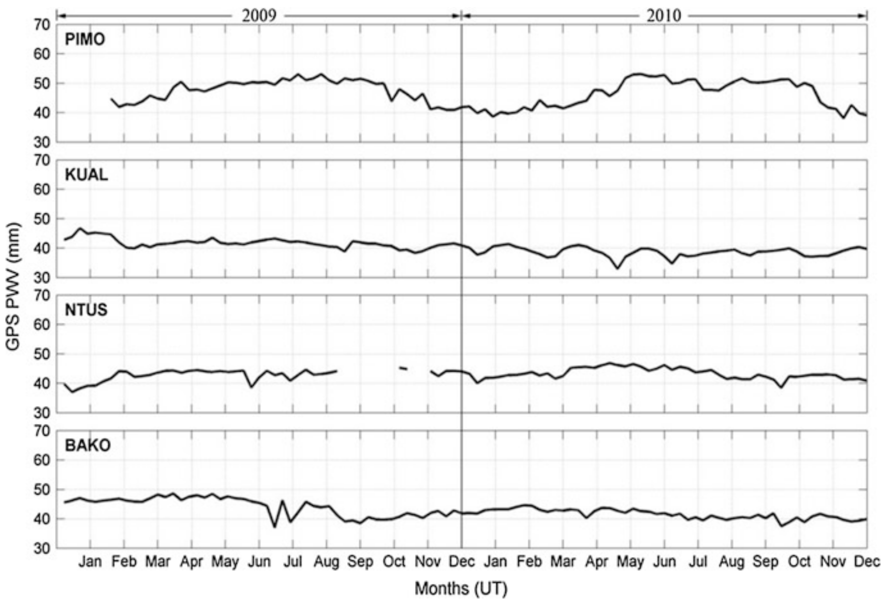

Fig. 4 The weekly average of PWV variation from GPS measurements for the year of 2009/2010

3 Results and Discussion

3.1 PWV and SSTa Variability

Figure 3 shows the weekly average of PWV variation from GPS measurements for the year of 2009/2010 at four selected stations. Based on the figure, the PWV pattern at each station is varied. For PIMO station, the range of PWV value was between 38 and 53.12 mm with an average of 46.90 mm. Another station like KUAL, NTUS and BAKO, the PWV value was lower than the PIMO station. Their averages of PWV were 40.20, 43.00 and 42.83 mm, respectively. Looked at the standard deviation (STD) value, the PWV for PIMO station was found higher of 4.33 mm than the other stations. The detail comparison of statistical analysis of PWV for all stations is presented in Table 3. From the figure, PIMO station showed a clear annual pattern of PWV, which is higher during the summer and lower during the winter. This trend almost followed by PWV at NTUS station, although the data is not completed. For BAKO and KUAL, the PWV trend is difficult to characterize although they appeared increased during the first inter-monsoon (April–May) and second inter-monsoon (October–November). The ripples peak of PWV occurred during June–July of 2009 at BAKO and NTUS stations shows that ENSO activity starting to disturb the atmosphere of both stations.

ENSO plays a crucial role in generating extreme conditions across the Pacific Ocean, in Indonesia and in the Borneo region. The more serious ENSO events with infamous their direct effects on communal health and livelihood were taken place in 1982/1983 and 1997/1998. For that reason, the ability to understand the ENSO pattern and predict its occurrences will allow for improved preparation to mitigate its effects and simultaneously support the preservation of the tropical rain forest in a targeted region. To observe their relevance to the water vapor changes during ENSO occurrences, two definitions to identify ENSO events can be applied. First, an ENSO event occurs when the 5-month running mean of the SST anomalies (SSTa) in the Niño 3.4 region is continuously higher than ±0.4 °C for 6 months [17]. The second definition was provided by the Japan Meteorological Agency (JMA) using a 1° meridionally narrower region of Niño 3 (4°N–4°S and 150°W–90°W), whereby an ENSO event is determined to have occurred when the 5-month running mean of the spatially averaged SSTa is larger than ±0.5 °C for six consecutive months [18]. The reason employed of 5-month running mean of SSTa is to average over the intra-seasonal variations in the tropical ocean. So that SSTa turns out to be a good indicator to detect ENSO activity.

