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REVIEW ARTICLE

Tropospheric water vapor retrievals by Ground-Based GNSS in Africa: A systematic review

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Abstract

Tropospheric water vapor is a complex parameter due to its spatial and temporal variability, but it is essential for meteorology and study of climate. Faced with high operating costs and traditional low resolutions, Ground-Based Global Navigation Satellite System (GNSS) is increasingly used for tropospheric water vapor retrieval. From databases and several query strings, this study examines in different ways the evidence-based studies of water vapor retrieval from African Ground-Based GNSS using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) protocol and specific criteria. 30 articles of empirical studies published between 2000 and June 2024 were analysed in depth vis-a-vis research questions. This Systematic Review (SR) includes a mapping of the selected literature, highlighting the distribution and focus of research efforts across Africa. This SR provides new insights by consolidating the evidence on the various approaches used with African Ground Stations. Water vapor time series obtained from GNSS data show consistency with traditional data sources, particularly for seasonal and diurnal cycles. It also highlights the under-exploited potential of GNSS networks in Africa, limited by uneven geographical coverage and a lack of standardization of methodologies, despite significant progress in atmospheric studies, as well as it highlights the advanced techniques that are under-exploredand proposes future research directions, while calling for closer collaboration between scientists and decision-makers to improve access to GNSS data, promote network interoperability, and explore methodological approaches adapted to Africa's specific climatic conditions, in order to maximise the applications of GNSS techniques for water vapor retrieval.

Key words: Water vapor, GNSS, Systematic review, Africa, PRISMA protocol, Troposphere

1 Introduction

The troposphere is the lowest layer of the atmosphere, marking the region where hydrometeors such as precipitations, hail and snow develop, together with meteorological phenomena such as clouds, fronts, cyclogenesis and thunderstorms. It is mainly composed of tropospheric water vapor, a greenhouse gas that is essential for maintaining the Earth's energy balance and the water cycle, accounting for more than 72% of greenhouse gases (Boniface, 2009). The retrieval of water vapor is important for weather forecasting and climate studies (Guerova et al., 2016; Jones et al., 2020) unlike meteorological parameters such as pressure and temperature, water vapor fluctuates rapidly in the atmosphere and exhibits greater complexity, and its high variability is generally associated with extreme weather phenomena, such as thunderstorms. Conventional techniques for surveying tropospheric water vapor, such as radiosondes, radiometers and Light Detection and Ranging (LIDAR), are not widely distributed, have poor temporal resolution and are generally unaffordable for African countries. Since the early 1990s, a technique developed by Bevis et al. (1992), initially used ground-based Global Positioning System (GPS) for retrieving tropospheric water vapor, such as Integrated Water Vapor (IWV). This approach, known as GPS meteorology, later expanded to incorporate other Global Navigation Satellite System (GNSS) constellations. GNSS is a broader category that includes GPS (United States), GLONASS (Russia), Galileo (European Union), and BeiDou (China).

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GNSS-based meteorology leverages all these satellite navigation systems for atmospheric studies, providing enhanced coverage and data diversity. GNSS meteorology leverages all satellite navigation systems for atmospheric studies, offering enhanced coverage and data diversity. The slant delays in signals from satellites due to the troposphere are projected onto the receiver's Zenith and estimated in GPS processing as Tropospheric Zenith Delay (ZTD). By observing meteorological parameters, this delay is converted into IWV. The development of methods for correcting the effects of signal propagation in the atmosphere and the multiplication of Continuously Operating Reference Stations (CORS) on Earth have allowed several studies to demonstrate the usefulness of GNSS meteorology in monitoring the troposphere by studying the spatial-temporal distribution of tropospheric water vapor, such as Bosser and Bock (2021). Several researchers have experimented and also obtained convincing results with an accuracy of around 1.8 mm in the real-time reconstruction of Precipitable Water Vapor (PWV), an operational parameter in meteorology (de Haan et al., 2009; Li et al., 2015; Lu et al., 2015) as well as its inclusion in the immediate prediction of precipitation (Benevides et al., 2015).

African countries are no different from multiple other locations suffering from climate disruption, which is currently causing a number of disasters. In the face of climate change, resilience policies will inevitably involve increasing the variability of weather and climate observation tools. In Africa, experiments have been conducted to use GNSS stations to model tropospheric water vapor for the study of climatic phenomena, including the more specifically regional African Monsoon Multidisciplinary Analysis (AMMA) (Bock et al., 2007b) for the study of the West African Monsoon in East Africa (Ssenyunzi et al., 2020). Several researchers have used Precise Point Positioning (PPP) and Double-Differencing (DD) processing techniques with different software tools for the estimation of ZTD. PPP is a method capable of processing undifferenced GNSS observations using precise satellite orbit and clock information to achieve high accuracy, while DD involves computing differences between observations from two receivers and two satellites to mitigate common errors such as clock biases (Teunissen and Montenbruck, 2017). The low-density number of Ground-Based GNSS in Africa compared to other continents makes studies less dense and leads to a geographical disparity in them. While some African countries, such as Morocco, have established a network of CORS dedicated to meteorology, the majority rely on national GNSS networks designed for geodesy, positioning, or geodynamics, as well as International GNSS Service (IGS) stations, which often have data gaps in certain periods across Africa (Osah et al., 2021). This issue, combined with the limited availability of Radiosonde (RS) or radiometer data near GNSS stations, makes IWV studies particularly challenging. Providing a concrete overview of the various experiences in retrieving water vapor using GNSS in Africa through literature analysis holds a promise of valuable research results.

Traditional literature reviews deal with fairly broad issues, using a method of selecting documents that is flexible for the researcher but difficult for peers to reproduce. As a result, the interpretation of the results of the review is very likely to be tainted by the researcher's personal opinion. Originating from the field of medicine, systematic literature reviews start with a precise question, identify all the evidence that meet the predefined eligibility criteria for a clinical question, and then evaluate and synthesise it using a rigorous scientific approach (Kitchenham and Brereton, 2013; Nambiema et al., 2021). Systematic Review (SR) helps to inform decision-making by providing scientific evidence, identifying best practices and the limitations of primary studies that should not be replicated, and therefore, avoiding wasted research time and helping maximise research efficiency.

The objective of this paper is to provide a transparent review of the literature on evidence-based experiments using African GNSS ground-based data, including the involved researchers, the applied methods, methods of validation and comparison used, and

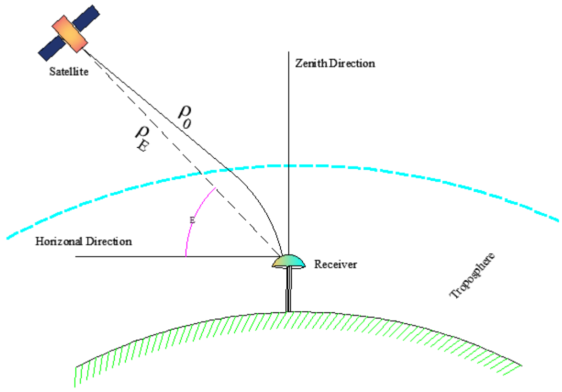


Figure 1. Tropospheric delay as the difference between the optical path of the electromagnetic wave and the geometric path

the limitations and perspectives identified. Section 2 deals with the fundamentals of water vapor reconstruction using GNSS, Section 3 focuses on the research questions that guide the methodology of the paper section using the PRISMA protocol, while Section 4 is concerned with the results and discussions from the analysed papers. Following a bibliometric analysis, this section presents the review and the limitations as well as future research directions. Finally, Section 5 concludes the study.

