



# Three Decades of Precipitable Water Vapour over Poland from GNSS Observations and ERA5 Reanalysis: Trends, Variability and Long-Term Consistency (1996-2026)

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**Abstract.** Atmospheric water vapour is a key greenhouse gas and an important indicator of changes in the hydrological cycle. A three-decade record of GNSS-derived precipitable water vapour (PWV) from five Polish stations of the EUREF Permanent GNSS Network was analysed for the period 1996–2026. The GNSS-derived PWV series were homogenised for documented antenna-configuration changes using ERA5 as a reference and were analysed together with ERA5 PWV. Long-term trends were estimated using harmonic regression with annual and semi-annual components and complemented by non-parametric trend analysis; changes in seasonal amplitude, monthly anomalies, annual PWV maxima, and GNSS–ERA5 consistency were also assessed. Statistically significant positive trends were obtained for the homogenised GNSS series at all five stations, ranging from 0.396 to 0.623 mm decade<sup>−1</sup>, compared with 0.418–0.598 mm decade<sup>−1</sup> for ERA5. At one station, homogenisation changed the estimated GNSS trend from a non-significant 0.200 to a significant 0.424 mm decade<sup>−1</sup>. Over a nominal 30-year interval, the fitted trends corresponded to PWV increases of 1.189–1.868 mm for GNSS and 1.253–1.795 mm for ERA5. Annual-cycle amplitudes increased at all stations, while trends in annual maxima of daily mean PWV exceeded the corresponding annual-mean trends. Monthly GNSS–ERA5 correlations ranged from 0.9991 to 0.9994, with biases of −1.491 to −0.178 mm and RMSE values of 0.292–1.512 mm. No statistically significant linear trend in the monthly GNSS–ERA5 differences was detected at any station. Positive PWV trends were therefore consistently observed across the analysed stations, while the change in the WROC trend after homogenisation showed the sensitivity of long-term GNSS trend estimates to instrumental discontinuities. The multi-year mean monthly MAE peaked in August (1.54 mm), whereas the strongest negative MBE occurred in September (−1.05 mm), indicating a seasonal dependence of GNSS–ERA5 consistency.

## 1 Introduction

Atmospheric water vapour is central to the Earth's radiation balance and hydrological cycle. It contributes substantially to the natural greenhouse effect, and its response to warming provides an important positive climate feedback (Held & Soden, 2000). Precipitable water vapour (PWV), expressed as the equivalent depth of liquid water contained in an atmospheric column, is a convenient measure of atmospheric moisture. Temperature is only part of the control. Moisture availability and



30 atmospheric circulation also shape long-term PWV evolution, so regional changes may depart from the broad thermodynamic expectation of a moister atmosphere in a warmer climate (Parracho et al., 2018). Long records are therefore needed to separate secular change from seasonal and interannual variability.

Ground-based Global Navigation Satellite Systems (GNSS) provide an established way to observe atmospheric water vapour continuously. The basic principle is straightforward: the atmosphere delays satellite signals. Bevis et al. (1992) showed that  
35 this delay can be used to retrieve integrated water vapour (IWV). In GNSS meteorology, zenith total delay (ZTD) is separated into hydrostatic and wet components, and zenith wet delay (ZWD) is converted into PWV using atmospheric temperature information. ZTD, ZWD and PWV are related, but they are not interchangeable. Continuously operating stations provide frequent measurements in clear and cloudy conditions, complementing radiosondes, radiometers and satellite observations. As the records have lengthened, GNSS has developed from a primarily meteorological observing technique  
40 into a source of multi-decadal atmospheric moisture information (Guerova et al., 2016).

Global studies have increasingly relied on reprocessed GNSS products. Parracho et al. (2018) compared GPS-derived IWV with ERA-Interim and MERRA-2 over 1995–2010 and recovered broadly consistent spatial and seasonal structures, but regional differences remained in both trends and variability. Record length, atmospheric dynamics and data inhomogeneities all affected the interpretation of those trends. Using IGS Repro2 products, Su et al. (2021) analysed reprocessed ZWD series  
45 from 320 globally distributed stations over 2002–2012 and compared GPS, GLONASS and combined solutions with ERA5, ERA-Interim, MODIS and AIRS. GPS-derived PWV agreed closely with ERA5 at broad scales, while technique-dependent differences remained visible.

