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RESEARCH ARTICLE

Evaluation of GNSS-Derived ZTD for Data Assimilation in Numerical Weather Prediction over Nigeria

J. A. Folaranmi[1]*, Y. D. Opaluwa[1], M. Baba[1], and L. M. Ojigi[2],

[1]*Department of Surveying & Geoinformatics, Federal University of Technology, Minna, Nigeria*
[2]*African Regional Institute for Geospatial Information Science and Technology OAU Campus Ile Ife, Nigeria*

*Corresponding author email: jamiufolaranmi23@gmail.com

Abstract

The accurate characterization of atmospheric water vapour is essential for improving Numerical Weather Prediction (NWP), particularly in data-sparse regions such as West Africa, where conventional meteorological observations are limited. This study evaluates the suitability of ground-based Global Navigation Satellite System (GNSS)-derived Zenith Tropospheric Delay (ZTD) over Nigeria for regional NWP data assimilation. Continuous observations from the Nigerian Permanent GNSS Network (NIGNET) were processed using Bernese GNSS Software v5.2. A network-based double-differencing strategy employing ionosphere-free linear combinations, a 30° elevation cut-off angle, Cos²(z) observation weighting, and hourly Wet-Neill mapping functions was adopted to estimate tropospheric delays and horizontal gradients. To ensure reliability, the derived ZTD estimates were validated against independent International GNSS Service (IGS) tropospheric products at the reference stations ADIS, NOT1, and RABT. Results revealed a clear latitudinal moisture gradient controlled by the seasonal dynamics of the West African Monsoon (WAM) and the migration of the Intertropical Discontinuity (ITD). Northern inland stations recorded lower mean ZTD values, such as 2233.77 mm at CGGN00NGA and 2289.30 mm at ZRKD00NGA, reflecting the influence of dry Harmattan winds. In contrast, southern coastal stations exhibited higher atmospheric moisture, with mean ZTD values of 2583.29 mm at LGLA00NGA and 2619.81 mm at PHRI00NGA due to persistent maritime air influx from the Gulf of Guinea. Network-wide ZTD values ranged from 2110.65 mm to 2706.26 mm. Validation results showed excellent agreement with IGS products ($R^2 > 0.98$ and low RMSE), confirming the accuracy of the estimates. The study demonstrates that GNSS-derived ZTD can provide continuous, high-frequency atmospheric moisture information for NWP data assimilation, improving mesoscale weather forecasting, convective simulations, and early warning systems across West Africa.

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1. INTRODUCTION

The precise characterization of atmospheric water vapour is a fundamental prerequisite for advancing the predictive capabilities of Numerical Weather Prediction (NWP) systems (Bannister *et al*., 2020; Li *et al*., 2023). As a key thermodynamic driver, atmospheric moisture governs cloud microphysics, convective initiation, and latent heat release, making it a critical variable in accurately forecasting severe weather events and long-term hydro-meteorological cycles (Bernini, 2026). Despite its paramount importance, water vapour remains one of the most highly variable spatiotemporal constituents of the troposphere, making it notoriously difficult to model continuously using traditional observation networks (Yao *et al*., 2018). Within modern data assimilation frameworks, the initialization of NWP models relies heavily on the quality and density of ambient moisture datasets. Consequently, any deficiency in these inputs directly manifests as a cascade of errors in short-to-medium-range regional weather forecasts (Wagner *et al*., 2022).

This atmospheric data gap is acutely pronounced over the West African sub-region, particularly within Nigeria, which represents a data-sparse territory under-sampled by conventional meteorological instrumentation. Traditional profiling techniques, such as radiosonde networks, are severely limited across the continent due to prohibitive operational costs, logistical constraints, and sporadic launch schedules (Parker *et al*., 2008). While space-borne remote sensing platforms offer a broader spatial swath, their utility in equatorial and tropical regions is frequently degraded by persistent cloud cover, coarse temporal resolutions, and systematic retrieval biases in the lower planetary boundary layer. This lack of continuous, high-resolution moisture observations hinders the initialization of regional NWP models, ultimately compromising the reliability of early warning systems in a region heavily vulnerable to extreme weather, changing monsoonal patterns, and agricultural volatility (Rhom *et al*., 2019).