2 Fundamentals of tropospheric water vapor retrievals by GNSS

The electromagnetic wave from the satellite is affected by a non-dispersive delay in the troposphere. The difference between the measured distance and the satellite-receiver geometric distance (Figure 1) is known as the tropospheric delay. Using mapping functions, the slant delay can be projected to Zenith, where it is referred to as the ZTD. In GNSS processing, the ZTD can be determined through PPP or DD techniques. The Saastamoinen model provides an a priori estimate of the Zenith Hydrostatic Delay (ZHD) using ground-based measurements such as pressure, temperature, and humidity. This model offers reliable results for the ZHD thanks to the assumption of hydrostatic equilibrium. However, the Zenith Wet Delay (ZWD), which is influenced by water vapor, requires refinement during GNSS processing, as the a priori values from the model are less precise for this component (Eqs. 1 and 2). The ZTD is composed of two parts: the ZHD, which accounts for the hydrostatic delay, and the ZWD, associated with water vapor (Eq. 5). For the hydrostatic delay, Saastamoinen (1972) model approximates the ZHD as a function of ground pressure (P, in hPa), receiver latitude (φ), and receiver altitude above sea level (H, in km), based on the assumption of hydrostatic equilibrium (Eq. 3):

$$\mathrm{ZTD} = \frac{0.002277}{\cos z}\left[P + \left(\frac{1255}{T} + 0.05\right) e - \tan^2 z\right], \quad (1)$$

$$\mathrm{ZTD} = \mathrm{ZHD} + \mathrm{ZWD}, \quad (2)$$

$$\mathrm{ZHD} = 0.002277 \frac{P}{1 - 0.0026\cos(2\varphi) - 0.000279H}, \quad (3)$$

where: T – ground temperature in Kelvin; e – partial pressure of water vapor; z – zenith angle of the satellite. IWV is obtained by dividing a conversion factor Π from the ZWD (Hogg et al., 1981):

$$\mathrm{ZWD} = \mathrm{ZTD} - \mathrm{ZHD}, \quad (4)$$

$$\mathrm{IWV} = \frac{\mathrm{ZWD}}{\Pi} \quad \text{and} \quad \mathrm{PWV} = \frac{\mathrm{ZWD}}{\rho_W \Pi}. \quad (5)$$

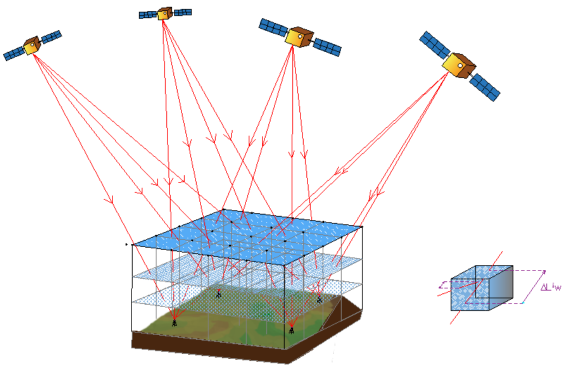


Figure 2. GNSS tomography by discretization

The conversion factor is given in Bevis et al. (1994):

$$\Pi = 10^{-6} \rho_W R_W (k'_2 + \frac{k_3}{T_m}), \quad (6)$$

where: T_m is the weighted mean temperature of the atmosphere, ρ_W is the density of water, R_W is the specific gas constant for water vapor in $J \cdot kg^{-1} \cdot K^{-1}$, k'_2 and k_3 are constant based on laboratory estimates calculated (Bevis et al., 1992, 1994). In the presence of a dense GNSS network, it becomes also possible to move beyond total water vapor estimates and apply GNSS tomography, which enables a detailed analysis of the vertical and horizontal distribution of atmospheric water vapor. By discretizing the atmosphere into a 3D grid of voxels and using delays such as: total, wet, or Slant Integrated Water Vapor (SIWV) as input data (see Figure 2). It can be used to reconstruct a 3D field and its temporal variations in water vapor density (Reverdy, 2008).

The SIWVs are formulated by Eq. (7) with: s – integration path on the GNSS line of sight; $e(s)$ – partial pressure of water vapor along the path L:

$$\mathrm{SIWV} = \frac{1}{\rho_W R_W} \int_L e(s)\,\mathrm{d}s. \quad (7)$$

The set of N voxels allows to discretize the integration along the path L where ΔL_W^i is the length of the path crossing voxel i and ρ_W^i is the water vapor density in voxel i:

$$\mathrm{SIWV} = \sum_{i=1}^{N} \Delta L_W^i \rho_W^i. \quad (8)$$

The sum of the SIWV for different lines of sight between the ground receiver network and the different satellites makes it possible to reconstruct a 3D tomographic image of the water vapor distribution.

3 Materials and methods

3.1 Research questions

This SR aims to shed light on current advances in the use of GNSS signals in the retrieval of tropospheric water vapor in Africa. Investigations into the research platforms showed that as of 24 May 2024 there were no active SRs dealing with the theme based in African stations. Vaquero-Martínez and Antón (2021) discussed only one experience in Africa, where the authors dealt with in a fairly broad and free manner with the potential of African GNSS Ground-based for climate monitoring (Isioye et al., 2015).

The formulation of the research questions is essential to help describe, and extract advances and perspectives on a very specific theme (Mateo, 2020). The following questions were formulated:

Table 1. Summary of inclusion and exclusion criteria

Inclusion criteria	Exclusion Criteria
- Original articles, Scientific articles - Period from 2000 to June 2024 - Studies using African stations and stations on islands close to Africa	- Conference articles, edited volumes, Master's theses, Phd Thesis, non-peer-reviewed books - Articles published outside the selected period - languages other than English. - Studies not using African stations - Studies based on radio occultation (RO)

i. Which GNSS constellations and GNSS data analysis strategies are most widely used in the literature in Africa?
ii. What are the different tools and complementary data for the transformation of ZTDs into IWV/PWV as per the relevant literature?
iii. What are the validation methods used for the different approaches?
iv. What are the different meteorological applications resulting from the modelling of GNSS data used in this research?
v. What are the current limitations and challenges facing researchers in the field of GNSS retrieval of tropospheric water vapor?

3.2 Research strategy

To carry out this systematic review in accordance with PRISMA recommendations, the following scientific databases were used: Google Scholar, Science Direct, Scopus, IEEE Xplore, Web of Science, African Journal Online, Cain, and Google.

The following keywords were entered in order to find potential relevant articles using the search equation, which was adapted according to the specific features of the databases in order to achieve a sufficient completeness rate: "GNSS", "water vapor", "Integrated", "GPS", "Ground-based", "tropospheric", "atmospheric", "precipitable", "GNSS meteorology", "Africa", "African countries", "Tropical".

The search, restricted to articles in English, was carried out between 2000–26 June 2024.

The documents retrieved were manually supplemented by grey literature, documents from previous downloads, university documentation center databases and personal communication with other researchers. All the articles were reorganized and classified according to title in order to identify duplicates. Most of the duplicates are the results of overlaps between data from different databases. In order to avoid reading hundreds of documents, various sorting stages were carried out to retain documents for their relevance in answering the research question. By analyzing first the titles and then the abstracts, we were able to create a list of 47 articles selected for verification, based on the full texts, those meeting the eligibility criteria separated from those that do not. Table 1 synthesizes the inclusion and exclusion criteria applied to the selected studies. All the articles selected were the result of experiments and produced IWV or PWV with comparisons with other techniques.

The PRISMA flow diagram (Figure 3) summarises the item extraction and selection process. Table 2 summarises the list of articles that have been retrieved using the PRISMA Protocol. The extraction and analysis of relevant information based on the research questions listed above was carried out using MAXQDA (VERBI Software, 2024) and Excel.

