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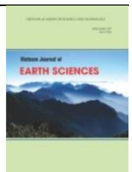

Precipitable water characterization using global navigation satellite system data: A case study in Nghia Do area, Vietnam

Pham Le Khuong[1,2*], Nguyen Xuan Anh[1,2], Hiep Van Nguyen[1,3], Hoang Hai Son[1,2], Nguyen Nhu Vinh[1], Bui Ngoc Minh[1]

[1]*Institute of Geophysics, VAST, Hanoi, Vietnam*
[2]*Graduate University of Science and Technology, VAST, Hanoi, Vietnam*
[3]*Northern Delta and Midland Regional Hydro-Meteorological Center, VMHA, Hanoi, Vietnam*

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ABSTRACT

This paper evaluates the estimated total precipitable water (TPW) and studies its characteristics in the Nghia Do area (Hanoi) using Global Positioning System (GPS) data and the Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP) processing technique and calculation tool. The TPW was estimated from GPS data from September 22, 2022 to March 31, 2023 using CSRS-PPP provided by Natural Resources Canada. The calculated TPW was validated with TPW products from Aeronet data and radiosonde data. Taking advantage of its high time resolution, the TPW estimated from GPS data was used to analyze the temporal variation of TPW during cold surges affecting the Nghia Do area. The results indicate a strong agreement between the estimated TPW from GPS data and TPW products derived from Aeronet and radiosonde data. The mean error (ME), root mean square error (RMSE), and correlation coefficient between the estimated TPW from GPS data and the Aeronet-derived product are 0.68 mm, 2.05 mm, and 0.988, respectively. The corresponding values between the estimated TPW and the radiosonde-derived product are -3.01 mm, 3.24 mm, and 0.996, respectively. The study of TPW variation over the Nghia Do area during the research period revealed that, generally, TPW values in December and January were lower than those in the other months. Before the arrival of a specific cold surge at a station, TPW tends to increase by about 6 mm within 12 hours as convection activities ahead of the cold front intensify. After the cold air passes over the station, the TPW value decreases by about 8 mm within 12 hours due to the influx of cold and dry winter air brought by the prevailing winds. This distinct TPW variation pattern suggests that GPS data can be effectively employed to define the arrival of cold surges in the station area.

Keywords: CSRS-PPP, total precipitable water (TPW), zenith wet delay (ZWD), radiosonde, Aeronet, GPS.

1. Introduction

Water vapor is a crucial component of the atmosphere, profoundly impacting the physical and thermodynamic processes within it. The distribution of water vapor plays a significant role in shaping atmospheric dynamics, weather, and climate of the Earth. This distribution exhibits substantial spatial and temporal variations. One of the quantities that characterizes water vapor in the atmosphere is the amount of water vapor in the atmospheric column or total precipitable water (TPW). TPW can be quantified through

*Corresponding author, Email: phamlekhuongigp@gmail.com

various approaches, including measurements via weather balloons, satellite estimations, and more. Among these methods, surface GPS devices contribute to TPW estimation by providing valuable data.

The GPS data is processed to obtain the Zenith Total Delay (ZTD). After subtracting the zenith hydrostatic delay (ZHD), we are left with the zenith wet delay (ZWD). ZWD occurs during the transmission of electromagnetic signals from the Global Navigation Satellite System (GNSS) to GPS devices as they traverse through humid air. This delay is a result of the interaction between the electromagnetic signal and water vapor molecules in the atmosphere. As electromagnetic signals travel through humid air, they come into contact with water vapor molecules, causing a reduction in the signal's speed. This delay becomes more significant when the signal passes through regions with higher moisture levels. By measuring the delay in the transmission of the electromagnetic signal, researchers were able to estimate the TPW in the air along the signal's path. Following this principle, the TPW is estimated from the ZWD (Bevis et al., 1992; Baelen et al., 2005; Gopalan et al., 2021).

According to Khanian and Farzaneh (2021), the Precise Point Positioning (PPP) method is a highly accurate technique used in Global Navigation Satellite System (GNSS) data processing to determine ZTD. This method focuses on improving the positional accuracy of a single satellite receiver by precisely determining satellite orbit information, correcting clock errors, and minimizing the impact of atmospheric parameters, including mitigating ionosphere interference effects. An important advantage of the PPP technique is that the estimated ZTD at one station remains unaffected by data from neighboring stations, and the processing speed is faster compared to that in other methods (Khanian and Farzaneh, 2021).

In 2003, the Geodetic Survey Division of Natural Resources Canada introduced the Canadian Spatial Reference System - Precise Point Positioning (CSRS-PPP) processing technique and calculation tool. The CSRS-PPP enables users to estimate ZTD using GPS data from a single station (Tetreault et al., 2005). Natural Resources Canada upgraded CSRS-PPP to version 3 in October 2020 (Banville et al., 2021). Several authors have assessed the quality of the estimated ZTD values from the CSRS-PPP. Previous studies consistently demonstrated that these estimated values align well with the ZTD product from the International GNSS Service (IGS) (Guo, 2015; Astudillo et al., 2018; El-Mewafi et al., 2019; Gratton et al., 2021). In the Iran region, the estimated ZTD values from the CSRS-PPP exhibit good agreement, reaching approximately 98%, with the corresponding values from the GAMIT software (Khanian and Farzaneh, 2021). Rose et al. (2023) conducted a comparison between the estimated TPW from the CSRS-PPP and radiosonde data in the Indian region, revealing a high level of consistency between these two data sources. Additional research findings further support the notion that the CSRS-PPP is highly effective for tropospheric delay estimations (Atiz and Kalayci, 2021).

In Vietnam, GPS signals have been utilized for estimating ZTD and TPW values. Le et al. (2009) assessed ZTD and TPW values based on GPS data in Vietnam. The researchers employed the GAMIT software to process GPS data from three stations located in Hanoi, Hue, and Ho Chi Minh City. The obtained results illustrate the amplitude and annual variation trends of ZTD and TPW values. Furthermore, the results reveal that the TPW calculated from GPS data significantly exceeds the values derived from global model products. The agreement between GPS-derived TPW and the TPW product from the global model is less favorable in South Vietnam compared to the North (Le et al., 2009). In a separate study, Lai et al. (2022) employed GPS data to estimate TPW. The findings suggest that TPW calculated from CORS (Continuously Operating Reference Station) stations demonstrates high reliability and can be effectively utilized in scientific research and meteorological forecasting (Lai et al., 2022).

Previous studies have utilized GPS data and hourly average temperature from global models to estimate TPW. The resulting findings were then employed to analyze annual and spatial variations in TPW. The CSRS-PPP has also been utilized to process GPS data for investigating crustal displacement (Tran et al., 2023). However, the application of the CSRS-PPP to estimate TPW from high-resolution GPS data over time has not been undertaken in Vietnam. To enhance data utilization efficiency, it is imperative to estimate TPW from GPS data with increased temporal resolution and to employ this data source for studying and monitoring variations in TPW associated with weather phenomena and weather forecasting, and climate prediction and researches.

Annually, Vietnam is affected by about 26-28 cold surges (Dinh and Vo, 2018). Currently, operational determining the impact of cold surges over the Vietnam region is based on wind data from the Bach Long Vi station and average daily temperature data from stations in the Northeast region (Nguyen, 2011). When cold surges move into the Vietnam area, they often result in dangerous weather phenomena such as thunderstorms, and heavy rainfall in the early and late months of winter (Dinh and Vo, 2018). Rainfall during the months is closely related to the TPW in the atmosphere, making the study of TPW variations during cold surge arrival important.

This paper initially presents the estimated ZWD values derived from GPS data at Nghia Do station using the CSRS-PPP. The estimated ZWD and temperature data from stations were utilized to estimate TPW with a one-minute interval resolution. To assess the accuracy of TPW estimated from GPS data, a comparison is made with TPW products from Aeronet data at Nghia Do station, as well as TPW data from the Hanoi radiosonde station. Subsequently, the TPW estimated from GPS data is employed to analyze the characteristics of TPW during the influence of cold air at Nghia Do station. The subsequent sections of the article are as follows: Section 2 presents data and methods, detailing data sources, calculation methods, and data quality assessment. Section 3 offers the primary findings of the study, analyzing data quality and the behavior of TPW during certain cold surges impacting the station. Section 4 contains the discussion. Section 5 is conclusion of the paper.