To mitigate these observational deficits, ground-based Global Navigation Satellite System (GNSS) meteorology has emerged as an innovative, cost-effective, and all-weather remote sensing alternative. As GNSS signals propagate from satellites to earth-bound receivers, they undergo refraction and propagation delays induced by dry atmospheric gases and water vapour along the line-of-sight. In the zenith direction, this cumulative retardation is quantified as the Zenith Tropospheric Delay (ZTD) or Zenith Total Delay (Hdidou *et al*., 2020). Because ZTD is directly coupled with the atmospheric state, it can be precisely partitioned into its hydrostatic and wet components (Opaluwa *et al*., 2013), the latter of which serves as a proxy for Integrated Water Vapour (IWV) or Precipitable Water Vapour (PWV). Boasting high temporal resolutions, continuous operation, and structural resilience against adverse weather conditions, GNSS-derived ZTD offers a sustainable mechanism to close the atmospheric data gap across Africa's underserved meteorological zones (Tine *et al*., 2025).

The implementation of GNSS meteorology within the West African monsoon environment requires rigorous processing configurations to account for local mesoscale convective systems (Nahmani *et al*., 2019). Geodetic research leverages data from networks like the Nigerian Permanent GNSS Network (NIGNET) to model the dynamic tropospheric structure over latitudes 4 °N to 14 °N and longitudes 2 °E to 15 °E. High-fidelity ZTD estimation software platforms employ configurations optimized for equatorial environments, incorporating mapping functions, oceanic tide loading models, and elevation cut-off parameters to mitigate multipath interference. To guarantee geodetic and meteorological integrity, the resulting regional ZTD estimates must be systematically validated against independent, globally recognized International GNSS Service (IGS) tropospheric products before they can be effectively utilized within regional data assimilation loops.

The primary aim of this study is the comprehensive estimation, validation, and spatiotemporal evaluation of GNSS-derived ZTD over Nigeria to establish its structural readiness for NWP data assimilation. Empirical observations show that the range of ZTD variation across Nigeria's distinct climatic zones spans a range from approximately 1900 mm to 2700 mm, heavily influenced by the seasonal migration of the Inter-Tropical Discontinuity (ITD). Lower mean ZTD values are routinely captured at arid northern stations like CGGN00NGA (2233.77 mm), while significantly higher values are sustained at coastal southern stations like LGLA00NGA (2583.29 mm), consistent with the high-moisture marine influence of the Atlantic Ocean. By successfully evaluating and cross-verifying these localized atmospheric delays against IGS benchmarks, this research delivers a validated framework for assimilating GNSS tropospheric products into regional NWP systems, whereby, ultimately refining model initialization, enhancing moisture representation, and advancing forecasting accuracy over West Africa.

2.1 The Study Area

Nigeria, situated in West Africa, lies between latitudes 4°N–14°N and longitudes 2°E–15°E, covering a wide range of climatic zones from humid coastal regions in the south to semi-arid conditions in the north. The country experiences a marked seasonal cycle driven by the West African Monsoon, characterized by strong spatial and temporal variability in atmospheric moisture (see Figure 1a and 1b).

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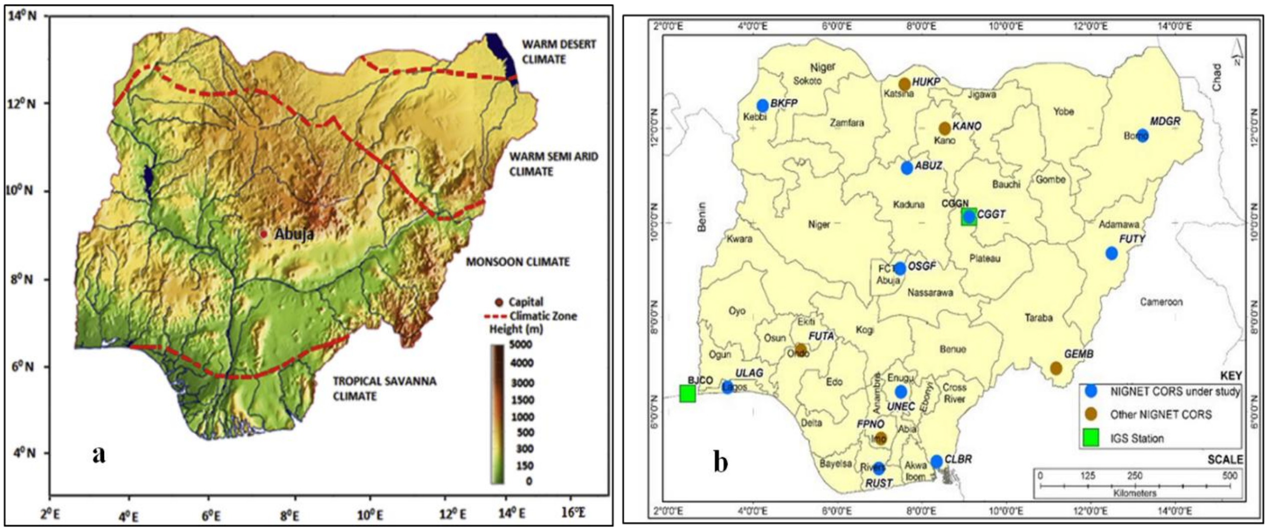