In Europe, the EUREF Permanent GNSS Network (EPN) provides a particularly valuable archive of long-term tropospheric observations. The second EPN reprocessing campaign, EPN-Repro2, produced consistently processed tropospheric estimates  
50 for 1996–2014. Pacione et al. (2017) described the combined product and evaluated it against radiosondes and ERA-Interim, demonstrating its suitability for atmospheric-model assessment and water-vapour studies. European developments were also supported by COST Action ES1206, Advanced GNSS Tropospheric Products for Monitoring Severe Weather Events and Climate (GNSS4SWEC), which ran from 2013 to 2017. The initiative linked the GNSS, meteorological and climate communities and addressed advanced processing, product evaluation and the use of long-term tropospheric records for  
55 climate monitoring (Guerova et al., 2016; Jones et al., 2020).

Reprocessing improves internal consistency, but technical breaks can remain. Baldysz et al. (2016) compared ZTD series from two consecutive EPN reprocessing campaigns and showed that estimated trends depend on both processing strategy and record length. Experiments with 20-year IWV series reached the same general conclusion: long-term parameters are sensitive to GNSS processing choices (Baldysz et al., 2018). Equipment changes add another source of discontinuity.  
60 Antenna or radome replacements and changes in the observing environment may introduce offsets that alter the estimated trend. Nguyen et al. (2021), comparing first- and second-generation IGS reprocessing data, showed that both change-point detection and homogenised trend estimates depend on the GNSS solution, reference reanalysis and time-series properties.



Station metadata and instrumental discontinuities therefore form part of the climate analysis itself, not only of data preprocessing.

65 Reanalysis comparisons address a second question: whether independent observing systems reproduce the same long-term evolution. For continental Europe, Yuan et al. (2021) assessed ERA5 IWV trends against GPS observations over 1994–2019 and showed that the treatment of temporal noise strongly affects trend uncertainty and inter-dataset differences. Yuan et al. (2023) extended the comparison to multiple timescales using observations from 108 European GPS stations over 1994–2018 and six reanalyses. ERA5 generally reproduced the annual cycle and long-term trends better than the other reanalyses, 70 although discrepancies remained at shorter timescales. A high correlation by itself is not enough. Long-term consistency also requires agreement in trend behaviour, seasonal variability and the evolution of inter-dataset differences.

Poland has already been studied with shorter but much denser GNSS records. Araszkiewicz et al. (2021) analysed twelve years of observations from more than one hundred ASG-EUPOS stations over 2009–2020, compared GPS-derived PWV with radiosonde observations and reported an overall positive trend of  $0.078 \text{ mm year}^{-1}$ . The dense network resolved spatial 75 differences associated with maritime and continental influences. A different perspective was obtained from atmospheric modelling. Ojrzyńska et al. (2022) developed a high-resolution PW climatology from WRF simulations for 1983–2010 and evaluated it against radiosondes; seasonally and vertically differentiated changes were found, while the increase in annual PW was not statistically significant. The two studies cover different periods and use different data sources, which makes the longest available GNSS records a useful test of how the inferred signal changes when the observation interval is extended.

80 Dense national networks provide detailed spatial information, but the earliest Polish EPN stations offer something different: time. Their records extend back to the mid-1990s and have not yet been evaluated over their full span. Nearly three decades are now available. This makes it possible to examine long-term PWV change and, separately, to test how documented changes in station equipment affect the inferred climatic signal.