2. Data and method

2.1. Data

This study utilizes GPS observations collected from Stonex's S800A device at Nghia Do station (21.048°N, 105.799°E). Nghia Do station, located in the inner city of Hanoi, is part of the Institute of Geophysics observation network and is installed on the roof of a 9-floor building. The Nghia Do area is affected by the winter monsoon with cold surges in the winter and a deep convective cloud system in the summer, resulting in extreme weather phenomena such as thunderstorms and heavy rainfall. The impact of these extreme weather conditions, characterized by high TPW values, on GPS signals makes the GPS data at the station useful for studying TPW characteristics over the research area. In addition to the GPS receiver device, the station is equipped with an automatic weather station. The data was collected during the period from September 22, 2022, to March 31, 2023. The dataset includes GPS, GLONASS, and Beidou satellite data with a 1-second time resolution.

Alongside the GPS data, temperature values from the automatic weather station (Davis 6162 Vantage Pro2) at Nghia Do station were also incorporated. The temperature data also has a 1-minute time resolution.

TPW products derived from Aeronet data at Nghia Do station and radiosonde data from the Hanoi radiosonde station (21.01°N, 105.80°E) were gathered for comparison. The Aeronet data's TPW products were calculated from the measurement data of the CE318T device, which is part of the Aerosol Robotic Network (AERONET) installed at Nghia Do station. This device measures solar radiation at nine wavelength bands, TPW calculated based on measurements of water vapor absorption band around 937 nm. The TPW data from the AERONET station are only available on sunny days. The daily average TPW data include 90 values during the research period acquired from NASA's AERONET database (https://aeronet.gsfc.nasa.gov). Meanwhile, TPW products from radiosonde data were obtained from the University of Wyoming's Upper Air Sounding program (https://weather.uwyo.edu/upperair/sounding.html). The geographical locations of Nghia Do station and Hanoi radiosonde station are depicted in Fig. 1. Data on cold-surge events affecting Vietnam during the research period were collected from the Vietnam Meteorological and Hydrological Administration. A cold-surge event was determined to affect northern Vietnam based on wind data observed at Bach Long Vi station and the decrease in temperature observed at the stations in that area.

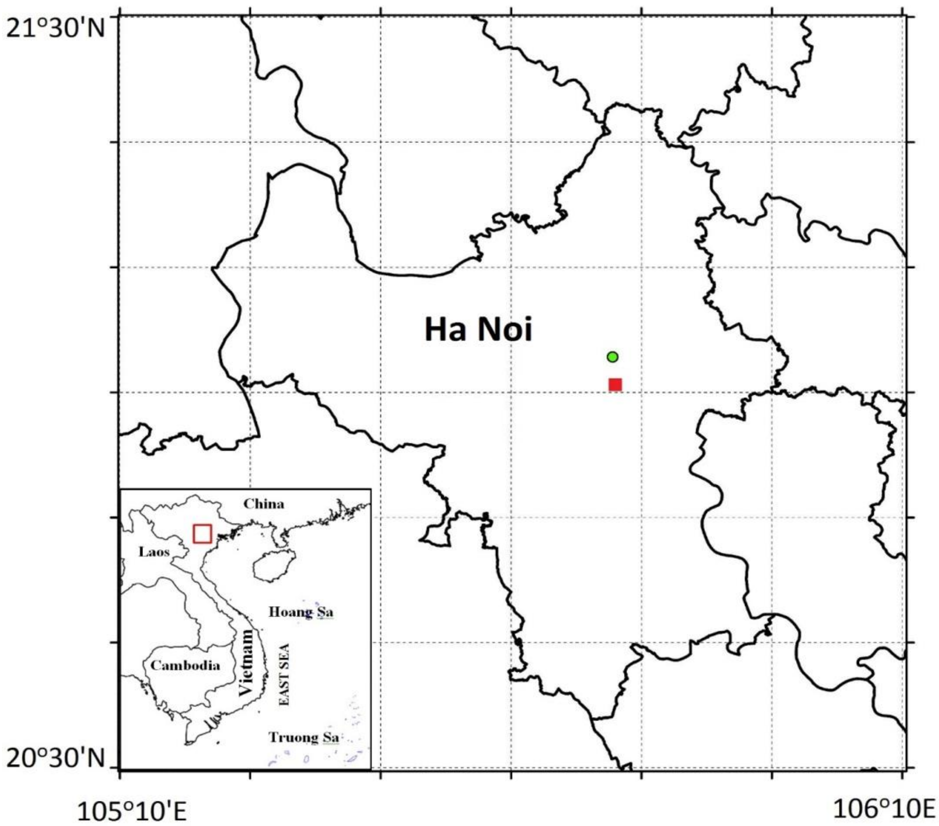

Figure 1. Location of Nghia Do station (circle, green) and Hanoi radiosonde station (square, red)

2.2. Method

2.2.1. Estimate the zenith wet delay from GPS data

Signals emitted from GPS satellites will be delayed by the troposphere before reaching the ground-based receiver. This phenomenon is referred to as tropospheric delay. The zenith tropospheric delay is defined as follows:

$$ZTD = \int_{H}^{+\infty}[n(z) - 1]dz \quad (1)$$

where ZTD represents the zenith tropospheric delay, n(z) stands for the refractive index of the atmosphere at the height z, and H is the height of the GPS receiver. The ZTD consists of two atmospheric delay components: the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD).

$$ZTD = ZHD + ZWD \quad (2)$$

The ZTD values can be determined through the processing of two-frequency GPS data. In this paper, GPS observations from the Stonex S800A GPS device were converted to Rinex format using the software installed on the device. The GPS observations were processed by the CSRS-PPP calculation tool, employing the ITRF2020 reference system. The output data results include the ZTD and ZWD values. The ZWD values were used to estimate the TPW with a 1-minute time resolution.

2.2.2. Estimate the total precipitable water

According to Baelen et al. (2005), the TPW values can be estimated from the ZWD values as follows:

$$TPW = ZWD/k \quad (3)$$

$$k = 461.5 * 10^{-5} * \left[3.719 * \frac{10^5}{T_m} + 16.4221\right] \quad (4)$$

where T_m is the average temperature of the column of the atmosphere.

T_m can be approximated by (Bevis et al., 1992)

$$T_m = 70.2 + 0.72 * \bar{T}_s \quad (5)$$

$\bar{T}_S$ is the hourly average temperature at the surface.

In this paper, to estimate the TPW values, the measured temperature values with 1-minute time resolution from the automatic weather station are used instead of the hourly average temperature.

2.2.3. Evaluation of the estimated TPW values

To evaluate the quality of the results, daily average TPW values estimated from GPS were compared with the mean daily TPW products from Aeronet data. Additionally, TPW values estimated from GPS at times 07:00 and 19:00 (local time) were compared with TPW products from radiosonde data. We used statistical parameters:

$$ME = \frac{1}{N}\sum_{i=1}^{N}(X_{GPS} - X_{PRO}) \quad (6)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_{GPS} - X_{PRO})^2} \quad (7)$$

$$R = \frac{\sum_{i=1}^{N}(X_{GPS} - \overline{X_{GPS}})(X_{PRO} - \overline{X_{PRO}})}{\sqrt{\sum_{i=1}^{N}(X_{GPS} - \overline{X_{GPS}})^2 \sum_{i}^{N}(X_{PRO} - \overline{X_{PRO}})^2}} \quad (8)$$

$$RMAE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{X_{GPS} - X_{PRO}}{X_{GPS}}\right| 100\% \quad (9)$$

where ME, RMSE, RMAE, R are mean error, root mean square mean error, relative mean absolute error (%), and correlation coefficient, respectively; X is the total precipitable water estimated from the GPS data (X_{GPS}), from either Aeronet data or radiosonde data (X_{PRO}); $\overline{X_{GPS}}$ is the mean of X_{GPS}; $\overline{X_{PRO}}$ is the mean of X_{PRO}; and N is the number of samples.