Table 3 The statistical analysis of PWV

Station	Minimum (mm)	Mean (mm)	Maximum (mm)	STD (mm)
PIMO	38.06	46.90	53.12	4.33
KUAL	32.95	40.20	46.78	2.24
NTUS	36.99	43.00	46.83	1.92
BAKO	37.01	42.83	48.59	2.83

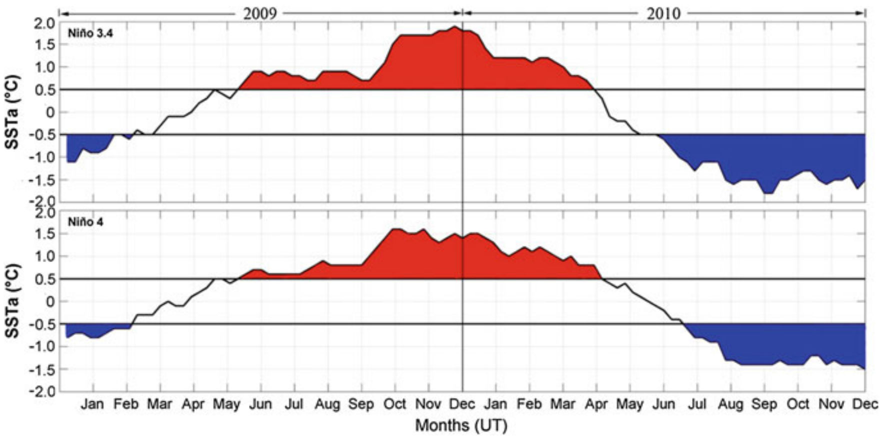

Fig. 5 The weekly SSTa variation at Niño 3.4 and Niño 4 regions for the year of 2009/2010

Figure 5 presents the ENSO identification according to JMA (SSTa > 0.5 °C) for eleven months or more is an ENSO warming (El Niño) event, while the shaded region with SSTa < −0.5 °C (JMA) is an ENSO for cooling phase (La Niña event), and otherwise is neutral. From these two definitions, we confident to propose an ENSO event will occurs when $SST_a > \pm 0.5$ °C at Niño 3 and Niño 3.4 regions. For the analysis, the weekly SSTa data throughout the year of 2009/2010 is presented. In general, from the SSTa changes at Niño 3.4 or Niño 4, the El Niño phase is occurred from the middle of June 2009 until April 2010. From the figure, it can also be seen that the maximum peak of El Niño was occurred in December 2009 for Niño 3.4 region with SSTa value of 1.9 °C and October–November 2009 for Niño 4 region with SSTa value of 1.6 °C. In our case, the selected site of study was located nearby the Niño 4 region.

3.2 Monitoring of GPS PWV Variability During El Niño Event

As mentioned previously, the correlative analysis is used to indicate the PWV response on El Niño event. During the event from June 2009 to April 2010, the relationship between GPS PWV and SSTa for Niño 3.4 and Niño 4 regions is varied at each station. Figure 6 shows the scatterplot between GPS PWV and SSTa for Niño 3.4 region for both increasing and decreasing phases. During the increased in intensity of El Niño in June−December of 2009 (Fig. 6a), a strong relationship was observed for PIMO station with a correlation coefficient of −0.90, moderate relationship was obtained for KUAL station with a correlation coefficient of −0.56 and found no correlation for NTUS and BAKO stations, which are all significant at the 99 % confidence level. A low correlation during decreasing in intensity of El Niño

