Ground-based GNSS for Meteorological Applications in Ghana

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Key words: ERA5 reanalysis; GNSS (Global Navigation Satellite System); Meteorology; Precipitable Water Vapour (PWV); Weather Forecasting

SUMMARY

Atmospheric water vapour is a critical and abundant greenhouse gas with significant implications for weather forecasting and climate monitoring. However, its spatial and temporal variability poses challenges to accurate observation. The low-latitude region, particularly Ghana, experiences large amounts and inhomogeneous water vapour content due to its proximity to the equator, making it susceptible to rapid weather changes over time. Severe weather forecasting in Ghana can be challenging due to the high spatiotemporal variability of water vapour. Water vapour content is under-sampled in the current meteorological and climate observing systems due to the lack of accurate, dense and continuous observation of water vapour data in Ghana, hampering the ability to keep track of water vapour in the atmosphere. To address this issue, the Global Navigation Satellite System (GNSS) offers continuous, accurate, and all-weather observations of water vapour through ground-based GNSS receivers. Ghana has seen an increase in the establishment and distribution of GNSS Continuously Operating Reference Stations (CORS), providing a more comprehensive dataset for retrieving and understanding Precipitable Water Vapour (PWV) in the country for meteorological and climatological applications. This study presents daily GNSS-derived PWV data from 49 established GNSS CORS in Ghana, utilising GNSS observation data from 2020. The GNSS-derived PWV values are compared with the fifth-generation reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF, ERA5) using various statistical measures, including Mean Bias (MB), Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and the correlation coefficient (R). The statistical analysis demonstrates that ground-based GNSS-derived PWV data in Ghana exhibit a high level of accuracy, with an overall mean bias, MAE, RMSE, and R of 1.29 mm, 1.96 mm, 2.48 mm, and 0.948, respectively. These findings emphasise the reliability and precision of GNSS-based observations for monitoring atmospheric water vapour in Ghana, offering valuable insights for weather forecasting and climate research.

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1. INTRODUCTION

Water vapour is a crucial component of the Earth's atmosphere. It exists mainly in the troposphere below 12 km above sea level and plays a significant role in the Earth's energy balance, hydrological cycle, formation of clouds, temperature regulation, and precipitation (Chen et al., 2021; Huang, Peng, et al., 2021; Perdiguer-Lopez et al., 2023; Zhao et al., 2022). As the primary greenhouse gas in the atmosphere, water vapour also influences atmospheric radiation and circulation, affecting weather patterns, climate change, and variability (Chen & Liu, 2016; Kawo et al., 2022; Mannel et al., 2021; Ssenyunzi et al., 2020; Z. Wang et al., 2023). The presence of water vapour in the atmosphere varies greatly both in space and time (Rocken et al., 1993). These variations can cause sudden and drastic changes in local weather patterns, resulting in extreme weather and climate conditions such as thunderstorms, severe colds, floods and other violent atmospheric phenomena. Therefore, accurate knowledge and understanding of water vapour and its variability are crucial for improving weather forecasts, understanding climate dynamics and modelling, managing water resources, and assessing the impacts of climate change (Chen et al., 2021; Li et al., 2018; Yu et al., 2021).

Ghana depends mainly on rainfall for its agricultural or farming activities, and accurate and timely meteorological information is crucial as the country is threatened by the downward push of the Sahara Desert (Fosu et al., 2007). Traditional meteorological observation methods, such as radiosondes and surface weather stations needed to provide accurate and timely forecasts, suffer limitations such as sparse spatial coverage, low temporal resolution, and high operational costs (Zhao et al., 2019). Ground-based Global Navigation Satellite System (GNSS) technology has emerged since the 1990s (Bevis et al., 1992) as a promising tool for atmospheric monitoring.

GNSS signals suffer delays when propagating through the Earth's atmosphere. While these signal delays are mitigated for precise positioning, navigation and timing (PNT) applications, they can also be inverted for Precipitable Water Vapour (PWV) and other atmospheric parameters (Bevis et al., 1992). Precipitable water vapour (PWV) represents the total atmospheric water vapour content measured in a vertical column of air per unit cross-sectional area above a given location (Xu & Liu, 2022). GNSS has the advantage of high precision, high spatio-temporal resolution, cost-effectiveness, reliability, and continuous operation under all weather conditions with global coverage (Zhao et al., 2019). The accuracy of GNSS-derived PWV has been proven to be within 1–3 mm, comparable with the radiosondes observations (Bevis et al., 1992; Duan et al., 1996; Gui et al., 2017; Rocken et al., 1993).

While GNSS technology has been explored globally for meteorological applications, its potential in Ghana remains untapped. Early works by Acheampong et al. (2015, 2017) used a single ground-based GNSS station at the Kwame Nkrumah University of Science and Technology (KNUST) in Kumasi, Ghana, to retrieve and analyse PWV. Though these studies provided valuable insights into PWV content, their scope was limited to a single location, and there is a lack of comprehensive research estimating PWV across multiple sites in Ghana.