Table 2a. Basic characteristics of selected articles

Reference	Newspaper	Number of African Stations	GNSS Final Products	Validation/ Comparison	Specific analysis	Post-Processing	PPP/ DD	Tm	Period
(Abdelfatah et al., 2022)	NRIAG Journal of Astronomy and Geophysics	8	PWV	RS	Time series – monthly cycle, spatial variation mapping	CSRS-PPP	PPP	$0.73T_s + 69.68$	2014
(Boutiouta and Lahcene, 2013)	International Journal of Remote Sensing	4	PWV	RS	Time series, T_m comparison	Bernese 5.0	PPP	Algerian T_m equation $0.9658T_s + 14.793$	2006–2008
(Abraha et al., 2015)	GPS Solutions	17	IWV	ECMWF	Spatial and temporal distribution – rainfall	GAMIT	DD	(Bevis et al., 1994)	2007-2011
(Baldysz et al., 2021)	Atmosphere	5	PWV	RS	Long term variability	Bernese	PPP	(Bevis et al., 1994)	2001–2018
(Bawa et al., 2022)	Geodesy and Cartography	15	PWV	ERA5	Subdaily, Diurnal and seasonal variation	NGL GIPSY/ OASIS-II	PPP	(Bevis et al., 1994)	2012–2013
(Combrink et al., 2004)	South African Journal of Science	10	PWV	RS		GAMIT	DD	(Bevis et al., 1994)	July 2023
(Swafiyudeen et al., 2021)	GeoPlanning Journal of Geomatics and Planning	13	PWV	NCEP	Spatial-temporal variability	GAMIT v10.70	DD	(Bevis et al., 1994)	2012–2013
(Bock et al., 2007b)	Geophysical Research Letters	4	PWV	ERA40	Seasonal cycle, inter-annual variability	IGS (Ge and Gendt (2004) procedure) for 8 IGS stations	DD	Bevis et al. (1994)	1997–2004 min. 1 year
(Bock et al., 2007a)	Quarterly Journal of the Royal Meteorological Society	9	PWV	RS/ AERONET/ SSM/ I/ Era40 NCEP2	Time series, intercomparison/ variability of PWV from reanalysis	IGS (Ge and Gendt (2004) procedure) for 8 IGS stations	DD	Bevis et al. (1994)	1999–2005
(Namaoui et al., 2017)	Advances in atmospheric sciences	3	PWV	RS/ Era-Interim	Time series	Bernese v5.0	DD	(Bevis et al., 1994; Song and Boutiouta, 2012; Namaoui, 2017)	August 2012/ 21.11–4.12.2012
(Bock et al., 2008)	Journal of Geophysical Research	10	PWV	RS	Time series/ rainfall	GAMIT v10.21 v10.32	DD	calculated from temp and humidity profiles from ECMWF	2005–2006
(Abdellaoui et al., 2019)	Arabian Journal of Geosciences	6	IWV	RS/ ECMWF ERA-Interim	Times series/ Rainfall/ spatial distribution/ interannual variation	Bernese 5.2	DD	ECMWF	2008–2014
(Koulali et al., 2012)	Atmospheric Research	4	PWV	RS/ NCEP and NCEP2 (NWP)	Time series/ seasonal cycle/ rainfall/ gradients too	GAMIT v10.32	DD	ECMWF	2001–2007
(Mengistu Tsidu et al., 2015)	Atmospheric. Measurement. Techniques	8	PWV	FTIR/ RS/ ERA-Interim/ Spatial mapping	Time series/ Diurnal cycle	GAMIT v10.32	DD	ECMWF	2007-2011
(Yuan et al., 2023)	Earth System Science Data	36	IWV	RS/ ERA	Spatial Mapping	NGL Gipsyx Oasis	DD	ERA5	2020

Table 2b. Basic characteristics of selected articles (cont.)

Reference	Newspaper	Number of African Stations	GNSS Final Products	Validation/ Comparison	Specific analysis	Post-Processing	PPP/ DD	Tm	Period
(Ssenyunzi et al., 2020)	Advances in Space Research	13	PWV	ERA5	Spatial variation mapping/ Time series / seasonal cycle	goGPS	PPP	ERA5/ (Bevis et al., 1994; Yao et al., 2014)/ MET Sensor pressure and temperature	2013–2016
(Koji et al., 2022)	Remote Sensing	9	PWV	ERA5/ RS	Time series/ Seasonal and diurnal cycles	GAMIT v10.71	DD	GPT2w model and ECMWF	2013–2020
(Isioye et al., 2017)	International Journal of Remote Sensing	5	PWV	Atmospheric Infrared Sounder AIRS and ERA-Interim	daily monthly seasonally temporal scales	GAMIT/ GLOBK	DD	Isioye et al. (2016): $0.5245T_s + 132.12$	2013–2014
(Jiang et al., 2024)	GPS Solutions	8	PWV	ERA5	Time series/ spatial mapping	IGS/ other	DD/ PPP	Relationship PWV function of ZTD	2016–2019
(Ding et al., 2022)	Remote Sensing	3	PWV	RS	seasonal and interannual variation	NGL Gipsyx	DD	T_m from VMF1 gridded NWM data	1994–2020
(Ssenyunzi et al., 2021)	East African Journal of Science, Technology and Innovation	13	PWV	ERA5		goGPS v1.0beta1	PPP	T_m linear model developed 2013	2014–2016
(Elouardi et al., 2022)	Modeling Earth Systems and Environment	9	IWV	AROMA	Time series	Bernese 5.2	DD	T_s, P_s from Arome	20 Feb–20 March 2018
(Acheampong and Obeng, 2019)	Journal of Geodetic Science	4	PW	Era-Eratim/ Time series	Forecast	gLAB	PPP	Chen and Yao (2015) with T_s from Era-Interim	2016–2017
(Wonnacott and Merry, 2006)	Survey Review	9	PWV	RS/ NWM	Time series	Bernese v4.2	DD	$\Pi = 0.16$	March 2004
(Acheampong et al., 2015)	Journal of Geodetic Science	1	PW	Era-Interim/ NCEP reanalysis	Times series	gLAB	PPP	$\Pi = 0.1629$	March 2013 – May 2014
(Acheampong et al., 2017)	South African Journal of Geomatics	1	PW	JRA Era-Interim NCEP	Time series	gLAB CSRS APPS	PPP	$\Pi = 0.1629$	September–December 2014
(Ojegbile et al., 2023)	Nigerian Journal of Environmental Sciences and Technology	7	PWV	ERA5	Spatial variation mapping/ seasonal variability	GAPS v6.00	PPP	Π (Isioye et al., 2017)/ T_s from GPT3 empirical model	2011–2016
(Kawo et al., 2023)	Climate Dynamics	9	PWV	ERA5/ CORDEX RCM	Time series/ Relation between PWV temperature heavy rainfall	GAMIT v10.71	DD		2013–2020
(Mlawa A. and Saria E. E, 2023)	Journal of Geosciences and Geomatics	1	PWV	ERA-Interim	Time series	gLAB and GAMIT/ GLOBK	PPP/ DD		June 2017–June 2018
(Van Malderen et al., 2022)	Remote Sensing	2	IWV	ERA-Interim/ GOMESCIA	spatial and temporal IWV variability/ seasonal cycle/ Linear Trends	IGS		T_m from ERA-Interim/ T_m (Bevis et al., 1994)/ T_m SYNOP/ T_m NCEP	1995–2010