3. Results

3.1. Estimated ZWD and TPW values from GPS data

The GPS data were continuously observed at Nghia Do station (Hanoi) during the 190-day period from September 22, 2022 to March 31, 2023. Because of some missing data days, a dataset spanning 183 days of GPS data was collected. The CSRS-PPP calculation tool was utilized to estimate ZWD values. Figure 2 illustrates the temporal variation of the estimated ZWD values derived from GPS data at Nghia Do station. The range of ZWD values extends from 57.2 mm (on November 2, 2022) to 413.7 mm (on September 30, 2022).

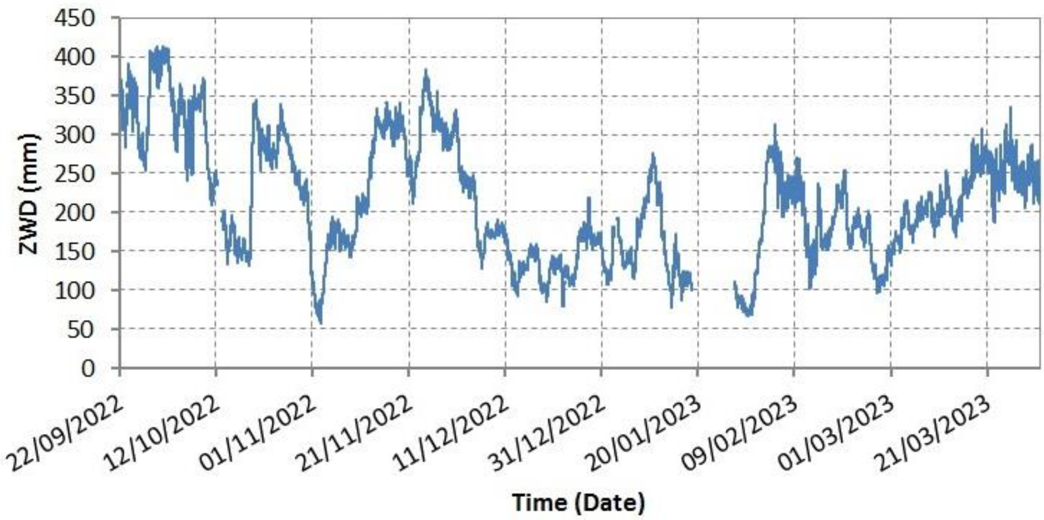

Figure 2. The zenith wet delay (ZWD) time series in the period from September 22, 2022 to March 31, 2023 at Nghia Do station.

The estimated ZWD values from GPS data, along with air temperature data with a temporal resolution of 1 minute, were used to compute TPW. Figure 3 displays the temporal evolution of the estimated TPW values derived from GPS data at Nghia Do station in Hanoi. The TPW values range from 9.3 mm to 66.8 mm. In general, the variable trend of TPW reveals that TPW values are lower in December and January compared to other months. The temporal pattern of TPW closely mirrors the variation observed in ZWD.

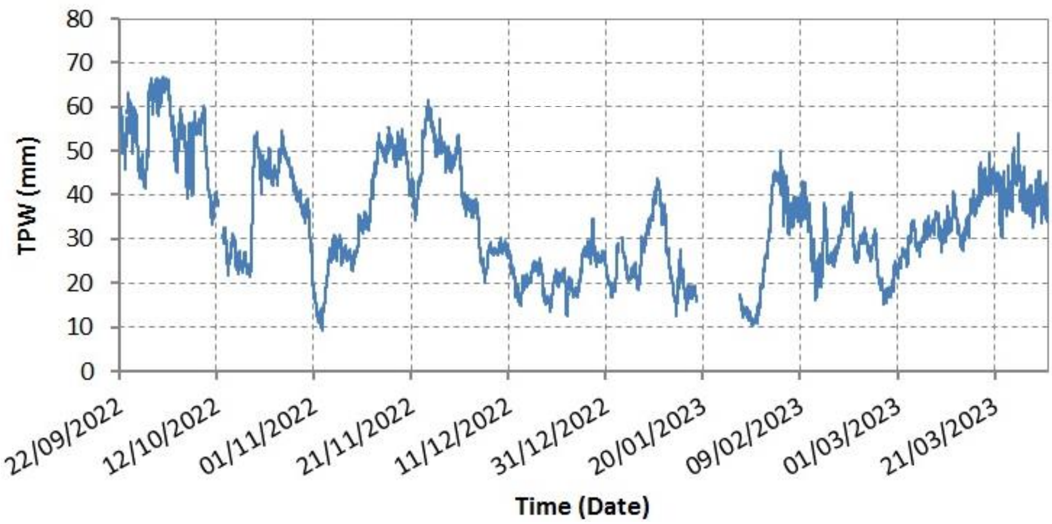

Figure 3. The temporal variation of the estimated TPW values in the period from September 22, 2022 to March 31, 2023 at Nghia Do station

3.2. Evaluation of the estimated TPW values from GPS data

The quality of the estimated TPW from GPS data (TPW_GPS) was evaluated through a comparison with TPW products from Aeronet data (TPW_AER) and radiosonde data (TPW_RS). Firstly, 90 values of daily average TPW_GPS were compared with those of TPW_AER at Nghia Do station (Fig. 4). Overall, the differences between TPW_GPS and TPW_AER are not significant. Their temporal variations are quite similar, with smaller values in December and January than those in the other months.

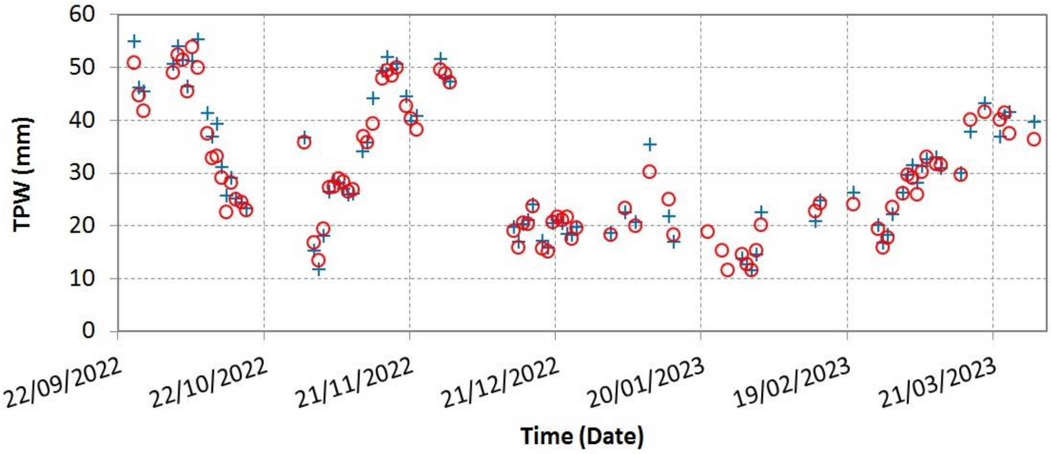

Figure 4. The daily average values of estimated TPW from GPS data (TPW_GPS) (+, blue) and the TPW product of the Aeronet data (TPW_AER) (circle, red) in comparison dataset at Nghia Do station

Figure 5 displays the relative absolute error values of TPW_GPS in comparison to TPW_AER. They range between 0.14% and 17.92%. The RMAE is about 5.04%, which is relatively small. The error values of TWP from these two data sources range between -3.28 mm and 6.11 mm. The ME value of 0.68 mm indicates a predominance of negative values over positive ones, suggesting that TPW_GPS generally exceeds TPW_AER. Both MAE and RMSE demonstrate relatively small values of 1.53 mm and 2.05 mm, respectively (Table 1).