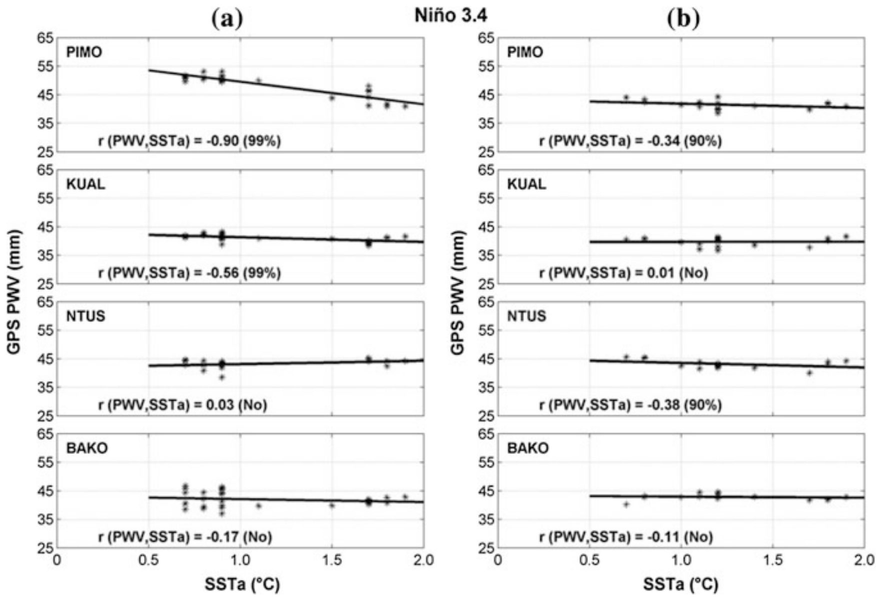

Fig. 6 Scatterplot between GPS PWV and SSTa for Niño 3.4 region during El Niño event for the year of 2009/2010 for **a** the increasing in intensity and **b** the decreasing in intensity

(December 2009–April 2010) was observed (Fig. 6b) for PIMO and NTUS stations with correlation coefficients are −0.34 and −0.38, respectively, while for KUAL and BAKO stations are found no correlation (as indicated by **No** in the figure).

For the analyzing of relationship between GPS PWV and SSTa for Niño 4 region, the scatterplot during El Niño event 2009/2010 is presented in Fig. 7. As shown in Fig. 7a, the relationship between GPS PWV and SSTa during the increased in El Niño intensity for PIMO and KUAL stations were observed moderate, except for NTUS and BAKO with a low correlation. While during the decreasing in intensity of El Niño (Fig. 7b), PIMO and KUAL was not correlated. A low correlation was observed for NTUS and BAKO stations with correlation coefficients of −0.39 and −0.40, respectively. From the figure, BAKO station was still with a low correlation, which likely low impacted by the El Niño event of 2009/2010. On the other hand, during increasing in intensity of El Niño, station located along the coast is more pronounced that the station in the land like NTUS and BAKO. The low effect of El Niño at specific site is probably due to season change from winter to summer.

The detail of the correlation coefficient value at all stations is compiled in Table 3. From the table, SSTa for Niño 3.4 shows the strong relationship on the GPS PWV. Moreover, the relationship between GPS PWV and SSTa at all stations during El Niño event is negative correlation, except for NTUS and BAKO during the increasing of El Niño intensity. The negative correlation indicated that the amount of GPS PWV is decreased during the event. This brings consequence that the delay of GPS signals from satellite to the receiver on the ground is larger. One