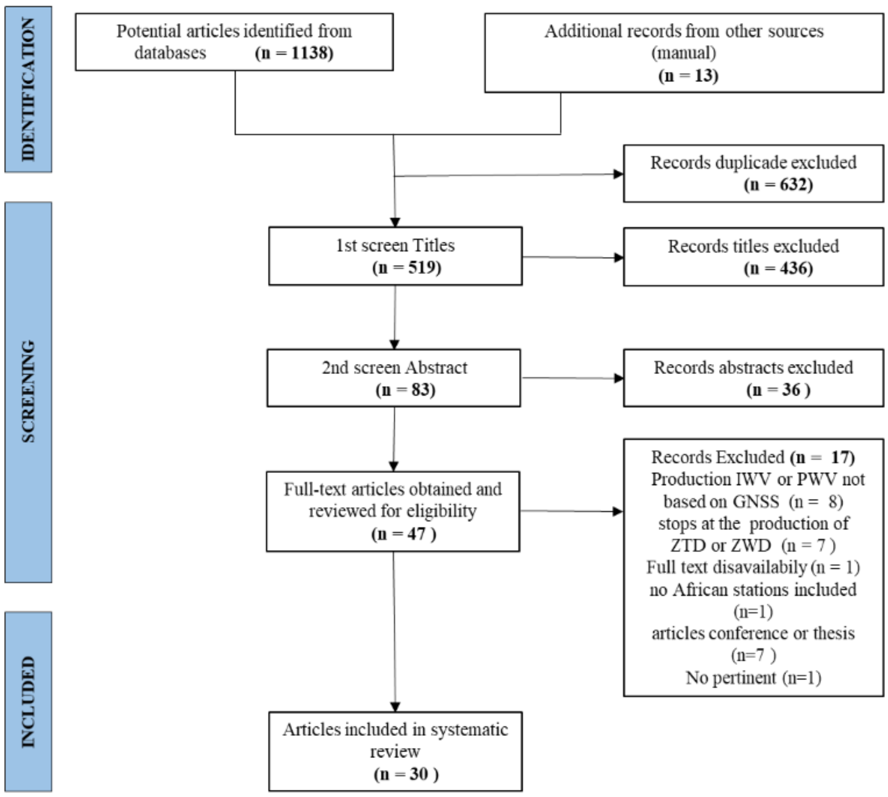


Figure 3. Study selection flow diagram PRISMA version 2020

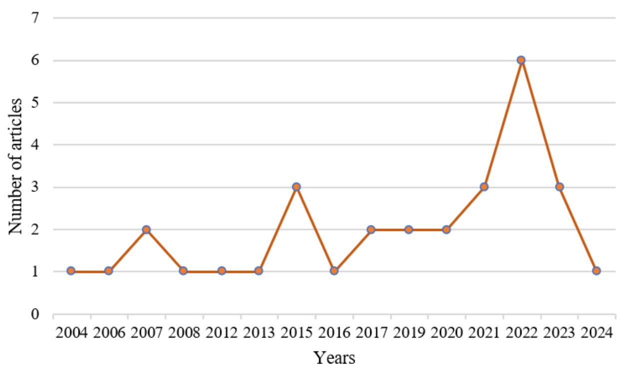


Figure 4. Evolution of articles by year

4 Results and discussions

4.1 Bibliometric Analysis

Evolution of articles and terminology

Before 2015, only 7 articles were focused on the retrieval of water vapor from GNSS stations in Africa. This extensive research helped to find the first experiments carried out on the continent more precisely in South Africa by Combrink et al. (2004) with a significant number of nine South African stations and one Namibian station followed by the experience of Wonnacott and Merry (2006). This shows that South Africa was ahead in the area of GNSS compared to other African countries. Figure 4 highlights that from 2015 the experiments have intensified with 24 articles between 2015–mid-2024, which quadruples the former period. There is likely to be more than one article published in the second half of 2024.

An analysis of the 30 articles enabled us to generate a word cloud, which, after removing prepositions and pronouns, shows the most frequent words in all the articles and confirms the predominance of key words such as “PWV” (2588), “GPS” (2266), “data” (1595), “water” (1476), “GNSS” (986), “IWV” (716) (Figure 5a). The linguistic importance of the terms is interesting for establishing links between adjacent or similar research works.

Figure 5b shows a high concentration of publications in journals in the fields of geolocation and remote sensing, since the approaches used GNSS tools whose basic applications were linked to these fields. This is followed by a relatively even balance of journals in the fields of “Meteorology, Climate, Atmosphere”, “Geosciences, Earth Sciences, Environment” and “Geophysics, Space, Astronomy”. This distribution shows that this research is interdisciplinary, covering several aspects of geodesy, atmospheric sciences, meteorology, geophysics and Earth science.

Geographical distribution of study stations

Most of the stations used in water vapor estimation studies are located in coastal countries. Apart from Ethiopia and Uganda, stations in countries such as: Kenya, Gabon, Ghana, Algeria, Nigeria, South Africa, Senegal, and Morocco with coastlines on the Mediterranean Sea, the Atlantic Ocean or the Indian Ocean were the most commonly used in the experiments (Figure 6). This is explained by the fact that IGS stations are the most sustainable in terms of data and their data feature better conservation. An overview of operational stations in September 2024 provided by International GNSS Service (IGS) (International GNSS Service, 2024), shows that most of them are located in these countries. From a climatic or meteorological point of view, coastal climates are of interest to most scientists, but geographical analysis leads to the conclusion that there is a research gap to be exploited to study the contribution of GNSS over Central Africa. A comparison between Figure 6 and the study of Koome et al. (2019) shows that there are indeed CORS networks in several other countries that are rarely used in water vapor retrieval in Africa, only in Egypt, Tunisia, and Libya. This unused potential follows from the fact that their vocation is more focused on Network Real-Time Kinematic (NRTK) than the observation of static data.

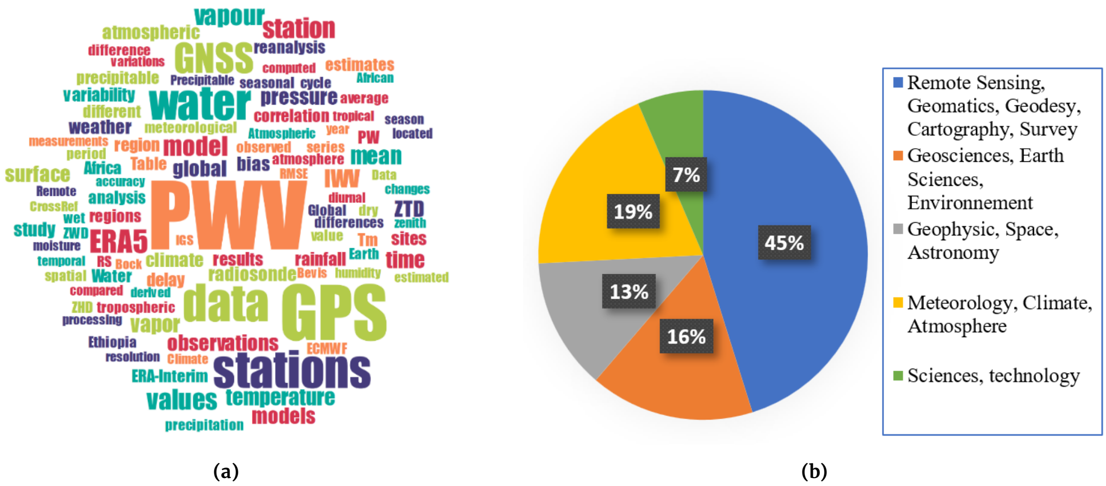


Figure 5. a) Word cloud generated from scientific papers; b) Fields of the different publication journals