Recently, a nationwide network of GNSS Continuously Operating Reference Stations (CORS) has been established by the Licensed Surveyors Association of Ghana (LISAG) and the partnership between GMX Systems Israel and Geo-Tech Systems Ghana. Although these CORS were originally designed purposely for survey, mapping, geoinformation, and geodetic applications, they can be fully utilised to estimate accurate spatio-temporal variations of water vapour information for meteorological applications in Ghana. This study, therefore, investigates the accuracy and reliability of ground-based GNSS-derived PWV over 49 networks of GNSS CORS spanning various geographical locations and climatic zones in Ghana for meteorological applications.

2. METHODOLOGY

This section outlines the methodology employed in this study. Section 2.1 describes the study area and its characteristics. Section 2.2 explains the data collection and processing procedures used in the study. The retrieval of Precipitable Water Vapor (PWV) from various data sources is detailed in Section 2.3. Section 2.4 outlines the analytical approaches used in the study. A workflow diagram summarising the main processes involved in the study is provided at the end of this section as shown in Figure 2.

2.1 Study Area

Ghana is situated along the west coast of Africa between latitudes 4° N and 12° N and longitudes 2˚E and 4˚W covering a land area of about 240, 000 Km^2. Ghana shares boundaries with Burkina Faso to the north, Togo to the east, Côte d'Ivoire to the west, and the Gulf of Guinea to the south (Atiah et al., 2019; Bessah et al., 2022; Yamba et al., 2023). The Greenwich Meridian passes through eastern Ghana at Tema, the port city, at longitude 0^o and latitude 5^o north of the Equator. This position is considered nearest or closest (only a few degrees above the Equator) to the centre of the Earth, where the Equator and the Prime Meridian coincide at longitude 0° and latitude 0°, (0°, 0°). Thus, Ghana is believed to be the closest country to the Earth's centre. Due to Ghana's proximity to the Equator, it mostly experiences a tropical warm climate, where the country receives an abundant supply of sunlight year-round. Ghana's climate is characterised by two distinct seasons: the wet (rainy) and dry (harmattan) seasons, influenced by the West African Monsoon (WAM) and the Inter-Tropical Convergence Zone (ITCZ).
Generally, Ghana is divided into six major agro-ecological zones: Sudan Savannah, Guinea Savannah, Forest Savannah Transition, Semi-Decideous Rainforest, High Rainforest and Coastal Savannah (Asare-nuamah & Botchway, 2019). However, for weather and climate

applications, the Ghana Meteorological Agency (GMet) has further divided the country into four main agro-ecological zones (Amekudzi et al., 2015; Baidu et al., 2017; Mensah et al., 2016; Yamba et al., 2023). These are the Savannah, the Transition, the Forest, and the Coastal Zones. These zones, illustrated in Figure 1, are defined and characterised based on climate, vegetation and soil conditions.
This study employed a network of 49 Continuously Operating Reference Stations (CORS) spanning 16 regions across Ghana. The specific locations and details of these 49 stations are visually represented in Figure 1.