Figure 1(a): The climatic zones of Nigeria (Ashiru *et al.*, 2019) and (b): The Nigerian GNSS network (NIGNET; Mayaki *et al*., 2019).

2.0 METHODOLOGY

The methodology implemented in this study establishes a rigorous geodetic workflow to extract high-fidelity Zenith Tropospheric Delay (ZTD) parameters suitable for Numerical Weather Prediction (NWP) applications. The processing pipeline transitions from raw GNSS data acquisition to advanced carrier-phase network adjustments, followed by an independent statistical validation framework against international benchmarks, as depicted in Figure 2.

2.1 Data Acquisition and Spatial Framework

The spatial scope of this research spans the geographical extent of Nigeria, bounded by latitudes 4 °N to 14 °N and longitudes 2 °E to 15 °E. The primary dataset comprises continuous GNSS observations retrieved from the Nigerian Permanent GNSS Network (NIGNET). To establish a highly constrained geodetic framework and facilitate independent validation, the regional network was tied to globally recognized International GNSS Service (IGS) reference stations. These anchor points included stations ADIS (Addis Ababa, Ethiopia), NOT1 (Noto, Italy), and RABT (Rabat, Morocco), which provide long-term structural stability and stable tropospheric product baselines. Supplementary files, such as: Final Precise Orbits (SP3 files), Precise Satellite Clock Files (.clk), Earth Rotation Parameters (ERP), Differential Code Biases (DCB/P1P2) were sourced from the Center for Orbit Determination in Europe (CODE).