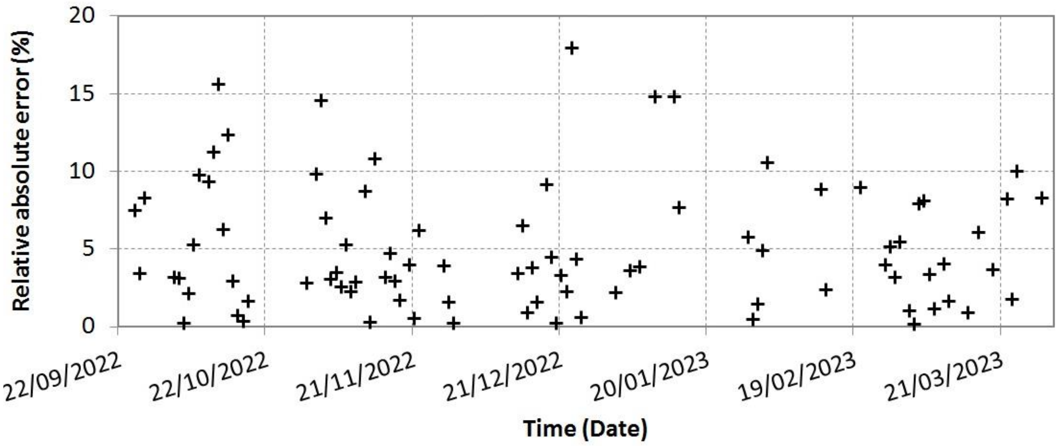

Figure 5. The relative absolute error between the estimated TPW from GPS data (TPW_GPS) compared to the product from Aeronet data (TPW_AER) at Nghia Do station

Table 1. Statistical comparison of the estimated integrated water vapor from GPS data (TPW_GPS) at Nghia Do station, the integrated water vapor product from Aeronet data (TPW_AER) at Nghia Do station, and the integrated water vapor product from radiosonde data (TPW_RS) at Hanoi radiosonde station

	ME (mm)	MAE (mm)	RMSE (mm)
TPW_GPS and TPW_AER	0.68	1.53	2.05
TPW_GPS and TPW_RS	-3.01	3.01	3.24

Figure 6 illustrates the scatterplots of the average daily values of TPW_GPS and TPW_AER. The correlation coefficient of 0.988 (R^2 = 0.9767) indicates a strong relationship between the two datasets. Furthermore, the data reveals that the variance between TPW_GPS and TPW_AER is not significant when the daily average TPW values are less than 30 mm. However, when the daily average TPW values surpass 30 mm, the TPW_GPS value is usually larger than that of TPW_AER.

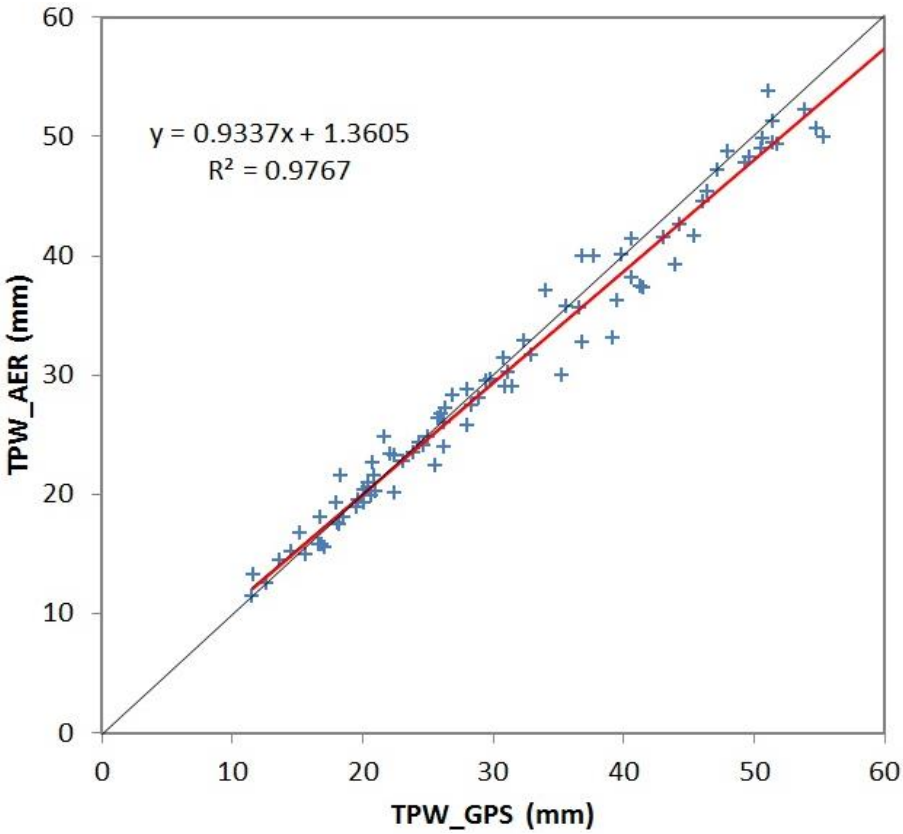

Figure 6. Scatterplots of the average daily values of the estimated total precipitable from GPS data (TPW_GPS) and product from Aeronet data (IWR_AER) at Nghia Do station, trend line (red)

The estimated TPW from GPS data was compared with the TPW product from radiosonde data, comprising 319 pairs of values at 7:00 AM and 7:00 PM (local time). Figure 7 depicts the temporal variation of TPW_GPS at Nghia Do station and TPW_RS at Hanoi radiosonde station at 7:00 AM and 7:00 PM. The results indicate that TPW_GPS values at 7:00 AM and 7:00 PM range from 10.5 mm to 64.6 mm, while TPW_RS values range from 12.8 mm to 68.8 mm. Upon comparing the changes of

TPW_GPS and TPW_RS with time, we observe a similar trend with matching extreme (maximum and minimum) points. The results also highlight that TPW_GPS values are consistently lower than TPW_RS values. Additionally, TPW_GPS and TPW_RS values in December and January are smaller compared to the other months, which is consistent with the TPW_AER data.

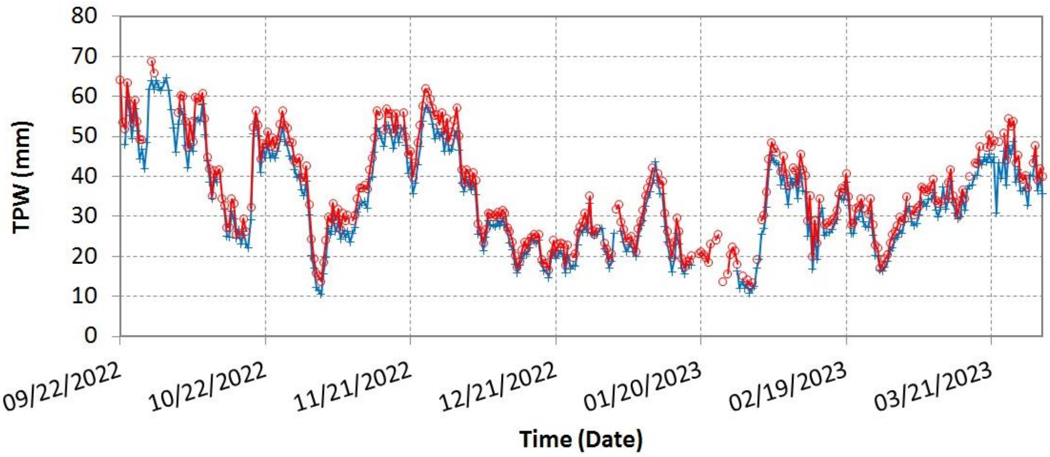

Figure 7. Variation of the estimated TPW from GPS data (TPW_GPS) (+, blue) at Nghia Do station and TPW product of the radiosonde data (TPW_RS) (circle, red) at Hanoi radiosonde station at 07h00 and 19h00 (local time)

Figure 8 shows the relative absolute error between TPW_GPS at Nghia Do station and TPW_RS from the Hanoi radiosonde station. The error values range between 1.28% and 31.49%. The Relative Mean Absolute Error (RMAE) is 9.56%, which is higher than the RMAE between TPW_GPS and TPW_AER. The error values (TPW_GPS - TPW_RS) are consistently negative, ranging from -0.37 to -6.99 mm. The ME value reaches -3.01 mm. The MAE and RMSE are relatively small with values of 3.01 mm and 3.24 mm, respectively (see Table 1). Figure 9 illustrates a high correlation coefficient (0.996) between TPW_GPS and TPW_RS data.