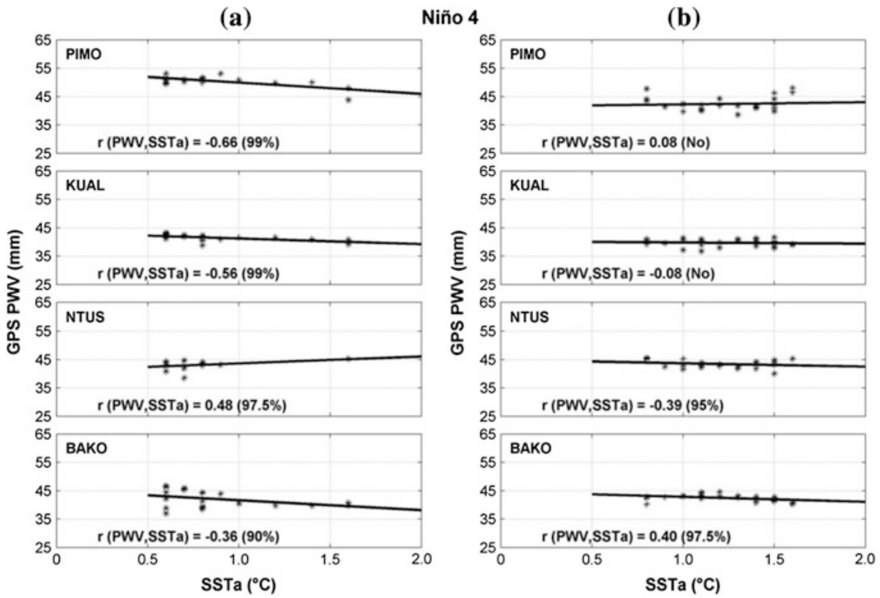

Fig. 7 Scatterplot between GPS PWV and SSTa from Niño 4 region during El Niño event for the year of 2009/2010 for **a** the increase in intensity and **b** the decrease in intensity

can be seen from Figs. 6 and 7 is that during increasing of El Niño intensity for El Niño 3.4 and El Niño 4 regions, the correlation trend is consistent for PIMO, KUAL and BAKO (decreasing trend) and NTUS (increasing trend). However, during decreasing of El Niño intensity at both Niño regions, only NTUS and BAKO was consistent in decreasing trend and PIMO and KUAL are opposite to each other. However, PIMO station experiences the highest El Niño effect than the other stations. This implies that the El Niño character in each year is apparently different which possibly due to the trade winds that across the region moved the water vapor over the ocean and occur too short or even occur too late (see Sect. 3.3 for detail comparison with precipitation). This depends on the latent heat of the sea surface temperature that will affect the distribution of water vapor in the atmosphere.

3.3 Analysis of Rainfall During El Niño Event

To strengthen the possible physical process of different response between PWV and SSTa variation, precipitation quantity from Tropical Rainfall Measuring Mission (TRMM) during a case of El Niño event is compared. Figure 8 shows the distribution of rainfall measured by TRMM-3B42.007 over the Southeast Asia region during El Niño from June 2009 to Aril 2010. From the figure, the most significant change in monthly average of rainfall was occurred in PIMO station (Philippines)