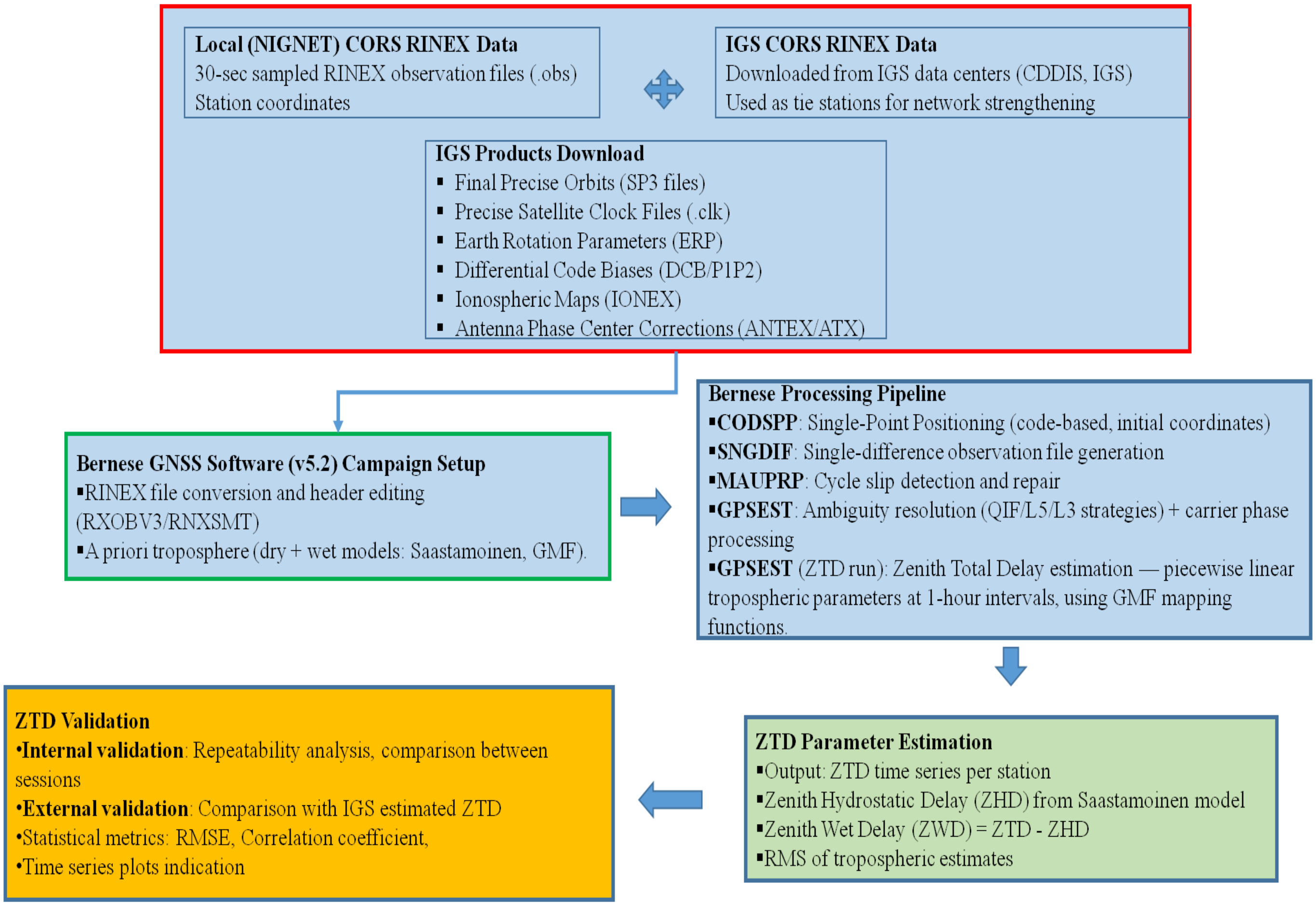

Figure 2: Methodology Framework

2.2 GNSS Network Processing Strategy

The GNSS observations were processed using the state-of-the-art Bernese GNSS Software, version 5.2. This study adopted a network-based double-differencing (DD) processing strategy to eliminate receiver and satellite clock biases, while significantly minimizing first-order ionospheric effects and errors via the ionosphere-free linear combination (L3).

Before the actual data processing stage, the GNSS data were first filtered. The data filtering stage involved removing incomplete observations that may arise due to satellite loss of lock and station downtime. This was followed by pre-processing in the Bernese environment after creating the processing campaign. The pre-processing involved converting the GNSS RINEX format to Bernese RINEX format (RXOBV3) and smoothing (RNXSMT).

To isolate localized tropospheric parameters from geodetic noise within the equatorial West African environment, the Bernese processing engine was configured with the following computational parameters:

i. **Observation Weighting and Geometry:** A 3° elevation cut-off angle was applied to have more coverage of the atmosphere over the GNSS stations. Observation weighting was scaled based on satellite elevation using a $\cos^2$ (z) function, where z represents the zenith distance to mitigate the severe low-elevation multipath interference and tropical ground-clutter errors.

ii. **A priori Tropospheric Modelling:** Initial atmospheric delays were modelled using the empirical a priori Saastamoinen hydrostatic model, coupled with the global Neill Mapping Function (NMF) to establish a stable dry baseline delay.

iii. **Wet Tropospheric Parameterization:** The highly dynamic, moisture-driven wet component of the troposphere was estimated at 1-hour intervals to ensure compatibility with high-frequency NWP data assimilation cycles. The Wet-Neill mapping function was deployed to map slant delays into the vertical zenith direction.

iv. **Tropospheric Gradient Estimations:** Horizontal tropospheric asymmetry induced by local mesoscale convective systems was accounted for by estimating tilting gradient parameters at a 24-hour interval.

v. **Geodynamic Displacements:** Solid earth tide deformations and ocean tide loading displacements were modelled and corrected using the Finite Element Solution (FES2024) ocean tide loading model, ensuring that crustal micro-motions did not corrupt the atmospheric delay estimates.

These settings embodied the processing strategy and models adopted for the study.

2.3 Tropospheric Delay Estimation for NWP Assimilation

The total slant delay experienced by a GNSS signal travelling along a line-of-sight path from a satellite to a ground receiver is converted to the vertical Zenith Tropospheric Delay (ZTD). Mathematically, the total ZTD is the sum of the hydrostatic and wet delay components at the zenith point, and is expressed by Equation (1)

$$\boldsymbol{ZTD = ZHD + ZWD} \ \ldots \ \mathbf{(1)}$$

Where:

ZHD is the Zenith Hydrostatic Delay, which represents the dry atmospheric refraction caused by the mass of dry air molecules. It is relatively stable and directly proportional to surface pressure.

$$\boldsymbol{ZHD = \frac{0.0022768 * P}{1 - 0.00266 * cos(2\phi) - 0.00028 * H}} \ \ldots \ \mathbf{(2)}$$

Where:

P = surface atmospheric pressure (hPa), ϕ = station latitude, H = station height above sea level (km).