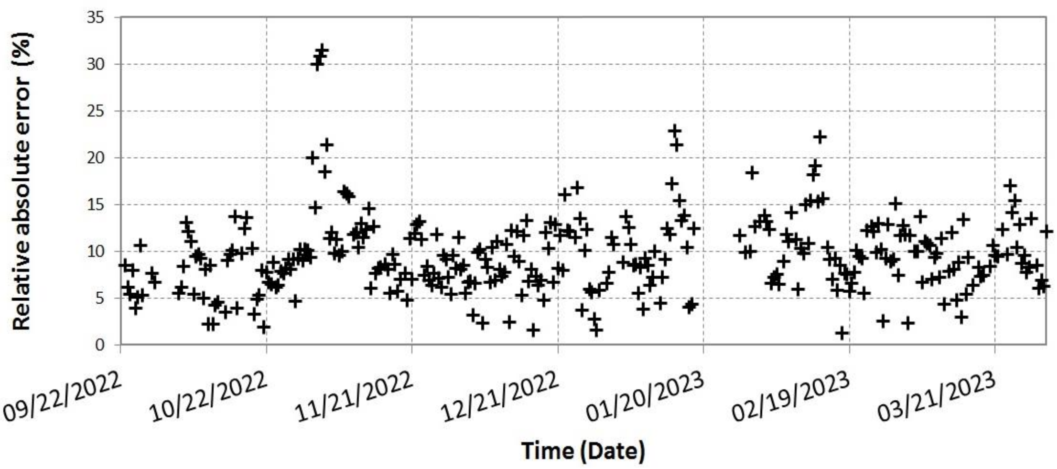

Figure 8. The relative absolute error between the estimated TPW from GPS data (TPW_GPS) at Nghia Do station and the TPW product of the radiosonde data (TPW_RS) from Hanoi radiosonde station

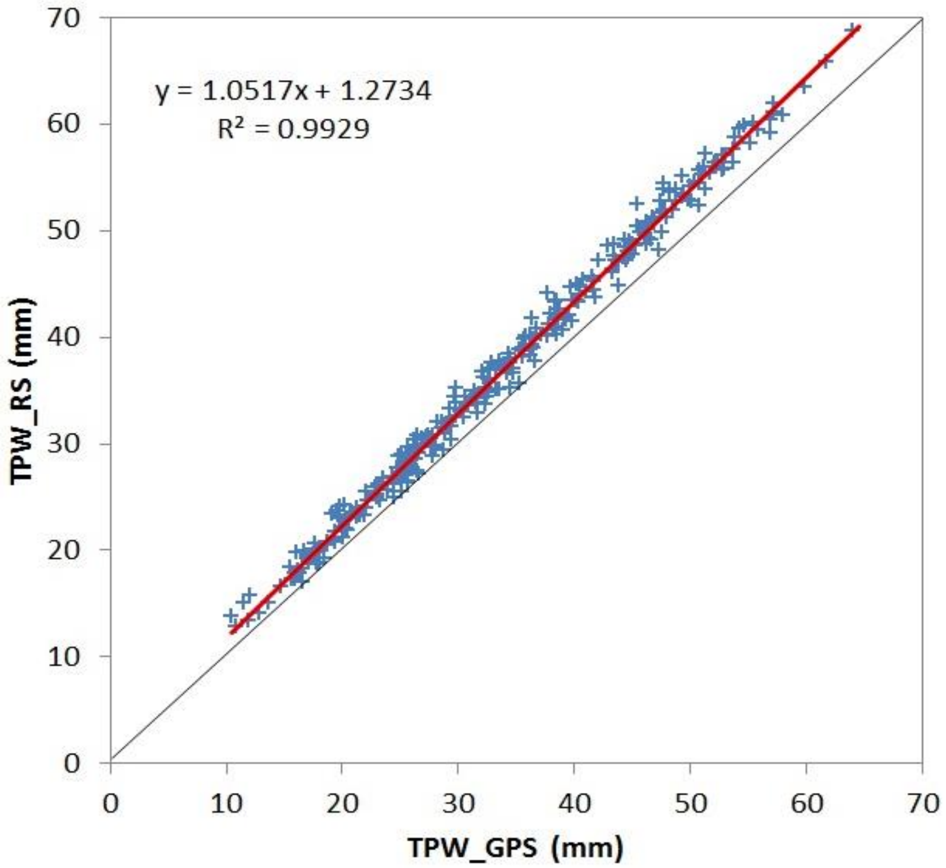

Figure 9. Scatterplots of the estimated TPW from GPS data (TPW_GPS) at Nghia Do station and the TPW product from radiosonde (TPW_RS) at Hanoi radiosonde station at 07h00 and 19h00 (local time), trend line (red)

3.3. The TPW variation in cold surges

In this section, the characteristics of TPW during cold surges are investigated. Figure 10 illustrates the temporal variation of daily average values of estimated TPW from GPS data and the daily average temperature at Nghia Do station during the period from September 22, 2022, to March 31, 2023. The results indicate that the daily average TPW_GPS values ranged from 11.6 mm to 64.7 mm. There were 15 cold surges that affected the Hanoi area during this period. The days when the cold surge affected the Hanoi area are denoted on Fig. 10 by black circles.

Considering the variation in daily average temperature, it is evident that during cold air intrusions in Hanoi, the mean daily temperature value experiences a sudden drop (Fig. 10). The extent of this temperature decrease depends on the intensity of the cold surge and environmental conditions over the station area. The daily average temperature can exhibit significant drops (e.g., by about 12.8°C on November 30, 2022) or more subtle decreases (e.g., about 0.4°C on December 04, 2022).

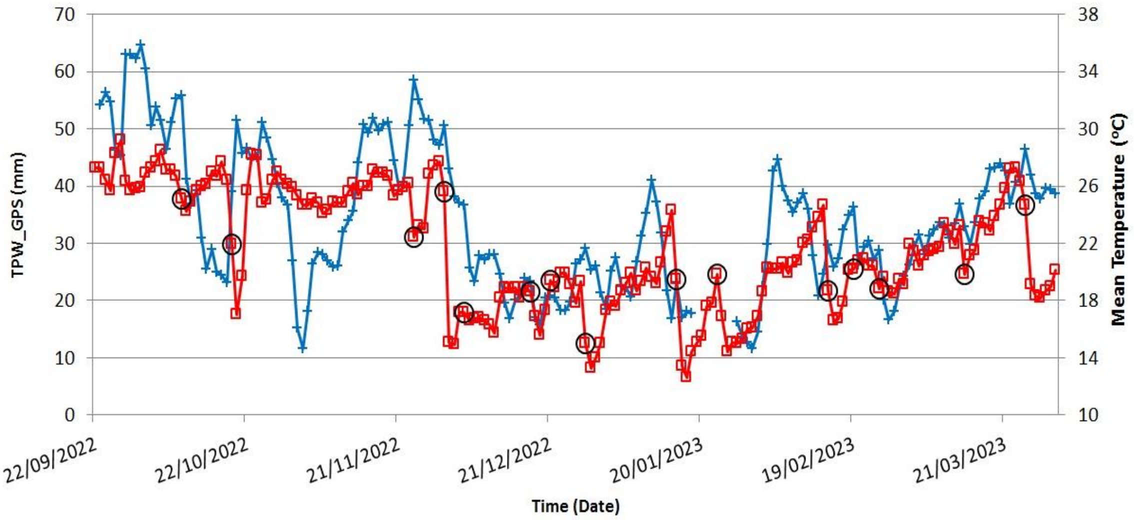

Figure 10. Variation of the daily average of the estimated TPW from GPS data (TPW_GPS) (+, blue) and the daily average air temperature at Nghia Do station (square, red). The black circle indicates the day when the cold surge affecting Hanoi area

Figure 11 depicts variations in the estimated TPW derived from GPS data and air temperature at Nghia Do station during cold surges. In some instances, the temperature experiences a sudden drop during the day when cold air influences Hanoi. In such cases, we can utilize the temperature change to determine the onset of the station being affected by the cold air. For instance, cold surges impacted the Hanoi region on the following dates: 09/10/2022, 30/11/2022, 28/12/2022, 14/02/2023, 24/02/2023, and 25/03/2023. During the cold surge affecting Hanoi on 09/10/2022, it is evident that the air temperature at the station starts to decrease rapidly after 12:30 (local time), signifying the commencement of the cold air's influence on the station. Figure 11a represents the estimated TPW derived from GPS data for this case. The TPW_GPS value exhibits an increase prior to the arrival of cold air at the station. Following the impact of the cold air, the TPW_GPS value begins to decrease. In this particular case, the TPW_GPS decreases by approximately 24.6 mm (Fig. 11a).