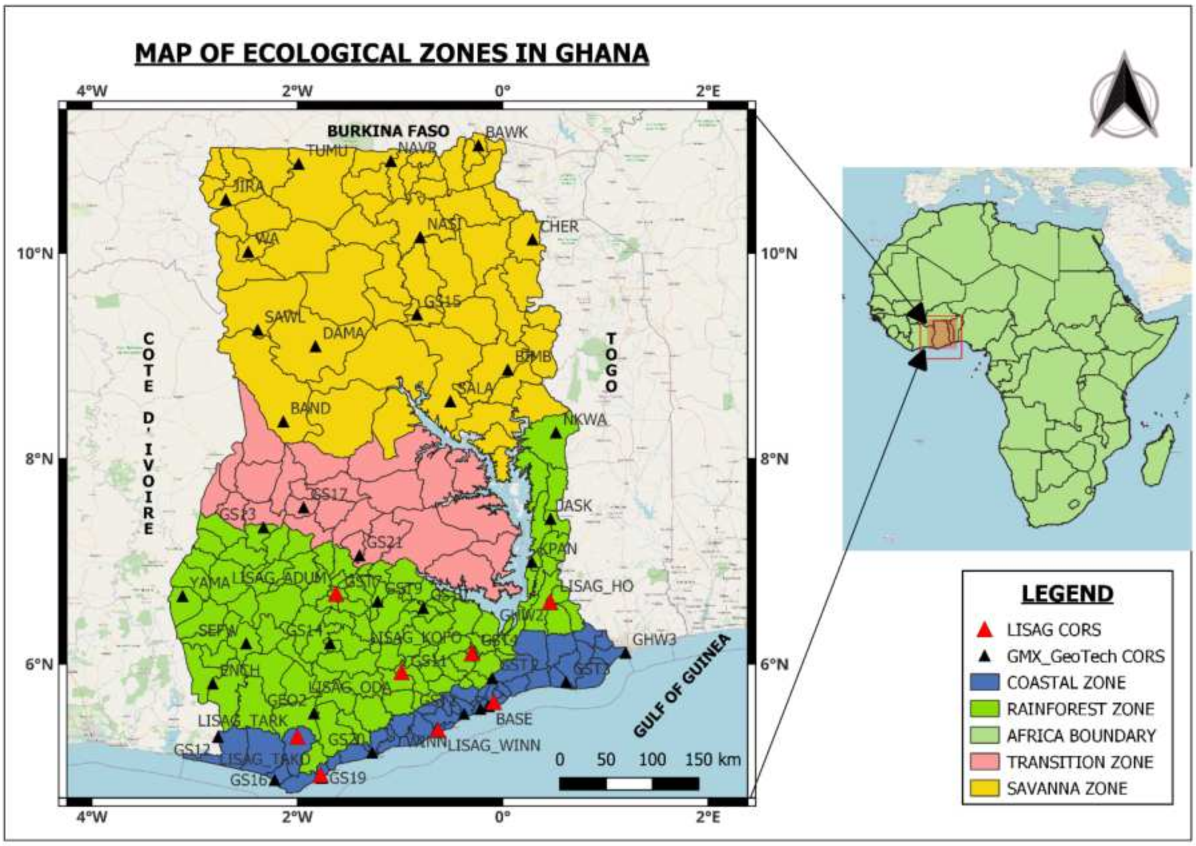

Figure 1: Map of Ghana showing the distribution of GNSS CORS.

2.2 Dataset

The study utilised daily datasets from GNSS observations and ERA5 reanalysis over 49 GNSS station networks in Ghana for eight months in 2022. Notably, the GNSS datasets exhibited substantial data gaps, and to enable a comprehensive analysis on a unified platform, a comparative assessment of the two datasets for each station was conducted. This resulted in extracting and organising corresponding days with available data for further analysis. This approach ensured that the study was based on complete and consistent data.

2.2.1 GNSS-ZTD Data

Eight months datasets of GNSS observations, spanning from May 1 to December 31, 2022, were collected from the 49 GNSS CORS deployed across the various regions of Ghana (Figure 1). The observation data in RINEX (Receiver INdependent Exchange) format was pre-processed and quality-controlled with the TEQC (Translation Editing Quality Checking) toolkit (Estey & Meertens, 1999). The pre-processed data were then processed in the post-processing static precise point positioning (PPP) mode using the latest up-to-date (Spark v3.54.2) Canadian Spatial Reference System PPP (CSRS-PPP) online service (Acheampong et al., 2017; Astudillo et al., 2018; Banville et al., 2021; Mireault et al., 2008; Tétreault et al., 2005) provided by the Geodetic Survey Division (GDS) of the Natural Resources Canada (NRCan). Detailed information about the CSRS-PPP online service processing protocols can be found in (Mireault et al., 2008; Tétreault et al., 2005) and at https://webapp.csrs-scrs.nrcan-rncan.gc.ca/. The processing options used via the CSRS-PPP service are given in Table 1. The processing results, including the positions, zenith hydrostatic delay (ZHD), zenith wet delay (ZWD), tropospheric gradients, receiver clocks, ambiguities, and code biases, are obtained via a URL (Uniform Resource Locator) link to users. The zenith tropospheric or total delay (ZTD) is obtained as:

$$ZTD = ZHD + ZWD \tag{1}$$

Table 1: The processing options for the CSRS-PPP service.

Software Version	Spark v3.54.2
Processing Mode	Static
Constellation	GPS
Frequency	L1, L2
Observation Processed	Code and Phase
Observation Interval	30 s
Antenna model	APC to ARP
Reference Frame	ITRF14 (2020.6)
Cut-off Angle	7.5º
Satellite Orbits and Clocks	IGS Final
Phase-centre Corrections	IGS (ATX)
Phase wind-up	Modelled
Solid Earth and Polar Tides	Modelled
Earth Rotation Parameters (ERP)	Applied
Ionospheric Model	ionosphere-free linear combination
Mapping Function	VMF1
Zenith Hydrostatic Delay (ZHD)	Estimated
Zenith Wet Delay (ZWD)	Estimated
Zenith Total Delay (ZTD)	ZHD +ZWD

2.2.2 ERA5 Reanalysis Data

ERA5 is the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis dataset, providing comprehensive information about land surface, ocean waves, and atmospheric parameters globally for environmental, climate, and weather studies. It is the latest climate reanalysis that replaces the ERA-Interim reanalysis, spanning 1979 to the present and generated from the Four-Dimensional Variational (4DVAR) data assimilation system based on the Integrated Forecasting System (IFS) Cy41r2 (Bell et al., 2021; Hersbach et al., 2020). ERA5 has higher spatial (0.25° x 0.25° (31 km) and 137 model levels) and temporal (1h) resolutions globally compared to ERA-Interim reanalysis (~80 km, 60 levels and 6-h) (Dee et al., 2011; Zhang et al., 2022; Zhou et al., 2020). Generally, meteorological data from ECMWF reanalysis are provided on two vertical profiles: Pressure-Level (PL) and Surface-Level (SL). Site-specific data are obtained through interpolations from the profiles (Jade & Vijayan, 2008; Wang *et al.*, 2016; Yang *et al.*, 2020; Li *et al.*, 2021). We acquired hourly ERA5 atmospheric parameters such as pressure (P), temperature (T), water vapour partial pressure (e), Weighted mean temperature (Tm), ZHD, ZWD, ZTD, and PWV using GMET (GNSS Meteorological Ensemble Tools) online service (http://gmet.users.sgg.whu.edu.cn/) provided by the Wuhan University (WHU), China. The GMET online service aimed to provide an interface to calculate meteorological parameters (P, T, e, Tm) at GNSS stations or user-defined sites from ERA5 reanalysis products for PWV retrieval using the open-sourced ray-tracing software RADIATE (Hofmeister & Böhm, 2017) by TU Wien (https://vmf.geo.tuwien.ac.at/). The parameter settings for estimating the meteorological and tropospheric parameters in this study from the GMET online service are summarised in Table 2.