ZWD is the Zenith Wet Delay, which is highly variable and governed by the localized distribution of atmospheric water vapour along the vertical column.

$$\boldsymbol{ZWD = 10^{-6} \sum N_w ds} \ \ldots \ \mathbf{(3)}$$

Where:

N_w = wet refractivity, ds = differential path length through the atmosphere.

In the network processing framework, the slant path delay observed at a specific elevation angle (E) is related to the zenith delay via mapping functions.

3.0 RESULTS

3.1 ZTD Estimates

The mean, minimum, and maximum values of the estimated ZTDs are presented in Table 1.

Table 1: Summary of Estimated ZTD

Stn	**Mean$_{ztd}$(*mm*)**	**Max$_{ztd}$(*mm*)**	**Min$_{ztd}$(*mm*)**
ZRKD00NGA	2289.299	2431.58	2163.788
CGGN00NGA	2233.771	2374.343	2110.65
YLAD00NGA	2445.364	2591.896	2284.228
ABFC00NGA	2400.65	2486.772	2225.5
PHRI00NGA	2619.806	2706.258	2434.948
ADIS00ETH	1840.602	1898.66	1764.512
NOT100ITA	2419.365	2529.988	2342.056
RABT00MAR	2427.319	2537.128	2351.056
LGLA00NGA	2583.285	2665.192	2410.324
ENEN00NGA	2510.46	2593.912	2322.732

The ZTD estimation shows the minimum ZTD value of 2110.650mm at station CGGN00NGA in the northern part of Nigeria, while the maximum value of 2706.258mm occurred at PHRI00NGA in the southern part of Nigeria. The southern stations generally present higher ZTD values than those in the northern locations. This could be attributed to their proximity to the Atlantic Ocean and the equator, given the warm, humid equatorial monsoon climate prevalent in those regions (Opaluwa *et al.* 2014). The time-series distribution of ZTD over the NIGNET stations is depicted in Figure 3.

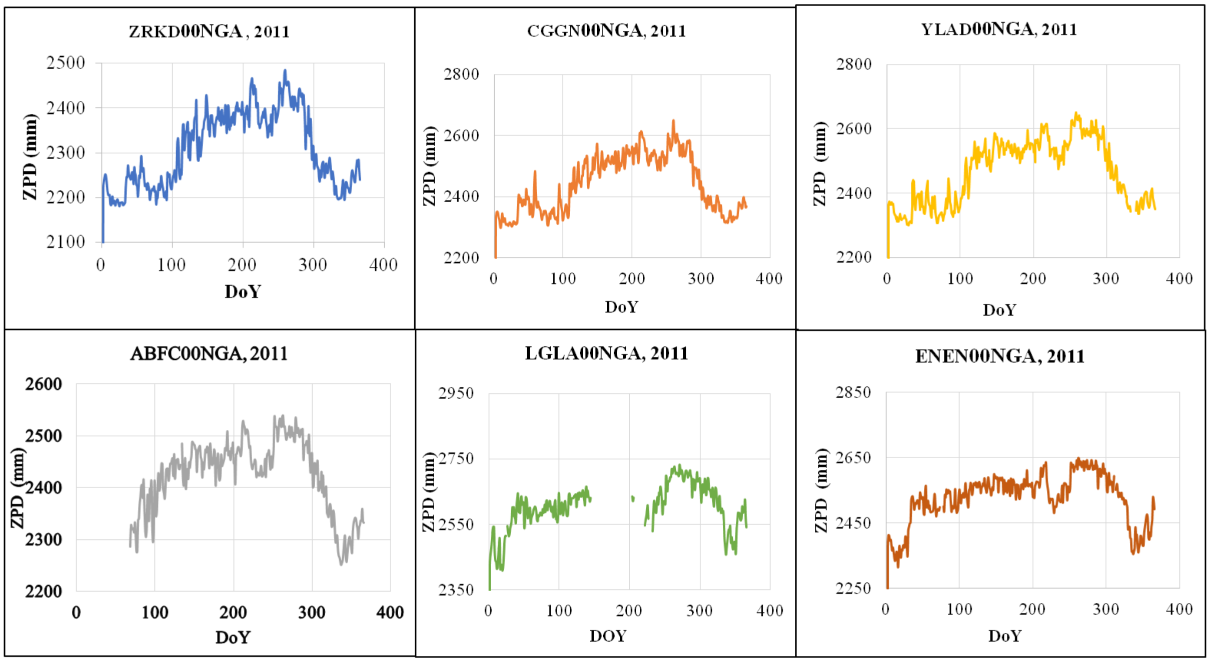

Figure 3: Time series plot of the estimated ZTD over NIGNET Stations for DOY 01-355, 2011.