In the case of cold air affecting the area on 30/11/2022 (Fig. 11c), it is evident that the air temperature dropped rapidly after 18:20 (local time) on that date, indicating the arrival of cold air in the station area. In Fig. 11c, an increase in the TPW value was observed before the cold air reached the station, followed by a decrease after its impact. The reduction in TPW reached a magnitude of 14.3 mm.

Similar patterns can be observed for cases of cold air affecting the Hanoi area on 28/12/2022, 14/02/2023, 24/02/2023, and 25/03/2023 (Fig. 11). The variations in TPW values follow a consistent trend across these cases, showing an increase before the arrival of the cold air at the station and a subsequent decrease after the cold air affects the station. The reduction amplitudes for TPW are 10.3 mm, 13.6 mm, 13.4 mm, and 15.0 mm, respectively (Figs. 11f, 11h, 11k, and 11m).

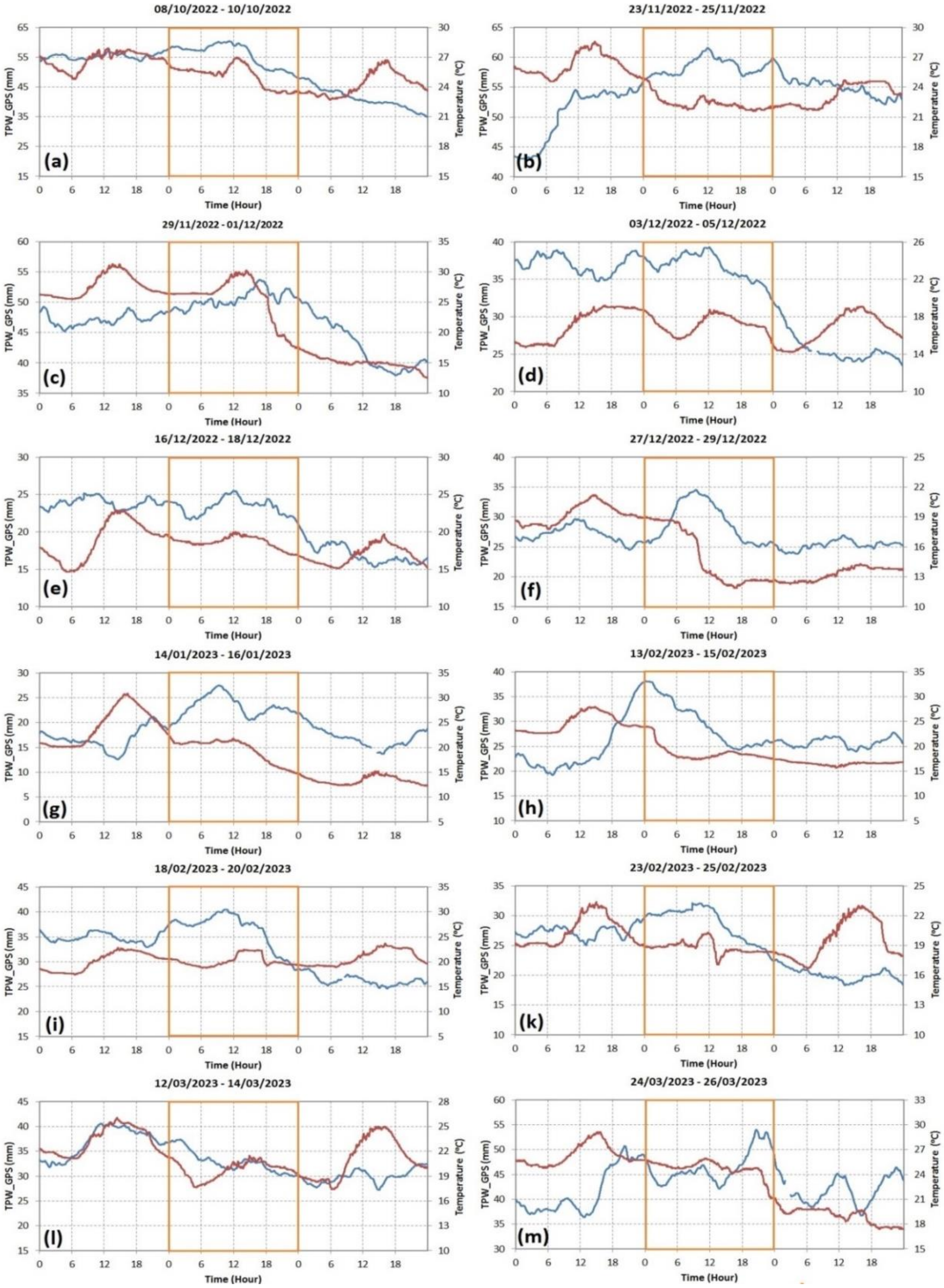

Figure 11. The estimated TPW from GPS data (TPW_GPS) (blue, mm) and air temperature (red, °C) at Nghia Do station in cold surges. The orange square indicates the day when the cold surges started affecting on the Northern Delta region

We did not observe a sudden decrease in the temperature variation diagram in other cases, including the cold surges that affected the Hanoi area on 24/11/2022, 04/12/2022, 17/12/2022, 15/01/2023, 19/02/2023, and 13/03/2023. Determining when cold air reached the station during these instances proved to be challenging if only temperature data are used. However, we did notice a consistent trend in the TPW: it initially increased, followed by a decrease on those days. The variation in TPW calculated from GPS data resembled the patterns seen in cases where cold air affected other stations, causing a rapid drop in air temperature upon the return of cold air to the station. Therefore, it is evident that high-resolution TPW data (measured in intervals of several minutes) can be utilized to define the time of cold air arrival at a specific location.

To further investigate the possibility of using TPW data to define the time of cold surge arrival at a specific location, Fig. 12 illustrates the results of variations in TPW and average temperature based on a composite of 14 cold surges within the period of ±48 hours from the time the TPW values reach their maximum (indicated as hour zero on the chart). The results demonstrate that the average TPW reaches its maximum value coinciding with the time when the average temperature begins to decrease rapidly over time. This clearly illustrates that TPW increases before cold surges affect the station and decreases after cold surges pass the station.

In general, the average TPW increases rapidly by about 6 mm during the 12-hour period before the cold surge affects the station and decreases rapidly by about 8 mm during the 12 hours after the cold surge has affected the area. Following the cold surge's impact on the station, the average temperature decreases by 4.5°C within 12 hours (Fig. 12).

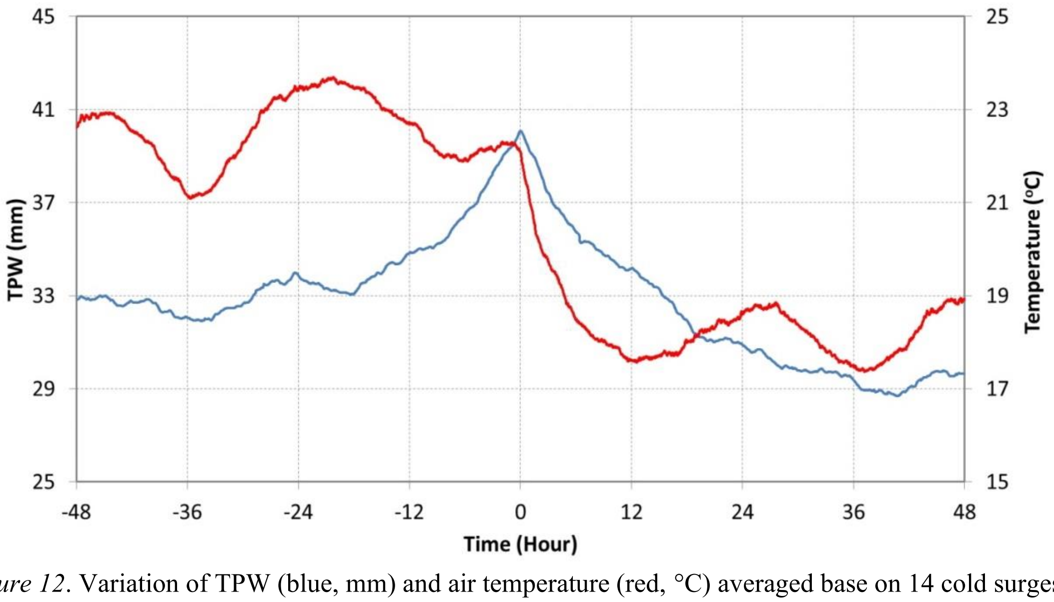

Figure 12. Variation of TPW (blue, mm) and air temperature (red, °C) averaged base on 14 cold surges in the period ±48 hours from the time when the TPW values are maximum

4. Discussions

The CSRS-PPP tool is a freely available online tool known for its efficient processing of GPS data. It enables the calculation of ZTD and ZHD parameters from a single station without the need for a reference station (Tetreault et al., 2005; Vázquez-Ontiveros et al., 2023). When utilizing this tool, the processing time for data is relatively fast, typically completing in only about 10 minutes after data submission. However, it's important to note that CSRS-PPP neither support the submission of large data files (> 300Mb) nor allow processing of data files containing more than 5 days of data.