Table 2: GMET parameter settings for estimating meteorological and tropospheric parameters.

Parameter	Settings
Software	RADIATE (https://vmf.geo.tuwien.ac.at/)
Data Source	ERA5
Temporal resolution	1 hour
Input parameters	Start time (UTC) End time (UTC) Site coordinates: latitude (°), longitude (°), height (m) in WGS 84 E-mail
Output parameters	P [hpa] , T [K], e [hpa], Tm [K], ZHD, ZWD, ZTD [m], PWV [mm]

2.3 PWV Retrieval from GNSS-ZTD and ERA5 Reanalysis Datasets

2.3.1 Retrieval of PWV From GNSS-Derived ZTD

The process of retrieving PWV from GNSS-derived ZTD typically involves two main steps (Chen et al., 2021):

1) **ZHD subtraction:** Subtracting the ZHD from the ZTD yields the ZWD.

$$ZWD = ZTD - ZHD \tag{2}$$

2) **ZWD to PWV conversion:** A conversion factor (Π) is applied to the ZWD to obtain the PWV.

For the first step, the Saastamoinen model (Saastamoinen, 1972) is commonly used to compute the ZHD, which accounts for the hydrostatic component of the atmospheric delay caused by the dry gases in the troposphere. This empirical model estimates the ZHD based on atmospheric pressure, temperature, and the latitude of the GNSS station. The formula for ZHD calculation is as follows (Bevis et al., 1992; Saastamoinen, 1972):

$$ZHD = \frac{0.0022779 * P_s}{f(\varphi, H)} \tag{3}$$

$$f(\varphi, H) = 1 - 0.00266\cos^2\varphi - 0.00028 * H \tag{4}$$

Where:

$f(\varphi, H)$ accounts for the variation in acceleration due to gravity at the station, P_s is the atmospheric pressure in hPa, φ is the latitude of the station in radians, and h is the station height above mean sea level in kilometres.

For the second step, the conversion of ZWD, which accounts for the wet component of the atmospheric delay caused by the water vapour in the troposphere, is typically done using a dimensionless conversion factor (Π) that relates the two quantities and accounts for the weighted mean temperature (Tm) of the atmosphere. This factor can be determined through various methods, including local meteorological data, empirical models, or by using a climatological value based on the location of the GNSS receiver. The conversion formula is as follows (Bevis et al., 1994):

$$PWV = \Pi \times ZWD \tag{5}$$

$$\Pi = \frac{10^6}{\rho_w \times R_w \times \left[\left(\frac{k_3}{T_m}\right) + k_2'\right]} \tag{6}$$

where k_2'= 22.1±2.2 K/hPa and $k_3 = 373900 \pm 1200\ K^2/hPa$ are atmospheric refractivity constants, ρ_w is density of liquid water ($1000\ Kg/m^3$), R_w is the specific gas constant for water vapour ($461.525\ JKg^{-1}K^{-1}$), Tm is the mean weight temperature, a function of temperature (T_s). We use Tm from (Bevis et al., 1992) (referred to as BTm hereafter) expressed as:

$$T_m = 0.72T_s + 70.2 \tag{7}$$

P_s and T_s were provided by ERA5 reanalysis data. Furthermore, the study employed the ERA5-Tm values (referred to as ETm hereafter) to retrieve PWV from the GNSS-ZTDs to facilitate a comparative analysis of how well the Tm values from (Bevis et al., 1992) performed in obtaining PWV from GNSS observations as a means of ensuring the reliability of the empirical model for GNSS-PWV retrieval in the study area.

2.3.2 PWV Retrieval from ERA5 Reanalysis Dataset

The ERA5 reanalysis dataset is pivotal in meteorological applications owing to its extensive and consistent time-series data availability. The values of ERA5 PWV (ERA5-PWV) were derived using the GMET online service, as indicated in section 2.2.2. They can be computed utilising specific humidity and air pressure data from reanalysis datasets, as detailed by (Jiang et al., 2016; Xu et al., 2022):

$$PWV = \frac{1}{\rho_w g}\int_{P_S}^{0} q(P)\,dP = \sum_{i}^{n-1}\frac{(q_i + q_{i+1})(p_{i+1} - p_i)}{2 * \rho_w * g} \tag{8}$$

$$g(\varphi) = 9.780325\left[\frac{1 + 0.00193185\sin^2\varphi}{1 - 0.00669435\sin^2\varphi}\right]^{\frac{1}{2}} \tag{9}$$

$$q = \frac{0.622e}{P - 0.378e} \tag{10}$$

Where n is the total number of layers, $q(P)$ denotes the specific humidity or mixing ratio (g/kg) of water vapour as a function of atmospheric pressure P (unit: Pa), integrated from the surface level (P_S) to the top of the atmosphere, e is the water vapour pressure (hPa), and q_i, p_i are the specific humidity and air pressure at the i^{th}layer, respectively. g represents the gravitational acceleration (m/s^2), a function of site latitude (φ, unit: rad) (Wang et al., 2016; Yuan et al., 2023).