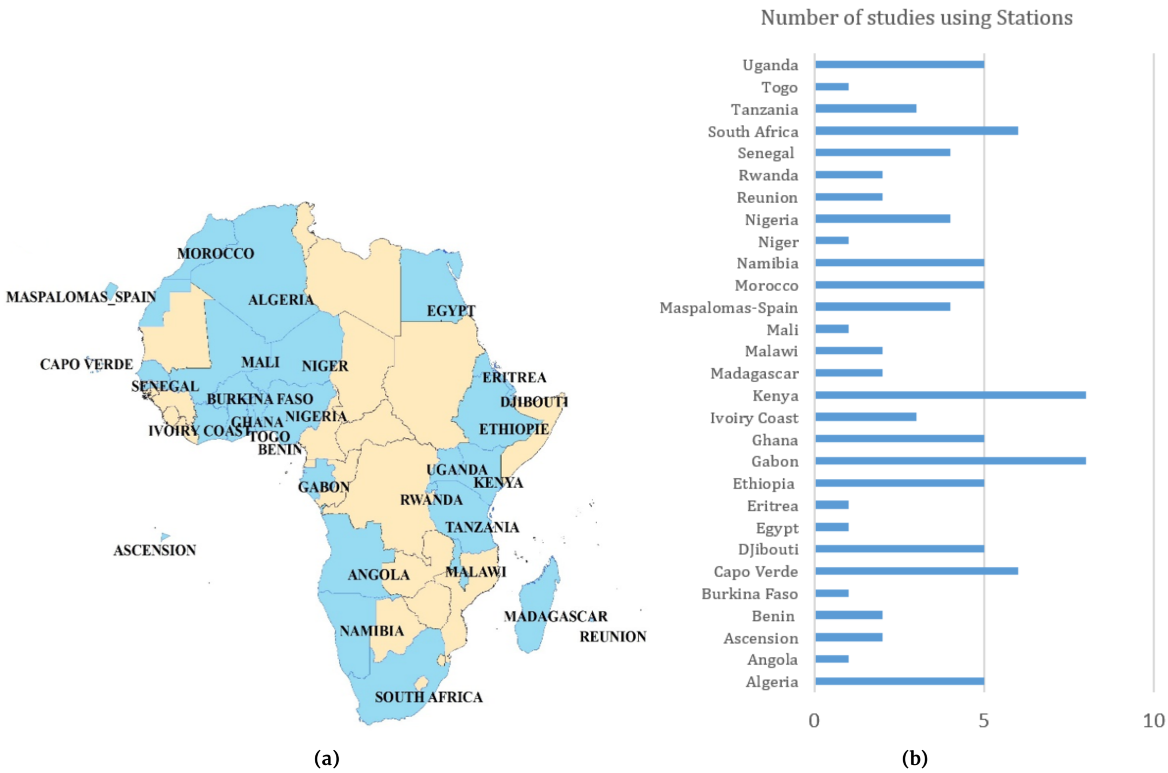


Figure 6. a) Countries hosting GNSS stations utilized in water vapor studies selected; b) Studies including stations from these countries

4.2 Review

Based on the research questions stated in Section 3, an in-depth review was conducted on the selected articles.

GNSS data analysis and conversions to IWV/PWV

Before 2017, the various research publications exclusively exploited the GPS constellation, while (Acheampong et al., 2017) introduced the use of GNSS signals for their experiments, facilitated by the development of multi-GNSS receivers in Africa. With regard to GPS/GNSS processing for the production of IWV convertible ZTDs, three types of approach have been applied, which is reflected in the literature: the software approach, on-line processing platforms and post-processed data retrieval. For the software approach to ZTD retrievals, being the most widely featured across all the studies, researchers have used scientific software, mainly Bernese, GAMIT/GLOBK, and the free software goGPS and gLAB with PPP and DD modes, using IGS stations. The online platforms, CSRS, APPS and GAPS were used using the PPP technique. Finally, tropospheric delay products from the IGS and Nevada Geodesy Laboratory (NGL) platforms, which produce reliable ZTD through adjustments based on precise orbits and clocks, were used in regional experiments combining data from stations in several African countries. Table 2 shows the different processing methodologies presented in the literature. The most commonly-used time resolutions are 30 s or 300 s.

The types of T_m estimation are diverse. Table 2 shows that the linear relationship of Bevis et al. (1992, 1994) and T_m from European Centre for Medium-Range Weather Forecasts (ECMWF) models are the most widely used. In the absence of RS data, local meteorological data and the deficiencies of studies on T_s/T_m correlations in large regions push the authors to extract the T_m directly from the ECMWF models. The bilinear interpolation techniques and the inverse of the distance are most commonly used. Some authors use a simplified relationship between the ZTD and IWV by approximating the value of Π which may not be sufficiently robust, given the complexity of the climate, especially in tropical areas.

The ability of the GNSS technique to compensate for the lack of meteorological data at the station level and the remoteness of the sounding balloon launch sites generally lies in the capability of integrating data from climate models and techniques for correcting the differences in altitude between sites.

Reviews of the articles show that, overall, the use of precise IGS products in PPP/DD processing makes it possible to obtain ZTDs for monitoring tropospheric water vapor in Africa. Baldysz et al. (2021) found that PWV GNSS time series from PPP processing can be successfully used in seasonal and interannual variability studies. DD processing is dependent on station choices. The DD requirements with the lack of IGS stations in some areas in Africa (Figure 7) and their frequent malfunctioning make the use of DD a complicated procedure. The comparison or validation approach is important in a procedure that is so scientifically robust.

Comparison and validation with other techniques

Comparisons of GNSS tropospheric Water Vapor (WV) products with data from other techniques, as well as the validation of numerical weather prediction (NWP) models are discussed in the publications mentioned in this SR.

The Atmospheric Infrared Sounder (AIRS) is an instrument installed on board the Aqua satellite of the Earth observation system in the polar orbit. Isioye et al. (2017) obtained larger deviations and biases between GNSS-PWV and AIRS sounder compared to the ERA-Interim model on a spatial resolution of 0.5° and temporal resolution of 6h in Nigeria. The ERA-Interim model is a global atmospheric reanalysis dataset developed by the ECMWF, following the ERA-40 reanalysis, which covers the period 1957–2002 providing long-term climate and weather data for research and model validation. Standard Deviation of Residuals (SDR) and biases between GNSS and ERA-Interim are, respectively, estimated at 4.6 mm and -1.2 mm, and the correlation coefficient is 0.8. These results are similar for the case of IWV-GNSS compared to the IWV derived from the AROME model of temporal resolution of 3h in Morocco, respectively, with a standard deviation of 4.3 mm and a negative bias of -0.40. The correlation coefficient obtained by Elouardi et al. (2022) is approximately 0.83. On the scale of several countries in West Africa, the AMMA experiment has made it possible to find strong consistency between GNSS PWV and the ERA-40 and National Centers for Environmental Prediction (NCEP) models (Bock et al., 2007a). The average correlation found is 0.81 and 0.67, respectively, with ERA-40 and NCEP.

One common in the selected literature dataset is ERA-Interim. Acheampong et al. (2017); Mengistu Tsidu et al. (2015) found higher correlations with ERA-Interim – around 0.85 and for local NCEP in Ghana – around 0.729. This confirms previous findings by Bock et al. (2010) that GPS PWV agree better with ERA-Interim PWVs than with the NCEP1 and NCEP2 re-analyses. However, Mlawa A. and Saria E. E (2023) find that GNSS PWV from GAMIT processing generally provides lower values than ERA-Interim PWV in the dry season as opposed to the rainy season, in which GAMIT PWV has oversampled ERA-Interim PWV by a large margin. Numerical weather models (NWM) are considered less direct than GNSS and RS, as they have undergone various smoothing and interpolation processes (Wonnacott and Merry, 2006).