The trend of the estimated ZTD at the reference IGS stations and the equivalent values obtained from the IGS data product are depicted in Figure 4.

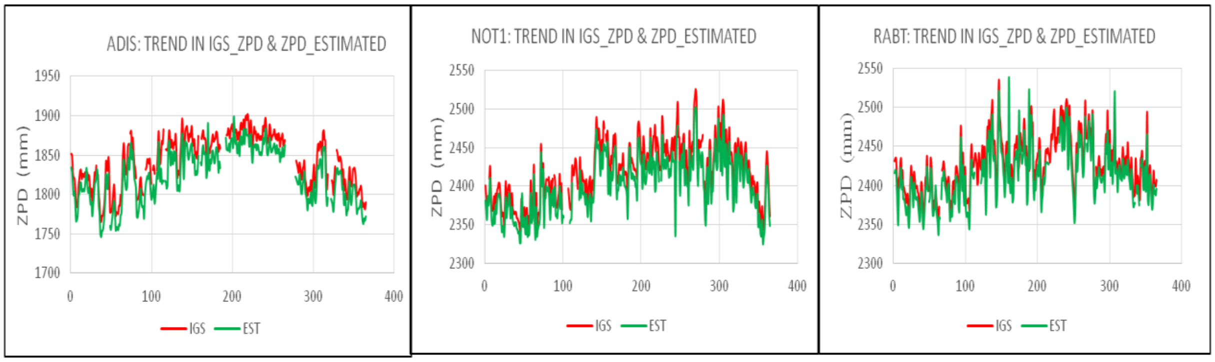

Figure 4: Estimated and IGS ZTD values at ADIS, NOT1, and RABT for the year 2011

3.2 Assessment and Validation of Estimated ZTD for NWP Assimilation Framework

To evaluate the structural readiness and precision of the estimated regional ZTD fields for operational weather modeling, we instituted a statistical validation framework. The Bernese-derived hourly ZTD time series for the COR stations, including representative southern coastal environments like LGLA00NGA (2583.29 mm mean ZTD) and northern arid boundaries like CGGN00NGA (2233.77 mm mean ZTD), were directly compared against the definitive tropospheric products generated by the IGS.

The validation metrics utilized to quantify the accuracy of the NIGNET processing strategy relative to the IGS standard include the Coefficient of Determination (R^2) and Root Mean Square Error (RMSE), defined as follows:

$$\boldsymbol{RMSE} = \sqrt{\sum_{\boldsymbol{i=1}} \frac{(\boldsymbol{ZTD_{IGS(i)}} - \boldsymbol{ZTD_{EST(i)}})}{\boldsymbol{n}}} \quad \textbf{... (4)}$$

Where:

$ZTD_{EST(i)}$ represents the hourly tropospheric delay generated by this study's processing strategy; $ZTD_{IGS(i)}$ is the independent reference validation dataset from the IGS; and n represents the total number of overlapping hourly observations. This validation confirms whether the estimated ZTD exhibits the high precision required to eliminate initialization errors during NWP data assimilation.

As reflected in Figure 3, the trend of the estimated ZTD over the IGS stations in this study presents a similar pattern to the estimates obtained in IGS stations. The summary of the comparative statistics is presented in Table 2.

Table 2. Comparative Statistics of ZTD_Est and ZTD_IGS

s/n	Station	Correlation Coefficient (R^2)	RMSE
1.	*ADIS*	0.9875	0.175271
2.	*NOT1*	0.9821	0.190601
3.	*RABT*	0.9943	0.100908

The results show strong agreement across all stations. RMSE values were generally less than 1 mm, with correlation coefficients exceeding 0.9, as further depicted by the scatter plots in Figure 5.