In this study, TPW is calculated from GPS data using temperature data from automatic weather stations. TPW was computed from GPS with a 1-minute temporal resolution, a significantly higher temporal resolution than in previous studies in Vietnam, where TPW was calculated from GPS data at a lower temporal resolution of some data points per day (Le et al., 2009; Lai et al., 2022). The trend of TPW shows that TPW values in December and January are lower than in other months (Fig. 2). The annual variation of TPW is consistent with previous research (Le et al., 2009).

Table 2 shows that the MAE between TPW_GPS and TPW calculated from global model data is 11.7 kg/m^2, 4.4 kg/m^2, and 5.7 kg/m^2 for Hanoi, Hue, and Ho Chi Minh City stations, respectively (Le et al., 2009). Meanwhile, the RMSE between TPW_GPS and TPW calculated from ERA5 data of the European Centre for Medium-Range Weather Forecasts is 5.42 mm in the Vietnam area (Lai et al., 2022). Overall, the MAE and RMSE values between TPW_GPS data and TPW products from AERONET data and radiosonde data in the Nghia Do region are relatively small. TPW_GPS is highly correlated with TPW products from AERONET and radiosonde data, as well as TPW estimated from global model data. The results indicate that the quality of our high-temporal resolution TPW at Nghia Do station is consistent with previous studies in Vietnam.

Table 2 also reveals that the RMSE and correlation between TPW_GPS and TPW products from AERONET data at Nghia Do station are not significantly different from other research findings (Gui et al., 2017; Zhao et al., 2020). The RMSE and correlation between TPW_GPS and TPW products from radiosonde data in the Nghia Do area are also consistent with previous results (Zhao et al., 2022; Domingo and Ernest, 2022). In general, the results of this study align with findings in other parts of the world.

Table 2. The ME, MAE and RMSE between TPW estimated from GPS and TPW products from other data reported in some previous studies

Authors	Between TPW_GPS and TPW from other data	ME (mm or kg/m^2)	MAE (mm or kg/m^2)	RMSE (mm or kg/m^2)	R	Region
Le et al. (2009)	TPW from global models data		11.7 4.4 5.7		0.95 0.91 0.75	Hanoi Hue Ho Chi Minh city
Lai et al. (2022)	TPW from ERA5 data			5.42		Vietnam
Zhao et al. (2020)	TPW from Aeronet data			1.13–2.04	0.93–0.97	China
Gui et al. (2017)	TPW from Aeronet data	-0.09		2.53	0.98	China
Domingo and Ernest (2022)	TPW from radiosonde data	-13.39 – -0.18		1.86–2.29	~0.97	Philippines
Zhao et al. (2022)	TPW from radiosonde data	-0.69–0.61	0.66–3.54	0.86–3.24		China
This study	TPW from Aeronet data	0.68	1.53	2.05	0.988	Hanoi
This study	TPW from radiosonde data	-3.01	3.01	3.24	0.996	Hanoi

The findings of this research indicate that, during the arrival of a cold surge, the variation of TPW exhibits distinct characteristics: it increases upon the arrival of cold air and then decreases sharply. However, it's important to note that when utilizing TPW data to determine the arrival of cold air at the station, the prevailing weather pattern during that period should exclude the influence of other mesoscale systems, such as typhoons, tropical depressions, and disturbances in the east wind region, which can significantly impact local weather conditions. In such scenarios, TPW might be predominantly influenced by deep convective cloud systems from a different weather system rather than solely by the leading edge of the cold air mass. This can result in variability for TPW that does not accurately represent the characteristics of the arrival of the cold air mass edge. A typical example of this scenario is the cold surge that occurred on October 19, 2022, coinciding with the presence of Typhoon No. 6 (Nesat) (Figs. 13, 14). Figure 13 illustrates that TPW increased concurrently with the arrival of cold air in the Nghia Do area and subsequently did not decrease. This behavior contrasts with the aforementioned cases of cold air influence. During this timeframe, the Northern Delta region was impacted by the moist air associated with the circulation of Typhoon No. 6 (Fig. 14). Figure 14a displays the spatial distribution of air temperature, sea level pressure, and surface-level wind fields at 19:00 (local time) on October 19, 2022. Across the Northern Delta region, a northeasterly wind pattern was observed (Fig. 14a).

Figure 13. Variation of TPW (blue, mm) and air temperature (red, °C) in Nghia Do station from October 18, 2022 to October 20, 2022. The orange square indicates the day when the cold surges started affecting on the Northern Delta region

Figure 14b shows the distribution of relative humidity and wind fields at the 500mb level at 19:00 on October 19, 2022, from the National Centers for Environmental Prediction (NCEP) Final Analysis (FNL) data. The data were downscaled to a 9 km horizontal resolution by the Weather Research and Forecasting Model (WRF). The results reveal a zone of high humidity (> 90%) extending from the Gulf of Tonkin to the Northern Delta. Southeast winds carry moist air from the sea into the Northern Delta. In this scenario, the circulation of Typhoon Nesat transports moisture from the sea to the Northern Delta, serving as the primary factor contributing to the increase in overall atmospheric humidity in the Nghia Do area. Consequently, the TPW did not decrease after the cold air had impacted the region.

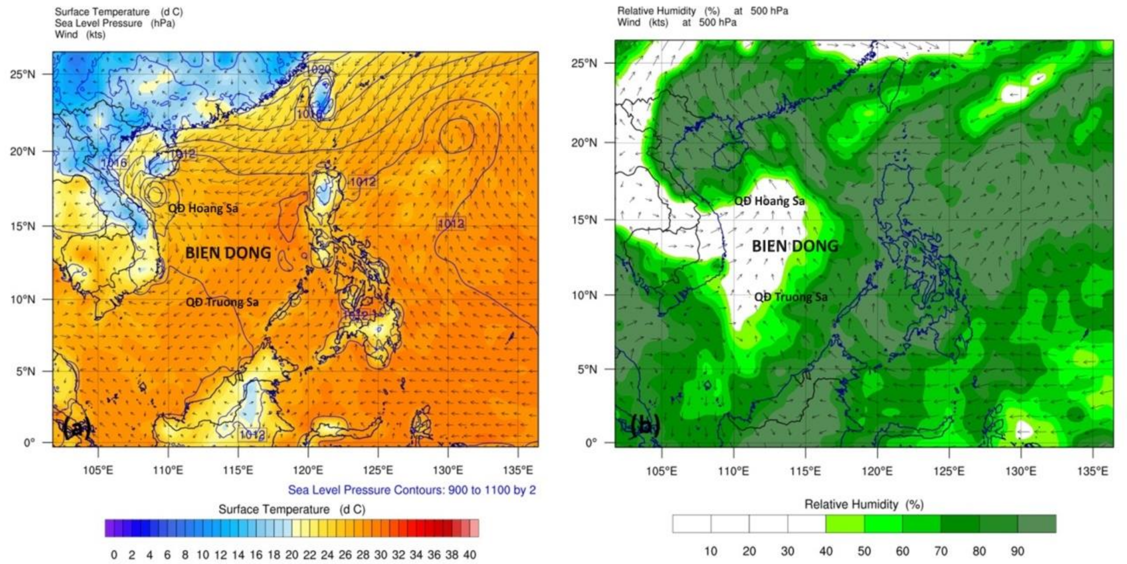

Figure 14. Distribution of (a) temperature at 2 m level (shaded, °C), sea surface pressure (contour, mb) , wind at 10 m level (vector, knots), and (b) relative humidity (shaded, %), wind (vector, knots) at 500mb level, at 19h00 on October 19, 2022 from NCEP FNL analysis data

5. Conclusions

In this study, GPS data was employed for the first time to estimate zenith wet delay and Total Precipitable Water with a one-minute time resolution in Vietnam. The GPS data, in conjunction with air temperature data from Nghia Do station, were used to estimate TPW between September 22, 2022, and March 31, 2023.