Five long-running EPN stations (BOGO, BOR1, JOZE, LAMA and WROC) are used here to examine PWV variability over 85 Poland during 1996–2026. GNSS-derived PWV is obtained from MUT Analysis Centre tropospheric products combining EPN Repro3 solutions with subsequent routine processing. Before the climate analyses, the series are adjusted for documented antenna, radome and antenna-eccentricity changes using differences relative to ERA5. The analysis covers long-term trends, changes in seasonal amplitude and monthly anomalies, annual maxima of daily mean PWV, and the temporal consistency between GNSS and ERA5. Corrected and uncorrected GNSS trends are compared directly. Because ERA5 is 90 used to estimate the homogenisation offsets, the later GNSS–ERA5 comparison is a consistency assessment rather than an independent validation.



## 2 Methodology

### 2.1 GNSS Dataset

The study was based on GNSS products generated by the Military University of Technology Analysis Centre (MUT AC) within its contribution to the third reprocessing (Repro3) campaign of the EUREF Permanent GNSS Network (EPN) (Bruyninx et al., 2019). The reprocessed dataset covers the period from 1 January 1996 to 27 November 2022 and provides a homogeneous long-term record of tropospheric delay estimates (Völksen et al., 2026). To extend the time series beyond the official EPN Repro3 interval, the reprocessed solutions were complemented with routine MUT AC products covering the period from 28 November 2022 to 30 May 2026. These solutions were generated using the same processing strategy and modelling standards as applied in the reprocessing campaign, ensuring full consistency of the combined dataset. Network processing was carried out using up to 8-16 subnetworks, each comprising approximately 25 stations. The GNSS processing was performed using GAMIT/GLOBK software version 10.71. The analysis included approximately 180 GNSS stations and was based on GPS observations throughout the entire observation period and GPS+Galileo observations from October 2016 onwards. The processing strategy employed the IGS20 antenna calibration model (Rebischung et al., 2022) and the FES2014b ocean tidal loading model (Lyard et al., 2021), while atmospheric tidal loading corrections were not applied. Tropospheric parameters were estimated at hourly intervals. The slant tropospheric delay for an observation at elevation angle ( $e$ ) and azimuth ( $A$ ) was represented by the standard decomposition into hydrostatic, wet, and horizontal-gradient components (Eq. 1):

$$STD(e, A) = m_h(e) \cdot ZHD + m_w(e) \cdot ZWD + m_g(e) \cdot [G_N \cos A + G_E \sin A], \quad (1)$$

where (ZHD) and (ZWD) denote the zenith hydrostatic and zenith wet delays, respectively; ( $G_N$ ) and ( $G_E$ ) are the north–south and east–west horizontal tropospheric gradient components. The hydrostatic and wet mapping functions, ( $m_h$ ) and ( $m_w$ ), respectively, were derived from the Vienna Mapping Function 1 (VMF1), based on ERA-40 and operational ECMWF products (Boehm et al., 2006), whereas the gradient mapping function, ( $m_g$ ), followed the formulation of Chen and Herring (1997). The hydrostatic component was modelled, while the residual wet delay and the north–south and east–west horizontal gradients were estimated within the GNSS adjustment.

For the purposes of this study, five Polish EPN stations characterized by the longest and most complete observation records were selected (Figure 1). Three stations (BOR1, JOZE, and LAMA) provide observations from 1 January 1996 to 30 May 2026, while the records begin on 1 July 1996 at BOGO and on 2 January 1997 at WROC. The resulting dataset spans nearly 30 years (1996-2026), representing the longest continuous GNSS-based record of atmospheric water vapour available in Poland. A uniform processing strategy was used throughout the observation period. Residual discontinuities associated with documented antenna-configuration changes were subsequently addressed through homogenisation of the derived PWV series.



**Figure 1: Locations of the five EPN stations included in the long-term GNSS-ERA5 PWV comparison.**

## 125 2.2 Retrieval of GNSS-Derived Precipitable Water Vapour

Precipitable water vapour (PWV) was derived from GNSS zenith total delay (ZTD) estimates obtained for the analysed EPN stations. To separate the hydrostatic and wet components of the tropospheric delay, meteorological parameters from the ERA5-Land reanalysis (Muñoz-Sabater et al., 2021) were incorporated into the processing workflow. Hourly surface pressure and 2-m air temperature were extracted at each station location. Surface pressure was used to calculate the zenith hydrostatic delay (ZHD) using the Saastamoinen model, while 2-m air temperature was used to estimate the weighted mean atmospheric temperature ( $T_m$ ) required for the conversion of zenith wet delay (ZWD) into PWV (Bevis et al., 1994). The wet delay was obtained as shown in Eq. (2).