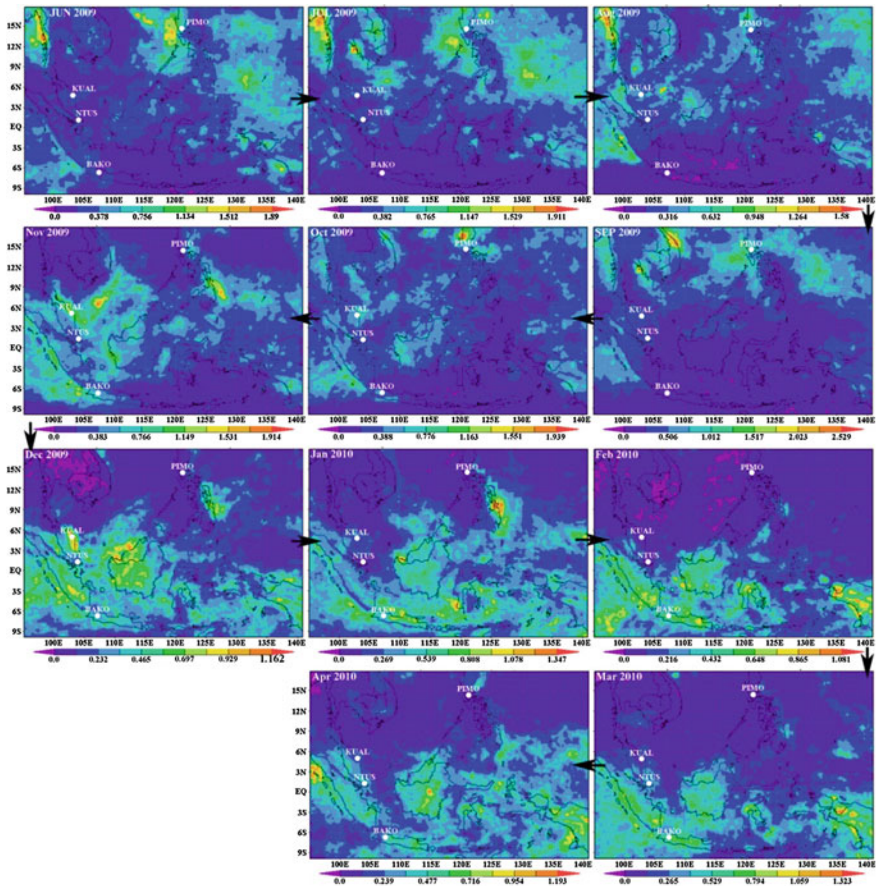

Fig. 8 Distribution of rainfall measured by TRMM-3B42.007 over the Southeast Asia region during El Niño event from June 2009 to April 2010

than the other stations. This is consistent with the PWV changes from GPS measurements. The beginning of El Niño event was from the month of June 2009 until September 2009, where the average of rainfall was higher, and the lower was occurred at KUAL, NTUS and BAKO stations. BAKO station is an area that has very low rainfall during the increasing of the intensity of El Niño from June to October of 2009. Along with the increasing intensity of the El Nino, high rainfall shifted towards the south. This causes an increase in rainfall for the station in KUAL, NTUS and BAKO. In addition to this condition, the drought occurred in the Philippines [19, 20] lead PIMO showed an opposite trend and gives a significant effect to the decreasing in agricultural production [21].

We here obviously obtained that the average of rainfall distribution is statistically comparable with PWV pattern as shown in Fig. 4. During increasing the intensity of El Niño, the monthly average of rainfall at PIMO station is increased

Table 4 The correlation coefficient between GPS PWV and SSTa during El Niño event for the case of 2009/2010

Station	The increase in intensity		The decrease in intensity	
	Niño 3.4	Niño 4	Niño 3.4	Niño 4
PIMO	−0.90	−0.66	−0.34	–
KUAL	−0.56	−0.56	–	–
NTUS	–	0.48	−0.38	−0.39
BAKO	–	−0.36	–	−0.40

Sign '–' indicates no correlation

and the PWV pattern is decreased. This clearly understood that when the rainy occurred, the water vapor content in the atmosphere is fall become a water. The low or no correlation obtained between GPS PWV and SSTa in Table 4 can be seen through the contours of Fig. 8. Instead, the different thing was occurred at BAKO station where the rainfall is increased during the decreased intensity of El Niño, which is a similar trend with PWV pattern. The low of precipitation and small effect on El Niño was difficultly to differentiate the relationship trend.

4 Conclusion

This study uses a correlation analysis to determine the relationship between GPS PWV and SSTa variability during the case of El Niño event. The data from PIMO, KUAL, NTUS and BAKO stations during the year of 2009/2010 were selected to calculate PWV. The relationship between GPS PWV and SSTa was found negative correlation, although the different trend was observed at each station. The negative correlation during the El Niño event can be interpreted that the PWV trend is decreased. Decreasing of PWV is correlated with a dry season, where water vapor is minimal in the atmosphere. On the other hand, rainfall is minimal at the location of a strong El Niño. For the case of 2009/2010 during increasing of El Niño intensity, the station located along the coast such as PIMO showed more affected than the other stations. In contrast, increased of PWV along the ocean-atmosphere interactions caused the delay of GPS signals is higher, which possibly existing the atmospheric phenomena above the ocean.

From the correlation obtained between PWV and SSTa, the ground-based GPS receiver is capable proposed as an alternative technique to be used to detect ENSO activity, especially El Niño event, and this is a new prospective method that has not been utilized before. It should be noted here that the El Niño can affect the GPS signals through indirect effects of PWV measurements. To clarify the clear response of GPS PWV on the SSTa variation, a strong ENSO event will be considered for future work to distinguish the unwanted noise in the analysis. More GPS PWV data during El Niño event are also needed to better understand the ENSO mechanism, both during the occurrences of El Niño and El Niña phases.

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