The comparison results demonstrated a strong agreement between the TPW estimated from GPS data and both the total precipitable product from Aeronet data and the total precipitable product from radiosonde data. The mean error, root mean square error, and correlation coefficient between the TPW estimated from GPS data and the Aeronet data product were 0.68 mm, 2.05 mm, and 0.988, respectively. The ME, RMSE, and correlation coefficients between the TPW estimated from GPS data and the radiosonde data product were -3.01 mm, 3.24 mm, and 0.996, respectively. These comparison results provide evidence that the application of the CSRS-PPP technique to estimate TPW from GPS data at Nghia Do station yields favorable outcomes.

With its one-minute temporal resolution, TPW estimated from GPS data can be effectively utilized for further analysis of TPW variation throughout the year. In terms of the variation during the study period, the zenith wet delay and TPW values in December and January at Nghia Do station are smaller than those observed in the remaining months. The decrease in TPW during December and January can be attributed to the strong northeast monsoon, which brings a cold and dry air mass from the north to the station area.

With a specific cold surge, during which the cold air mass becomes active independently of other mesoscale systems such as typhoons, tropical depressions, and disturbances in the east wind zone, the variation trend of TPW during the movement of cold air into the station's region exhibits distinct characteristics. Specifically, before the cold air arrives at the station, TPW tends to increase by about 6 mm within 12 hours.

This rise in TPW, preceding the influence of cold air on the station, may be attributed to convection activity ahead of the cold front. This convection transports moisture from lower levels to higher levels in the troposphere.

After the cold air passes over the station, the TPW value decreases by about 8 mm within 12 hours due to the influx of cold and dry winter air brought by the prevailing winds. The distinctive behavior of estimated TPW implies that GPS data can effectively indicate the arrival of cold air in the station's vicinity. The outcomes of this study contribute to a better understanding of the characteristics of the annual variation of TPW and the relationship between hourly to daily variation of TPW and the arrival of cold air in the study area.

The results of this work suggest that the estimated total precipitable water from GNSS signals is reliable. In fact, GNSS signals are available everywhere, allowing us to build a network with dense GNSS receivers to accurately measure TPW in Vietnam with very high temporal and spatial resolution. This approach provides a low-cost solution for cold surge research, as well as for extreme weather research and forecasting in other regions of Vietnam.

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References

Astudillo J.M., Lau L., Tang Y.-T., Moore T., 2018. Analysing the Zenith Tropospheric Delay Estimates in On-line Precise Point Positioning (PPP) Services and PPP Software Packages. Sensors, 18(2), 580. Doi: 10.3390/s18020580.

Atiz O.F., Kalayci I., 2021. Performance assessment of PPP-AR positioning and zenith total delay estimation with modernized CSRS-PPP. Artificial Satellites, 56(2). https://doi.org/10.1007/s12040-022-02034-5.

Baelen J.V., Aubagnac J.-P., Dabas A., 2005. Comparison of Near-Real Time Estimates of Integrated Water Vapor Derived with GPS, Radiosondes, and Microwave Radiometer. Journal of Atmospheric and Oceanic Technology, 22, 201–210.

Banville S., Hassen E., Lamothe P., Farinaccio J., Donahue B., Mireault Y., Goudarzi M.A., Collins P., Ghoddousi-Fard R., Kamali O., 2021. Enabling ambiguity resolution in CSRS-PPP. NAVIGATION, 68(2), 433–451. Doi: 10.1002/navi.423.

Bevis M., Businger S., Herring T.A., Rocken C., Anthes R.A., Ware R.H., 1992. GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. J. Geophys. Res., 97, 15787–15801.

Dinh H.D., Vo V.H., 2018. Applying perfect prog method to forecast total number of cold surges in the mid-winter in seasonal scale. Vietnam Journal of Hydro Meteorology, 696, 54–61.

Domingo A.L.S., Ernest P.M., 2022. Temporal Analysis of GNSS-Based Precipitable Water Vapor during Rainy Days over the Philippines from 2015 to 2017. Atmosphere, 13(3), 430.

El-Mewafi M., Zarzoura F.H., Saber M., 2019. Studying and Assessment the Tropospheric Delay at Different Weather Conditions in Egypt. Journal of Scientific and Engineering Research, 6(10), 185–198.

Gopalan K., Shukla B.P., Sharma S., Kumar P., Shyam A., Gaur A., Sunda S., 2021. An Observational Study of GPS-Derived Integrated Water Vapor over India. Atmosphere, 12, 1303. https://doi.org/10.3390/atmos12101303.

Gratton P., Banville S., Lachapelle G., O'Keefe K., 2021. Kinematic Zenith Tropospheric Delay Estimation with GNSS PPP in Mountainous Areas. Sensors, 21, 5709. https://doi.org/10.3390/s21175709.

Gui K., Che H., Chen Q., Zeng Z., Liu H., Wang Y., Zheng Y., Sun T., Liao T., Wang H., Zhang X.,

2017. Evaluation of radiosonde, MODIS-NIR-Clear, and AERONET precipitable water vapor using IGS ground-based GPS measurements over China. Atmospheric Research, 197, 461–473.

Guo Q., 2015. Precision comparison and analysis of four online free PPP services in static positioning and tropospheric delay estimation. GPS Solutions, 19(4), 537–544. https://doi.org/10.1007/s10291-014-0413-5.

Khanian A.S., Farzaneh S., 2021. Tropospheric delay efficiency from CSRS-PPP calculation tool for meteorologists in Iran. Numerical Methods in Civil Engineering, March, 5, 67–77.

Lai V.T., Du D.T., Mai K.H., 2022. The solution and result of calculating total precipitation water vapor (PWV) from GNSS data in Vietnam. Vietnam Journal of Hydro-Meteorology, 744, 93–103.

Le H.M., Masson F., Duchesne P.L., Bourdillon A., Tran T.L., Pham X.T., Nguyen C.T., Tran N.N., Hoang T.L., 2009. Preliminary results of the estimation of the zenith total delay and the integrated water vapour of the troposphere by GPS data in Vietnam. Vietnam J. Earth Sci., 31(3), 201–211.

Nguyen V.L. (project manager), 2011. Research to identify weather systems and patterns affecting Vietnam for weather forecasting, especially dangerous weather phenomena. Summary report on the project of the Ministry of Natural Resources and Environment. Hanoi University of Natural Resources and Environment.

Rose M.S., Sunil P.S., Zacharia J., Sreejith K.M., Sunda S., Mini V.K., Sunil A.S., Kumar K.V., 2023. Early detection of heavy rainfall events associated with the monsoon in Kerala, India using GPS derived ZTD and PWV estimates: A case study. Journal of Earth System Science, 132(1). https://doi.org/10.1007/s12040-022-02034-5.

Tetreault P., Kouba J., Heroux P., Legree P., 2005. CSRS-PPP: An internet service for GPS user access to the Canadian Spatial Reference frame. Geomatica, 59(1), 17–28.

Tran D.T., Nguyen D.H., Vu N.Q., Nguyen Q.L., 2023. Crustal displacement in Vietnam using CORS data during 2018-2021. Earth Sciences Research Journal, 27(1), 27–36. https://doi.org/10.15446/esrj.v27n1.102630.

Zhao Q., Yang P., Yao W., Yao Y., 2020. Hourly PWV Dataset Derived from GNSS Observations in China. Sensors, 20(1), 231.

Zhao Q., Zhang X., Wu K., Liu Y., Li Z., Shi Y., 2022. Comprehensive Precipitable Water Vapor Retrieval and Application Platform Based on Various Water Vapor Detection Techniques. Remote Sens., 14, 2507.