$$ZWD = ZTD - ZHD, \quad (2)$$

and subsequently converted to PWV according to Eq. (3).

$$135 \quad GNSS \, PWV = \Pi(T_m) \cdot ZWD, \quad (3)$$

where  $\Pi(T_m)$  denotes the temperature-dependent conversion factor. Formal PWV uncertainties were propagated from the uncertainties of the original GNSS ZTD estimates.

Reference PWV estimates were obtained from the ERA5 reanalysis. Hourly Total Column Water Vapour fields from the ERA5 single-level product (Hersbach et al., 2020) were downloaded for a domain covering Poland and interpolated to the coordinates of each GNSS station using bilinear interpolation. The resulting ERA5 PWV values were collocated with the GNSS observations and used for both homogenisation and subsequent consistency assessment.

Before further analysis, GNSS-derived PWV was adjusted for antenna-configuration changes documented in station metadata, including antenna, radome and antenna eccentricity changes (Bruyninx et al., 2019; Fabian et al., 2021).



Homogenisation is important because artificial discontinuities can affect the magnitude and statistical significance of long-term atmospheric moisture trends, even when the underlying GNSS observations have been consistently reprocessed (Ning et al., 2016; Nguyen et al., 2021). Several approaches have been developed to identify and correct these discontinuities. Relative methods analyse differences between GNSS estimates and a reference series: examples include the penalised maximal t test accounting for first-order autoregressive noise (PMTred), applied to GPS–ERA-Interim IWV differences by Ning et al. (2016) and to GPS–ERA5 ZTD differences by Bai et al. (2023). Other approaches use penalised likelihood segmentation with explicit modelling of seasonal biases and monthly varying noise variance (Nguyen et al., 2021). Absolute methods, which operate without an external reference series, have also been proposed for GNSS-derived PWV, including an adaptive procedure combining seasonal–trend decomposition with a penalised maximal F test accounting for red noise (Zhu et al., 2021). Within COST Action ES1206 GNSS4SWEC, a dedicated benchmark evaluated eight break-detection methods using synthetic IWV difference series constructed from the characteristics of GPS and ERA-Interim observations. The experiments demonstrated that homogenisation can reduce errors in estimated trends, although performance depends on noise characteristics, data gaps and the homogeneity of the reference series (Van Malderen et al., 2020). In the present study, correction epochs were prescribed by the documented antenna-configuration changes. Offsets were estimated from the mean ERA5–GNSS PWV differences over complete configuration periods, after iterative  $3\sigma$  filtering performed separately within each period. Earlier GNSS observations were then adjusted so that the mean ERA5–GNSS difference in each eligible period matched that of the most recent configuration period, which remained unchanged. This follows the segment-mean adjustment principle adopted by Van Malderen et al. (2020) and subsequently applied by Nguyen et al. (2021). The impact of antenna changes varied among stations. For example, no antenna changes occurred at BOGO, and therefore no correction was applied to its time series. The largest adjustment was introduced at the WROC station, as illustrated in Figure 2.

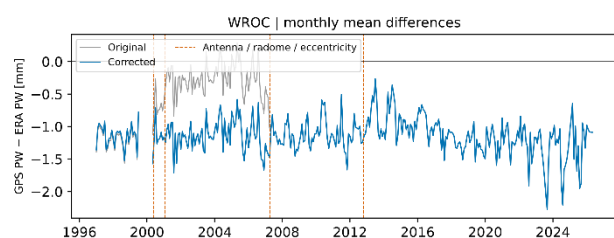


**Figure 2. Monthly mean GNSS–ERA5 PWV differences at WROC before and after homogenisation. Grey and blue lines represent the original and corrected GNSS series, respectively. Vertical dashed lines indicate documented antenna, radome or antenna eccentricity changes.**

The homogenisation procedure aligns period-specific mean GNSS–ERA5 differences with the most recent antenna configuration; it does not force the overall difference to zero. Because that final configuration defines the reference level, correcting a discontinuity can leave the absolute bias, MAE or RMSE unchanged and may even increase these metrics. Agreement after correction is therefore treated as consistency with the homogenisation reference. Offset uncertainties were estimated separately and were not propagated into the subsequent trend confidence intervals.