The correlation between GPS IWV and IWV ERA-Interim IWV exceeds 0.85 at different time scales at 99.9% significance level in Ethiopia (Abraha et al., 2015). More recent studies involved the latest generation reanalysis from the ECMWF, ERA5, which presents a spatial resolution of 0.25° × 0.25° (31 km) with a temporal resolution improved by 1h as compared with ERA-Interim (6h). The comparison of GNSS PWV with ERA5 PWV showed strong correlations R^2 greater than 0.90 with Root Mean Square Error (RMSE) ranging from 0.57 mm to 3.78 mm and mean differences between -0.21 mm and 3.62 mm in the work of Koji et al. (2022). The RMSEs are reduced when compared with ERA5 compared with ERA-Interim. These results are consistent with those of Bawa et al. (2022); Ojegbile et al. (2023) in Nigeria but also with Ssenyunzi et al. (2020) in East Africa. The authors also report that correlations decrease slightly near the Equator and in humid regions due to limitations of ERA5 in humid regions and to a lack of observations in some areas.

However, poor-quality recorded GNSS data can significantly reduce the correlation between GNSS IWV and that from models, which has been observed by Abdellaoui et al. (2019) with a decrease in the average correlation to 0.66.

In the scientific community, RS observations are considered the best reference in meteorology to provide essential information on the state of the atmosphere by measuring vertical profiles of temperature, humidity, wind and pressure up to 40 km altitude. However, in Bock et al. (2007b); Dirksen et al. (2014); Wang et al. (2002), limitations such as differences between radiosondes from different manufacturers and generally considered ry bias issues in humidity data can complicate comparison with other data sources. A day-night shift in observations using Vaisala RS92 probes,also noted by Bock and Nuret (2009), manifests itself by an additional dry bias during the day (12:00) caused by a warming due to solar warming. Nevertheless, this direct method remains a preferred reference and Moradi et al. (2013) recommend the use of the same type of probe for long studies, which was the case in 45% of the selected studies of this SR.

Combrink et al. (2004); Wonnacott and Merry (2006) report strong correlations (>0.89) between GNSS PWV and radiosondes in South Africa. In Ethiopia, Koji et al. (2022) observe a similarly high correlation (0.98) over 2013–2020, with low bias and RMSE values. These findings align with those of Mengistu Tsidu et al. (2015) for the same Addis Ababa station (2007–2011), where using observed surface pressure improved accuracy as compared to GPT-based pressure, which introduced higher RMSE and bias. Namaoui et al.

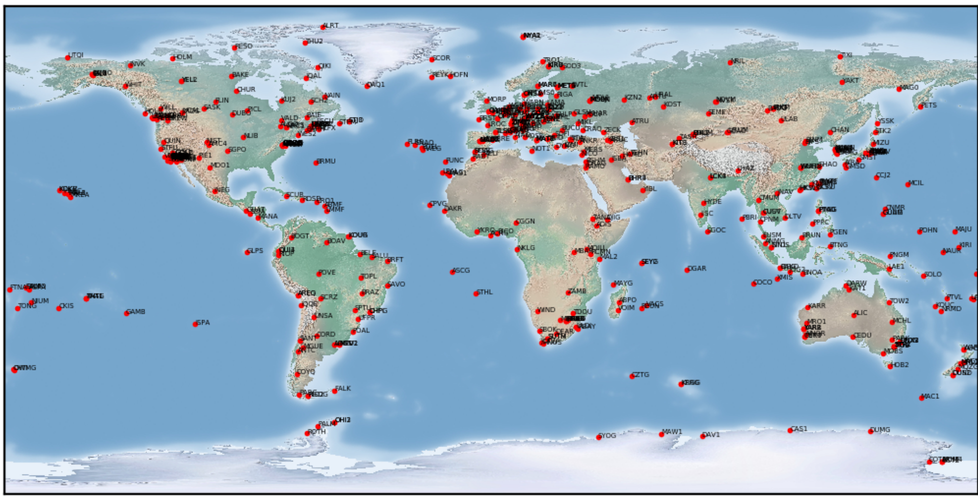


Figure 7. IGS stations (Source: International GNSS Service, November 2024)

(2017) found sufficient matches between the datasets.

In comparison with alternative methods: while rare in Africa, Fourier Transform InfraRed (FTIR) data showed high agreement with GNSS PWV (Mengistu Tsidu et al., 2015), the AMMA project revealed tight concordance between GPS PWV and data from AERONET sun photometers and Special Sensor Microwave/Imager (SSM/I) sensors (Bock et al., 2007a); the GOMESCIA program groups the IWV data from three European satellites (GOME, SCIA-MACHY, GOME-2) between 1995 and 2015, harmonized to offer a monthly global coverage with a resolution of $1^\circ \times 1^\circ$. The agreements found between the GNSS IWV and GOMESCIA data are strong in Africa and similar to the results for the European stations in the global study by Van Malderen et al. (2022). However, the consistency remains stronger between GNSS IWV and ERA-Interim than with GNSS IWV and COMESCIA.

The general trend of biases between GNSS PWV and other techniques reveals a larger estimation of the amount of PWV by GNSS, also confirmed for IWV of stations located in coastal and humid climate zones but also in dry climate zones (Abdellaoui et al., 2019). It is noted that the concordances gradually improved during the period covered by this review.

Relationship between water vapor, surface waters and altitude

Abraha et al. (2015) observe a negative correlation between water vapor content and altitude in Ethiopia, with low-altitude coastal stations recording higher IWV averages (30–40 kg/m^2) than high-altitude stations (15–28 kg/m^2) (Figure 8). Similar findings were reported for Egypt by Abdelfatah et al. (2022) using GNSS and RS data for PWV mapping with spatial interpolation. These findings align with the well-established principle that water vapor concentration decreases with altitude, as lower atmospheric layers generally contain more moisture. The resulting maps show that PWVs are higher in coastal areas and areas with high vegetation cover. In Nigeria, a similar spatial-temporal study procedure has shown that, in addition to the agreement between ERA5 PWV and GNSS PWV data in the dry and wet seasons, high PWVs are found in the Mangroves close to the Atlantic Ocean.

Mengistu Tsidu et al. (2015) conclude that the bias increases with altitude relative to ERA and the correlation decreases. Abraha et al. (2015) observe an overestimation of ECMWF IWV over the lowlands and an underestimation over the highlands for wet periods, and an underestimation over the lowlands, and an overestimation over the highlands for dry periods. Below the Equator the long-term variability of PWV appears to be strongly affected by Atlantic sea surface temperature anomalies (Baldysz et al., 2021).

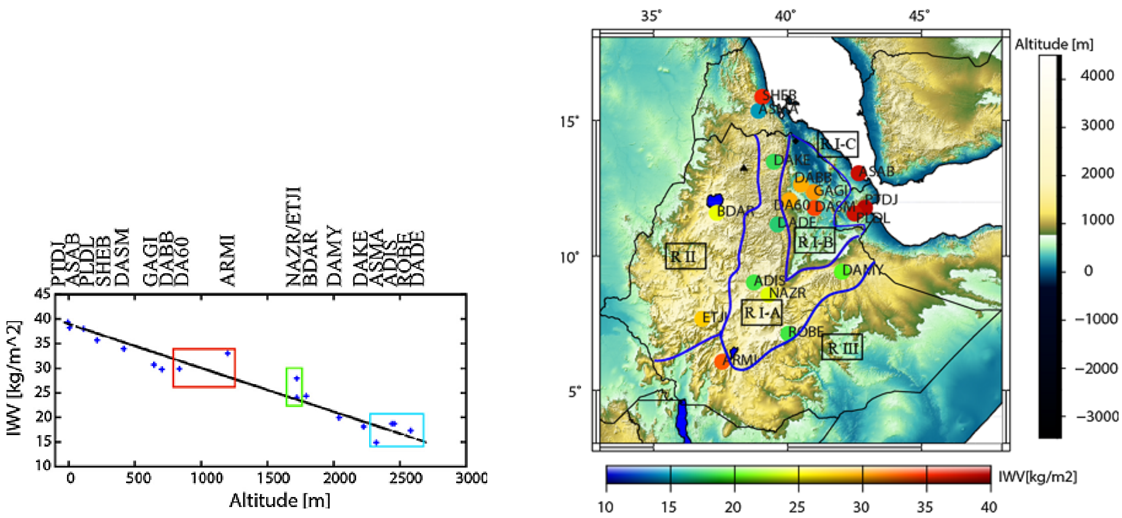
These observations are consistent with the expected distribution of water vapor, driven by altitude and proximity to water bodies or vegetation.