2.4 PWV comparison and analysis

To assess the accuracy and reliability of GNSS-derived PWV estimations, daily average GNSS-PWV values were compared against the corresponding daily mean PWV products from ERA5. Four statistical metrics were employed in this evaluation: the standard deviation (STD), mean bias (MB), root mean square error (RMSE), and Pearson correlation coefficient (R). These metrics provide insights into the variability, systematic bias, overall error, and linear relationship between the GNSS-derived PWV and ERA5 PWV data. The metrics are expressed as follows:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|\left(PWV_i^{GNSS} - PWV_i^{ERA5}\right)\right| \tag{11}$$

$$MB = \frac{1}{N}\sum_{i=1}^{N}\left(PWV_i^{GNSS} - PWV_i^{ERA5}\right) \tag{12}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(PWV_i^{GNSS} - PWV_i^{ERA5}\right)^2} \tag{13}$$

$$STD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(PWV_i^{P} - \overline{PWV}^{P}\right)^2} \tag{14}$$

$$R = \frac{\sum_{i=1}^{N}\left[\left(PWV_i^{GNSS} - \overline{PWV}^{GNSS}\right)\left(PWV_i^{ERA5} - \overline{PWV}^{ERA5}\right)\right]}{\sqrt{\left[\sum_{i=1}^{N}\left(PWV_i^{GNSS} - \overline{PWV}^{GNSS}\right)^2\right]\left[\sum_{i=1}^{N}\left(PWV_i^{ERA5} - \overline{PWV}^{ERA5}\right)^2\right]}} \tag{15}$$

Where PWV_i^P, PWV_i^{GNSS}, PWV_i^{ERA5} represent the i^{th} product (GNSS or ERA5) PWVs and $\overline{PWV}$ their respective means. N is the total number of observations.

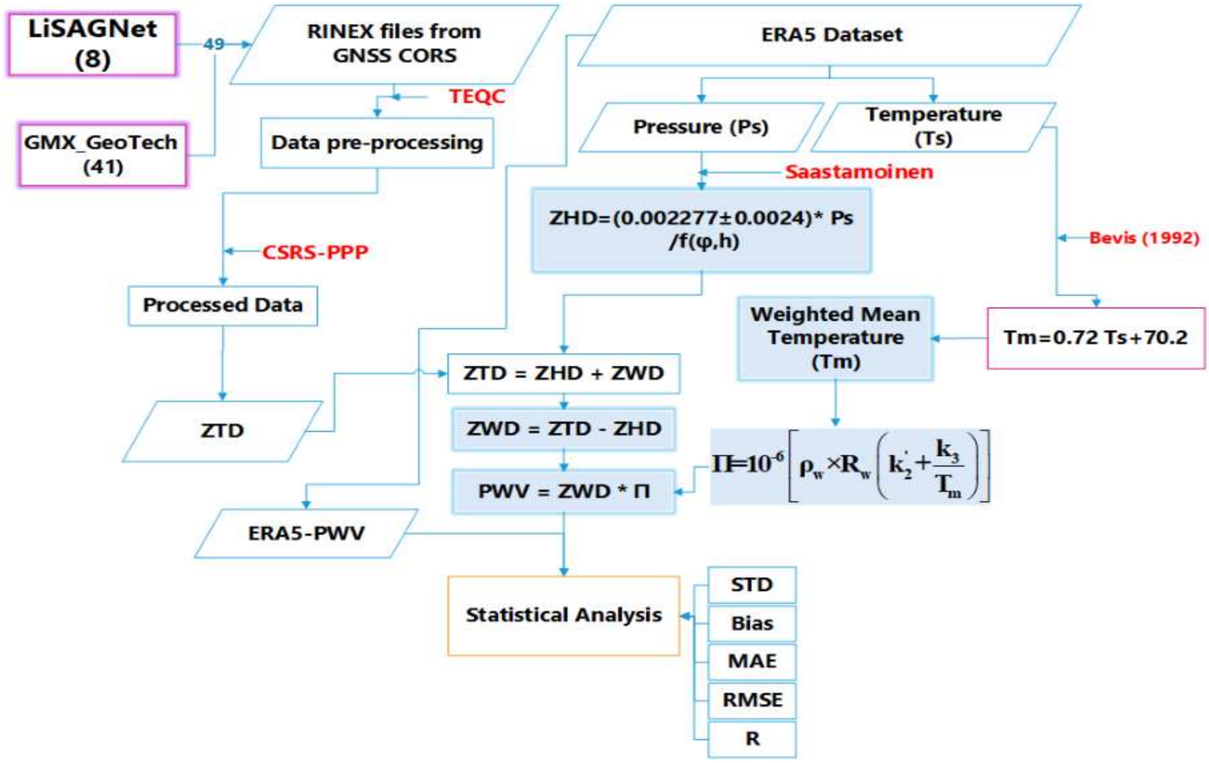

Figure 2: Workflow of GNSS Precipitable Water Vapour retrieval procedure from GNSS CORS in Ghana.