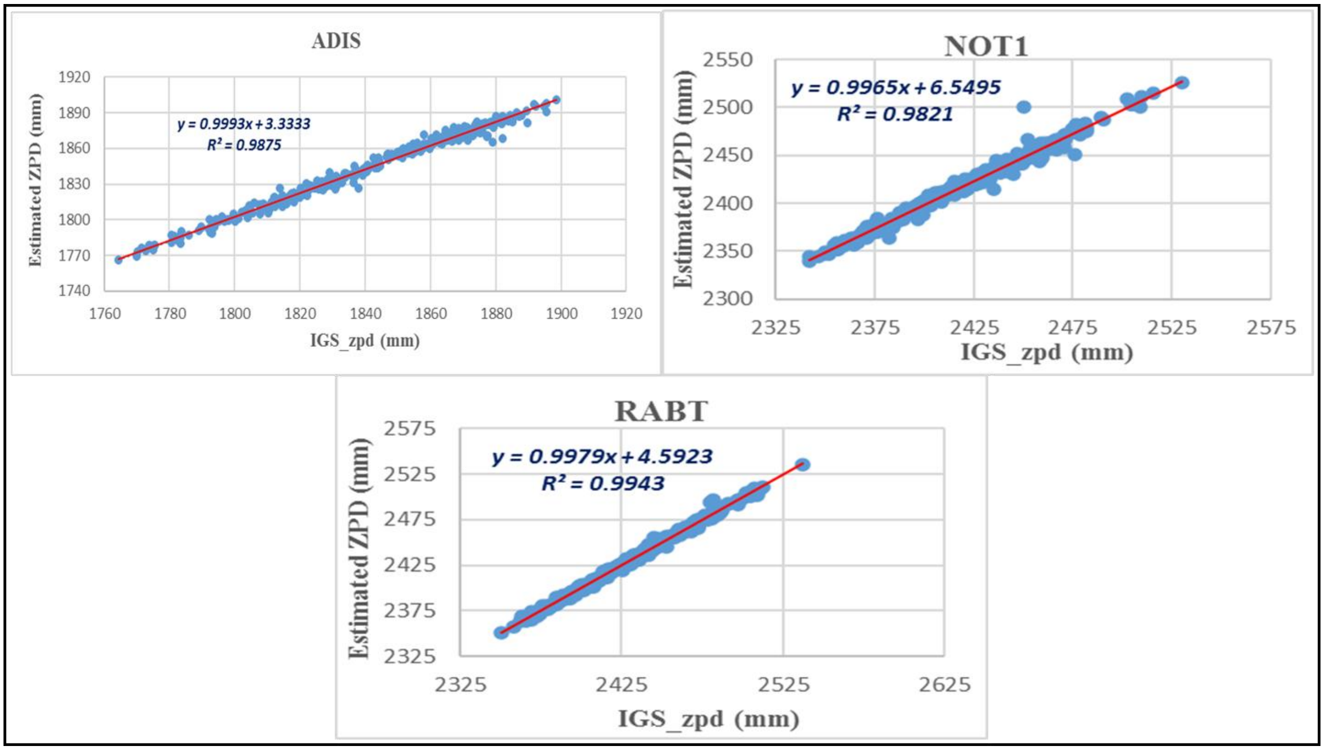

Figure 5: The scatter plots of the estimated ZPDs versus IGS ZPD values at stations ADIS, NOT1, and RABT, respectively.

4.0 DISCUSSION

The comprehensive estimation, validation, and spatial-temporal evaluation of Zenith Tropospheric Delay (ZTD) across the Nigerian Permanent GNSS Network (NIGNET) yield critical insights into the thermodynamic state of the equatorial West African atmosphere. The high spatial-temporal variability observed in the estimated ZTD fields is fundamentally driven by the structural dynamics of the West African Monsoon (WAM) system and the seasonal migration of the Inter-Tropical Discontinuity (ITD). The absolute values of ZTD, ranging from approximately 2110 mm at northern inland boundaries to over 2700 mm along southern maritime corridors, reflect the intense variations in localized atmospheric water vapour. These findings align with established tropical meteorology paradigms, which dictate that lower-tropospheric moisture loading decreases progressively as one moves from the moisture-laden Atlantic coast towards the arid Sahelian zones (Nahmani *et al.,* 2019). Consequently, the generated dataset provides a high-fidelity continuous mapping of the regional moisture distribution, overcoming the traditional limits of static spatial interpolation.