GNSS meteorology in variability studies

Due to its rapid expansion in Africa and its ability to make observations over long periods independently of weather conditions, Ground-Based GNSS are used to study climate variability. The low spatial and temporal resolution of radiosonde observations limits their uses in climate studies. Boutiouta and Lahcene (2013) note that GPS PWV can be used as references in recovering radiosonde humidity errors and biases. There is a consensus that saturation of water vapor in the atmosphere does not necessarily imply precipitation, but that precipitation is the result of a high concentration of water vapor (Abdellaoui et al., 2019; Abraha et al., 2015).

However, there are discrepancies as to the existence of a correlation between water vapor and precipitation. Koji et al. (2022) state that although high integrated water vapor content is observed during periods of heavy precipitation, no remarkable correlation is observed between precipitation and water vapor. Meanwhile, Ssenyunzi et al. (2020) relies on the existence of a temporal auto-correlation between the two sets according to Holloway and Neelin (2010) and its results to assert that PWV variations can be used to predict precipitation. According to Abdellaoui et al. (2019), there is a spatiotemporal correlation between variations in GNSS-derived IWV and rainfall. The relevant analysis of PWV time series alongside rainfall histograms indicates that GNSS-PWV increases several hours before precipitation begins, peaks shortly before rainfall, and then decreases a few hours after the precipitation ends, which confirms the results of the study by Koulali et al. (2012): the minimum PWV occurs after the maximum precipitation. The experiment established negative correlations between GPS PWV and precipitation including the maximum value in absolute value. Their study carried out in Morocco identified a positive correlation between daily variations of PWV and monthly average precipitationm which confirms that heavy precipitation is related to large fluctuations in PWV due to the passage of weather systems, such as: mesoscale convective systems, fronts, and cyclones.

In equatorial stations, Bock et al. (2007b) observed a double peak of PWV in April-May and October-November, corresponding to the passage of the Intertropical Convergence Zone (ITCZ) and influenced by the El Niño Southern Oscillation. Like Bock et al. (2007b); Abraha et al. (2015) also find peaks in inter-annual variability during dry seasons for all stations and offer a similar explanation: the presence of these peaks could be due to interferences between dry



(a) (b)

Figure 8. a) Yearly averaged IWV values for 2010 as a function of altitude; b) Yearly averaged IWV content values for 2010 on topography map (Source: Abraha et al. (2015))

and humid air and by rainy episodes during dry months.

A consensus is emerging in the work of Bawa et al. (2022) and other authors that seasonal variability is a function of geographic latitude and climatic zone. From GPS IWV, a very high diurnal cycle was observed at stations located in an area with high evapotranspiration and in areas with very high temperature (Abraha et al., 2015). Peak times differ across locations in Africa. This is explained by local breeze factors and oceanic and continental processes (Bock et al., 2007b).

The research highlights the importance of monitoring water vapor variability from GNSS stations located in Africa combined with other techniques. This would allow for a better understanding of the impacts on global circulations and climate change in mid-latitudes. Seasonal variations in PWV in West Africa have helped characterize the African Monsoon System, which greatly impacts precipitation (Bock et al., 2008). Combinations of ECMWF and GNSS data are recommended as they agree on long time scales. However, Bock et al. (2010); Mengistu Tsidu et al. (2015) report that the reanalysis data exhibit a time shift on the PWV peaks, which could compromise their combinations in studies of diurnal cycles. Bock et al. (2007b) previously found that the PWV ERA40's representation of the diurnal cycle was not accurate. This is related to the weaknesses of the water cycle in global circulation models.

In East Africa, GNSS PWVs are consistent in seasonal variability studies. Time series of PWVs obtained in the 3 climatic zones of Ethiopia with low temperature variations. This division based on the rainfall cycle, linked to the north-south movements of the ITCZ is consistent with the seasonal variations of GNSS PWV (Koji et al., 2022). The presence of a diurnal cycle has been demonstrated in Ethiopia (Koji et al., 2022; Mengistu Tsidu et al., 2015), however there is a disparity in the amplitudes of the diurnal cycles between the stations. Stations close to water bodies and dense vegetation present strong amplitudes influenced by surface evaporation. The subdaily variations of the RMSE observed between GNSS and ERA5 data appear weaker than the diurnal variations, suggesting an increased stability on short time scales. This observation is consistent with the results of Bawa et al. (2022), which also noted similar differences in the daily variations.

The linear trends between GNSS IWV and ERA-Interim are positive and concordant for the African stations (R^2~0.66) of the study (Van Malderen et al., 2022). The average amplitude of the decadal trend is around 0.26 mm. Autoregression models have been shown to be effective for PW prediction (Acheampong and Obeng, 2019).

The authors conclude from their results that GNSS data offer a great opportunity to study multi-scale interactions in particular (Baldysz et al., 2021; Bock et al., 2007a, 2008), which is of particular interest in the study of atmospheric processes.

4.3 Limitations and possible future research directions

Research perspectives emerge from the analysis of key articles: water vapor quantity estimates from GNSS offer low-cost monitoring with high temporal resolution but lack vertical resolution (Boutiouta and Lahcene, 2013). In Africa, some of the selected studies present disparities in the periods of GNSS observations which can introduce temporal biases linked to the seasons but also compromise the robustness of the analyses of long-term trends.

Limitations of the techniques developed with African ground stations in the retrieval of atmospheric water vapor raised in the relevant literature include: the lack of detailed information on the vertical profile and the validity of the information on a spatial radius centered on the antenna, which necessitates densifying GNSS networks in order to experiment with 3D Tomography, although there are some studies of retrievals from a single station (Barriot et al., 2021; Bi et al., 2006). For island areas where the implementation of dense networks is complex, tomography with a single GNSS ground station could be tested. Further research is recommended to detect threshold effects at the spatial-temporal scale that suggest that above an IWV level precipitation will be triggered (Abdellaoui et al., 2019).

According to Koji et al. (2022) the low distribution of GNSS stations in mountainous areas, such as the Great Ethiopian Rift, as well as the lack of observed meteorological and climatic data remain limitations of the analysis of certain areas. The authors recommend the addition of meteorological sensors at the level of GNSS stations which would facilitate the conversion of ZTD into IWV but also the multiplication of GNSS stations. A resolution of 1° in the horizontal plane (about 110 km) of the GNSS network for monitoring atmospheric water vapor has been considered in Ghana (Acheampong et al., 2015). The potential of CORS stations for water vapor observations in Africa remains largely underexploited. To maximise the use of CORS stations in Africa, it is essential to exploit not only Real-Time Kinematic (RTK) data but also recorded static data and to promote the exchange of the latter, which would allow for better integration into water vapor analysis and other atmospheric applications.