3. RESULTS AND DISCUSSION

In this section, we analysed the agreement, consistency, reliability, and accuracy between Precipitable Water Vapor (PWV) values derived from GNSS observations and those from the ERA5 reanalysis dataset across four distinct ecological zones in Ghana: Savannah, Transition, Rainforest, Coastal.

3.1 Comparing GNSS and ERA5 PWV Estimates over Ghana

3.1.1 Spatial Distribution and Variability of PWV Over Ghana

To assess the spatial variability of water vapour values over Ghana between GNSS and the ERA5 reanalysis data, the study focused on four agro-ecological zones categorised by the GMet. Figure 3 illustrates the spatial distribution of mean PWV values across these ecological zones. The results reveal that the GNSS-derived PWV pattern closely aligns with ERA5-PWV value across the ecological zones, with higher PWV values concentrated in southern regions, particularly the coastal and rainforest zones, and gradually decreasing towards the northern regions, the savanna zone. The Savanna exhibits the lowest mean PWV values across the two data sources. The lower PWV values in this zone are consistent with the dry semi-arid climate characterised by prolonged dry seasons, reduced moisture availability, and limited precipitation.

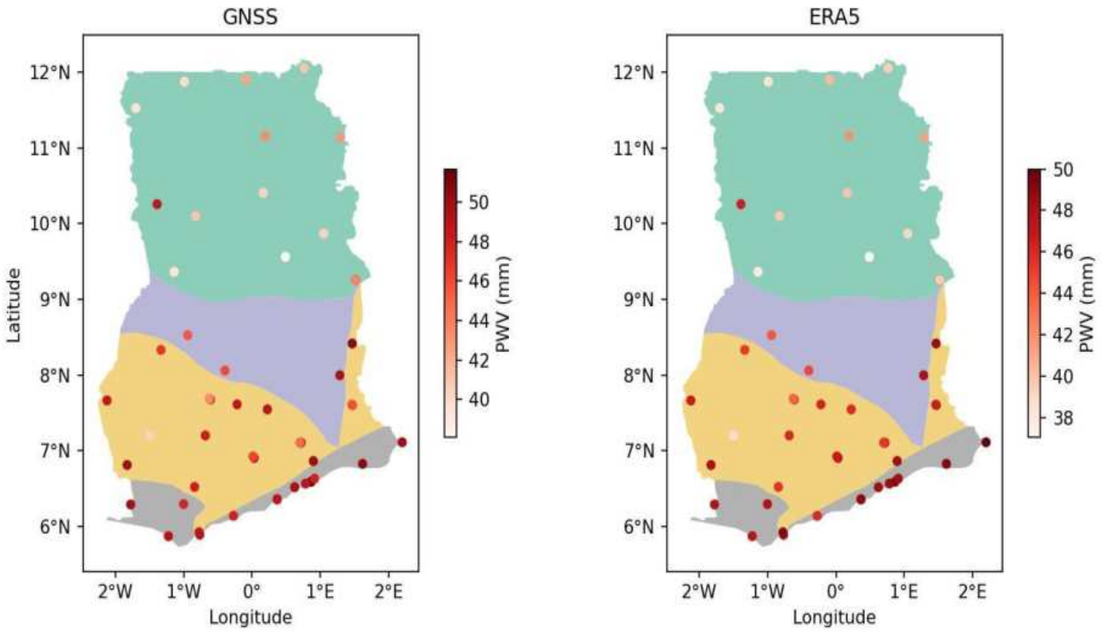

Figure 3: Spatial distribution of mean PWV values across ecological zones of Ghana derived from GNSS using the Bevis weighted mean temperature models (BTm) and ERA5 reanalysis data. The four ecological zones represented are the Savanna (light green), Transition (cyan), Rainforest (yellow), and Coastal (brown) zones. The colour bars on the right indicate the respective PWV value ranges for each dataset.

The Transition zone shows slightly higher mean PWV values compared to the Savanna zone. These moderate PWV values suggest a comparatively higher amount of moisture in the atmosphere, likely due to increased vegetation cover, proximity to water bodies and the gradual transition towards a more humid climate as you move southwards. The Rainforest zone exhibits higher mean PWV values across all data sources. These high PWV values align with this zone's prevailing moist and humid conditions. The Coastal zone shows the highest mean PWV values among the four ecological zones. This pattern is consistent with the expected climatic behaviour in the coastal zone. Proximity to water bodies, oceanic influence, and higher humidity levels contribute to the observed elevated PWV values in the Coastal zone.