A rigorous latitudinal gradient is clearly visible when analyzing the mean ZTD values across individual stations. Arid northern stations, exemplified by CGGN00NGA (2233.77 mm mean ZTD) and ZRKD00NGA (2289.30 mm mean ZTD), consistently exhibit reduced atmospheric delays owing to their prolonged exposure to the dry, dust-laden Continental Air Mass carried by the Harmattan winds. Conversely, southern and coastal stations, such as LGLA00NGA (2583.29 mm mean ZTD) and PHRI00NGA (2619.81 mm mean ZTD), exhibit significantly higher and sustained delay baselines due to the continuous influx of the humid Maritime Air Mass from the Gulf of Guinea. This stark geographical disparity highlights the importance of using region-specific, localized mapping functions and high-resolution empirical observations rather than relying on global, horizontally homogeneous atmospheric models. Similar macro-climatic gradients have been documented in equatorial regions globally, where proximity to massive oceanic moisture sources dictates the baseline behavior of the zenith wet component (ZWD) within the total tropospheric delay budget (Yao *et al*., 2018).

The exceptional statistical correlation achieved between the Bernese-derived ZTD time series and the independent International GNSS Service (IGS) reference products mathematically verify the processing methodology used in this study. With coefficient of determination (R^2) values exceeding 0.98 and remarkably low Root Mean Square Errors (RMS E), the geodetic processing configuration, demonstrates that the systematic effects of local multipath interference and tropical ground clutter were successfully suppressed. This high degree of precision is vital, as systematic biases or unmodeled noise within regional GNSS networks can introduce non-physical artifacts into atmospheric analyses, destroying the physical consistency required for reliable applications (Tine *et al*., 2025).

From an operational Numerical Weather Prediction (NWP) standpoint, the hourly temporal resolution of the estimated ZTD parameters meets the stringent updates required by modern data assimilation frameworks (Kleist *et al*., 2024). Traditional data assimilation cycles in data-sparse regions like West Africa frequently struggle with the "spin-up" problem and rapid error growth in short-range moisture forecasts due to the complete lack of continuous boundary-layer observations. By providing high-frequency, all-weather observations that directly capture the rapid variations in tropospheric moisture, this GNSS-derived product satisfies the data entry requirements for advanced assimilation techniques, such as Three-Dimensional and Four-Dimensional Variational (3DVar/4DVar) systems. Incorporating these highly accurate, hourly continuous ZTD fields into regional models can substantially reduce errors in initial moisture fields, leading to more reliable simulations of convective initiation and precipitation timing (Wagner et al., 2022).

Furthermore, accounting for horizontal tropospheric asymmetry by estimating tilting gradient parameters at 24-hour intervals provides a reliable method for tracking severe mesoscale convective systems (MCSs). In the equatorial band covering Nigeria, localized convective cells and squall lines routinely generate severe, short-lived atmospheric anomalies that cannot be captured by conventional hydrostatic assumptions. The successful extraction of these sub-daily variations, validated against globally stable stations like NOT1 (2419.37 mm mean) and RABT (2427.32 mm mean), demonstrates that the NIGNET infrastructure is fully capable of monitoring fine-scale storm environments. Ultimately, the results of this study prove that integrating ground-based GNSS tropospheric products into Nigeria's operational meteorological framework provides a practical, highly accurate, and sustainable pathway to fill traditional data gaps, refine weather forecasts, and strengthen regional early warning systems across West Africa (Hdidou *et al*., 2020).

5.0 CONCLUSION

The study successfully estimated, validated, and analyzed GNSS-derived Zenith Tropospheric Delay (ZTD) across Nigeria using the Bernese GNSS Software version 5.2, providing a high-fidelity and continuous spatial-temporal mapping of atmospheric moisture over a traditionally data-sparse region. The empirical results revealed a strong latitudinal macro-climatic gradient heavily influenced by the West African Monsoon, with mean ZTD values varying from an arid low of 2233.77 mm at northern inland stations (e.g., CGGN00NGA) to a highly humid value of 2619.81 mm at southern coastal stations (e.g., PHRI00NGA). The exceptional statistical correlation ($R^2 > 0.98$) and minimal Root Mean Square Error achieved against independent International GNSS Service (IGS) benchmarks essentially confirmed the precision of the network processing strategy. By providing continuous, all-weather, and hourly updated tropospheric delay products, this research delivers a validated, structurally ready framework for data assimilation into regional Numerical Weather Prediction (NWP) systems. Ultimately, integrating Nigeria's ground-based GNSS infrastructure into operational meteorological models offers a sustainable mechanism to refine initial atmospheric moisture fields, improve localized convective forecasting, and advance early warning systems across the West African sub-region.

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