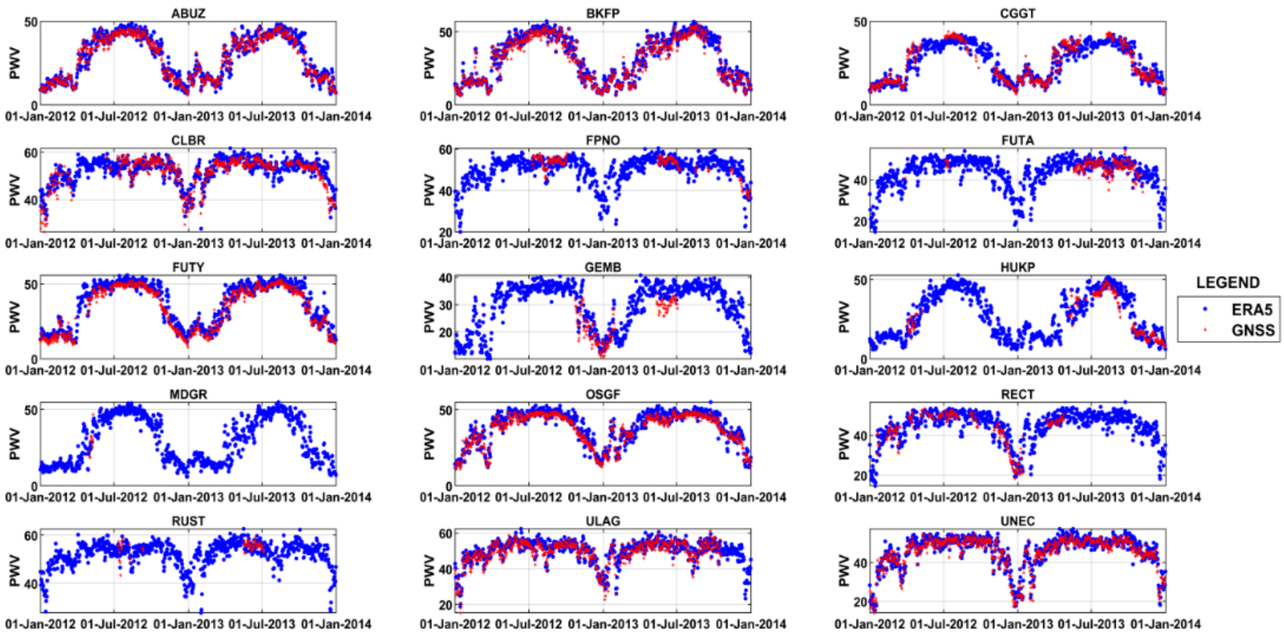


Figure 9. Diurnal variation of PWV derived from GNSS and ERA5 during the period 2012–2013 (units are in mm or kg/m^2) (Bawa et al., 2022)

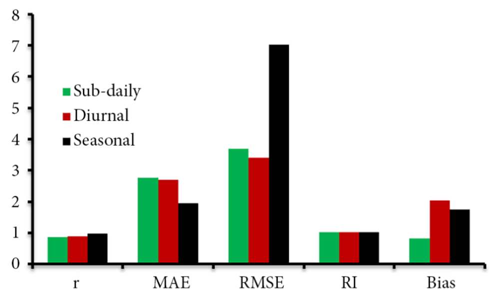


Figure 10. Aggregated performance indices. Five statistical metrics were utilized to assess the performance of the two GNSS and ERA5 datasets: mean absolute error (MAE), root mean square error (RMSE), reliability index (RI), correlation coefficient (r) (Bawa et al., 2022)

Decadal trends from African land stations are poorly studied, largely due to the lack of sufficiently long and uninterrupted data. 38 years would be needed to detect the decadal trend, according to Weatherhead et al. (1998). For example, stations set up by the AMMA Project no longer exist or have not been replaced. To estimate trends, it is essential that GNSS IWV time series are obtained using uniform parameters, in order to ensure data homogeneity over long periods. Additional resources will be needed for the inclusion of accurate meteorological data and the development of powerful calculation tools in the water vapor reconstruction procedure. Isioye et al. (2017) proposes the combination of ERA-Interim and GNSS data to calibrate each other. However, the recent study of Bawa et al. (2022) as well as the comparison results raised in Figures 9 and 10 indicate the usefulness of the extraction of ERA5 data for the reconstruction of water vapor by GNSS in the absence of meteorological sensors linked to African GNSS stations. Future research should place a more significant emphasis on improving T_m modeling in tropical Africa. Additionally, developing robust linear T_m/T_s relationships is crucial, given the disparity of conversion methods between ZTD and water vapor.

RS are limited in the ability to study large-scale interactions, particularly in the tropics, where the main mode of variability is the diurnal cycle (Baranowski et al., 2019). It would be important to favor GNSS for the study of diurnal cycles in addition to RS.

In recent years, Africa has been faced with catastrophic floods, causing thousands of deaths, millions of displacements and considerable socio-economic losses (WHO, 2024). This shows the urgent need to strengthen nowcasting capabilities in Africa. However, the integration of GNSS products from ground stations into nowcasting is complex and has been dealt with insufficiently in the literature. It would be important to draw inspiration from near-real-time pilot projects (Hadas et al., 2016; Wu et al., 2023; Li et al., 2015, 2021). The analysis of the databases showed the untapped potential of the association with on-board GNSS data for spatial-temporal monitoring of water vapor in African maritime and coastal areas. Recent advances, as described in (Boniface et al., 2012; Bosser and Bock, 2021; Panetier et al., 2023) open the way to a promising synergy between on-board GNSS antennas and their terrestrial counterparts. This combination would allow a more complete understanding of the regional climate, the study of storms and feed reanalysis models and local systems.

The integration of multi-GNSS signals and advancements in real-time GNSS tropospheric retrievals. Hadas et al. (2016); Li et al. (2021); Wu et al. (2023) notice valuable scientific prospects for enhancing nowcasting capabilities. The development of GNSS processing techniques requires an evaluation of the performance of PPP-AR (PPP with Ambiguity Resolution) compared to traditional PPP, particularly in the African context. The adoption of the VMF3 model, which offers superior spatial resolution, coupled with the assimilation of complementary sensor datasets and the implementation of cooperative artificial intelligence frameworks, holds significant potential for capturing fine-scale variations in atmospheric water vapor.

5 Conclusion

This systematic review provides relevant insights into current research on tropospheric water vapor retrieval from Ground-Based GNSS in the African continent and its applications, which help optimize research and ensure the success of initiatives and future research. The study examined various methods of incorporating GNSS data into tropospheric water vapor estimation studies to improve atmospheric research processes, climate modeling efforts and nowcasting. GNSS data offer improved accuracy and temporal resolution compared to traditional approaches, making it an essential low-cost tool for water vapor monitoring in Africa. The African territory is poorly covered by other measurement techniques, such as RS, responsible for gaps in data availability. It has been proven in this SR that WV time series better reflect diurnal cycles and give sufficient agreements with RS and Reanalysis models especially ERA5. It is observed that the agreements between GNSS and RS, Reanalysis and satellite data sets in seasonal and annual cycles improved progressively during the period covered by this review.

Although significant progress has been made in research with African stations, several directions remain to be explored. Despite their potential, the use of GNSS networks in Africa remains limited by uneven geographical coverage and a lack of standardization of methodologies. In addition, indirect techniques require a synergy between precise local meteorological observations and in-depth processing for a wide range of applications. Lack of this synergy is worrying because many African countries urgently need to strengthen their capacities to monitor and analyze atmospheric parameters for applications ranging from meteorology and climatology to the impacts of climate change. To optimize the use of GNSS data, it is essential that scientists, policy makers, and research organizations cooperate to improve access to data, promote the interoperability of GNSS networks and basic meteorological sensors and develop methodological approaches adapted to African climatic specificities. This study provides several suggestions including the use of ERA5 for the extraction of meteorological parameters in the absence of associating sensors with GNSS receivers. Although traditional PPP techniques obtain satisfying results, it is also recommended to experiment with the use of emerging data analysis strategies, such as PPP-AR and PPP-IAR but also the use of the VMF3 model. Convincing experiences in the assimilation of GNSS IWV data into NWP models, the implementation of 3D GNSS Tomography as well as the combination of African ground stations with GNSS shipbornes are insufficient to densify the applications of GNSS water vapor retrieval techniques.

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