3.1.2 Temporal Variation of PWV Over Ghana

To further investigate the reliability and consistency of the GNSS-derived PWV values with ERA5-PWVs, PWV time series from both datasets over four selected stations representing the four ecological zones in Ghana are plotted in Figure 4, allowing a quantitative temporal comparison between GNSS and ERA5 PWV estimates at each ecological zone.

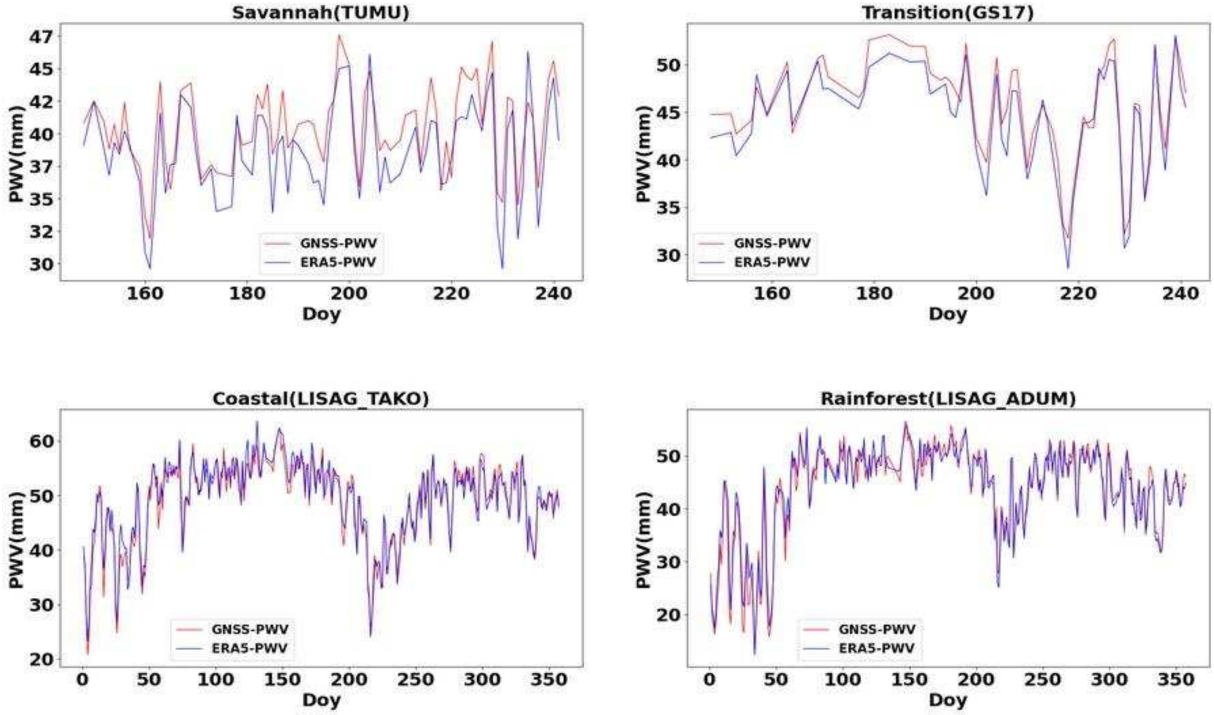

Figure 4: Time series comparison of PWV datasets from GNSS and ERA5 reanalysis at four stations representing the four ecological zones in Ghana: the Savanna, Transition, Rainforest, and Coastal zones over the study period.

Figure 4 indicates that GNSS-PWV and ERA5-PWV datasets exhibit good overall agreement in capturing the daily and seasonal fluctuations of PWV content across all ecological zones. Even though the two datasets show similar trends and patterns, some differences were observed in the magnitude and timing of PWV peaks and troughs. The dissimilarities are most likely due to the spatial resolution of ERA5 data and the inherent differences between point-based GNSS measurements and gridded reanalysis data. In the Savannah (TUMU) and Transition (GS17) zones, GNSS-PWV tended to have higher peaks and lower troughs compared to ERA5-PWV. This could be due to sparse observational data from data assimilation systems, which leads to less accurate reanalysis outputs. In contrast, in the Rainforest (LISAG_ADUM) and Coastal (LISAG_TAKO) zones, occasional differences in the magnitude of PWV values were observed, with GNSS-PWV sometimes showing higher or lower values compared to ERA5-PWV. This could be attributed to more consistent local climatic conditions and better model performance due to denser data inputs.

3.1.3 Accuracy Assessment of GNSS-derived PWV with ERA5 PWV

To assess the precision and accuracy of GNSS-derived PWV estimates across different ecological zones in Ghana, we analysed five key statistical evaluation metrics: standard deviation (STD), mean bias (MB), mean absolute error (MAE), root mean square error (RMSE), and correlation coefficient (R). The statistical analysis is based on daily average PWV values and the number of datasets at individual stations using ERA5-PWV values as the reference. The results are presented in Table 3, summarising the overall mean STD, MB, MAE, RMSE, and R for each ecological zone. This provides a comprehensive overview of how well the GNSS-derived PWV values perform in comparison to the ERA5 reanalysis data.

Table 3: Statistical Comparison of GNSS and ERA5-Derived PWV over the four ecological zones in Ghana.

ZONE	STD (mm)	MB (mm)	MAE (mm)	RMSE (mm)	R
Savanna	4.31	1.62	2.16	2.77	0.920
Transition	5.24	1.31	1.57	1.89	0.967
Rainforest	6.26	1.40	2.33	2.96	0.949
Coastal	6.86	0.81	1.80	2.29	0.956
Average	**5.67**	**1.29**	**1.96**	**2.48**	**0.948**

The results in Table 3 show varying levels of accuracy and precision across the zones. These differences can be attributed to factors such as variations in vegetation, topography, climate, atmospheric conditions, and the performance of ERA5 in certain regions in terms of data quality, observational data coverage, and data assimilation system. The STD quantifies the degree of variation or dispersion of measurement error distribution, with a low standard deviation indicating high precision. The STD values are higher in the rainforest (6.26 mm) and coastal (6.86 mm) zones when compared to the savannah (4.31 mm) and transition (5.24 mm) zones. This indicates greater fluctuations in atmospheric moisture content over time in the rainforest and coastal zones, which aligns with their climatic characteristics, such as convective activity and oceanic influence.

The MB measures the average deviation of a measured value (GNSS-PWV) from the actual value (ERA5-PWV), indicating whether measurements are higher or lower than the actual values. Negative and positive MB values represent underestimation and overestimation, respectively. MAE gives the average magnitude of errors between the GNSS and ERA5-derived PWV without considering the direction of the errors. The RMSE gives an overall measure of accuracy by indicating how closely GNSS-PWV values match ERA5-PWV values. The lower the MB, MAE, and RMSE values, the closer the GNSS-PWV values are to the ERA5-PWV values, and the better the agreement or accuracy. Table 3 shows smaller positive MB values across all the ecological zones, implying that GNSS has minimal systematic overestimation over Ghana. The highest MB value is seen in the savannah zone with 1.62 mm, followed by the rainforest zone with 1.40 mm, and the transition zone with 1.31 mm. The smallest MB value is seen in the coastal zone with 0.81 mm. The minimal MB values across all the zones indicate that GNSS-PWV is consistent with ERA5-PWV over Ghana. The MAE and RMSE values are also low across all zones, indicating good overall agreement between ERA5 and GNSS-derived PWV. The transition zone has the lowest MAE (1.57 mm) and RMSE (1.89 mm), indicating the best accuracy in this zone. This is followed by the coastal zone with an MAE of 1.80 mm and RMSE of 2.29 mm. The savannah zone has slightly higher

MAE and RMSE values of 2.16 mm and 2.77 mm, respectively, compared to the rainforest zone, with the highest MAE (2.33 mm) and RMSE (2.96 mm) values.

R expresses the degree of relationship or association between the GNSS-PWV and ERA5-PWV, ranging from –1 to +1. An R-value of 0 denotes no correlation, while a value closer to 1 signifies a stronger positive linear relationship between the two datasets. The results in Table 3 demonstrate consistently high R-values ranging from 0.92-0.967 across all zones, indicating a strong positive correlation between ERA5-PWV and GNSS-PWV. The Transition zone has the highest R-value (0.967), followed by the coastal zone (0.956) and the rainforest zone (0.949). The Savanna zone has the lowest R-value (0.920).

The overall average statistics, as shown in Table 3: STD of 5.67 mm, MB of 1.29 mm, MAE of 1.96 mm, RMSE of 2.48 mm, and R-value of 0.948 across Ghana show that GNSS-derived PWV data aligns closely with ERA5 reanalysis data. The observed bias, RMSE, and R magnitudes are within acceptable ranges and consistent with previous studies (Hai et al., 2011; Hu et al., 2021; Huang et al., 2021; Wijaya et al., 2024). This suggests that GNSS-PWV measurements are generally reliable and accurate for climatological and meteorological studies and operations (Huang et al., 2021; Wang et al., 2013) in Ghana.

4. CONCLUSIONS

This study has comprehensively evaluated the accuracy and reliability of ground-based GNSS for precipitable water vapour (PWV) estimation across various ecological zones in Ghana. Analysing GNSS observations from a network of 49 CORS across the country, we found strong agreement between GNSS-derived PWV and ERA5-derived PWV with minimal systematic overestimation across all ecological zones. While some differences were observed, likely due to the inherent limitations of reanalysis data and the point-based nature of GNSS measurements, the statistical analysis revealed high precision and accuracy of GNSS-derived PWV with an overall mean STD, bias, MAE, RMSE, and R of 5.67 mm, 1.29 mm, 1.96 mm, 2.48 mm, and 0.948 respectively, over Ghana. The low mean bias, MAE, and RMSE values, along with the strong positive correlation coefficient, indicate the reliability and consistency of GNSS as a valuable tool for meteorological applications in Ghana. Thus, the GNSS technology offers a robust alternative to conventional meteorological methods, enhancing the accuracy of Ghana's weather forecasting and climate analysis.

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