## 2.3 Trend Analysis

Long-term PWV trends were estimated using a harmonic regression model consisting of a linear trend together with annual and semi-annual seasonal components. This framework separates secular change from periodic variability, an approach also relevant to the analysis of long-term and cyclic environmental changes (Wahl and Plant, 2015). Monthly PWV values were calculated from daily means and retained when at least 70% of calendar days contained valid observations. Statistical significance and 95% confidence intervals were assessed using heteroskedasticity- and autocorrelation-consistent (HAC) standard errors based on the Newey–West covariance estimator (Newey and West, 1987), with 12 monthly lags. Accounting for serial correlation in this way follows applications of robust uncertainty estimation in environmental and geodetic time-series analyses (Waring et al., 2023; Lee et al., 2026). As an additional methodological comparison, monthly climatological means were removed from the homogenised GNSS and ERA5 series to obtain anomaly records. These anomalies were analysed using the Mann–Kendall trend test (Mann, 1945) and Sen’s slope estimator (Sen, 1968), providing non-parametric measures of trend significance and magnitude. This combination is widely used for long-term trend assessment in atmospheric and climatological time series (Gocic and Trajkovic, 2013; Collaud Coen et al., 2020), including analyses of precipitable water vapour derived from radiosonde, GNSS/GPS, and satellite observations (Wong et al., 2015).

## 2.4 Seasonal Variability and Anomalies

Seasonal behaviour was characterised using the annual and semi-annual harmonic components derived from the regression model. Assessing changes in these components complements the analysis of mean conditions by identifying changes in the seasonal cycle, as illustrated for other environmental time series by Wahl and Plant (2015). Harmonic amplitudes were estimated within moving 10-year windows advanced in one-year steps. Changes in amplitude were quantified as the fitted linear slope multiplied by the time span between the first and last available window centres. Monthly anomaly series were further used to assess PWV variability through centred 5-year and 10-year rolling standard deviations. These measures describe changes in variability around the monthly climatology, separately from changes in the amplitude of the mean seasonal cycle.

## 2.5 Extreme Events and GNSS-ERA Consistency

Changes in extreme atmospheric moisture conditions were evaluated using annual maximum PWV values. Annual maxima were calculated from daily mean PWV for years with at least 75% valid daily coverage, and their trends were compared with trends in annual mean PWV. Monthly GNSS–ERA5 consistency was evaluated using Pearson correlation, bias, MAE and RMSE. Trends in the paired monthly difference series, defined as  $\Delta\text{PWV} = \text{PWV\_GNSS} - \text{PWV\_ERA5}$ , were estimated using harmonic regression. A non-significant trend was classified as no statistically detectable linear drift at the 5% level. It was not treated as evidence of equivalence or complete temporal stability.



To examine the seasonal structure of the differences, monthly MBE and MAE were additionally calculated from paired hourly GNSS–ERA5 PWV differences. Before–after comparisons used identical epochs retained by the common monthly  $3\sigma$  filtering mask, and station-months required at least 15 days of observations. Monthly network values were obtained by equally weighting the available stations; the multi-year seasonal curves then equally weighted the available years for each calendar month. These within-month error measures were distinguished from the consistency statistics calculated between monthly mean PWV values.

### 3 Results

#### 3.1 Trend Analysis

The homogenised GNSS-derived PWV series exhibited statistically significant positive trends at all five analysed stations (HAC-adjusted  $p < 0.001$  for all stations). The largest increase was observed at BOGO ( $0.623 \text{ mm decade}^{-1}$ ), followed by JOZE ( $0.572 \text{ mm decade}^{-1}$ ), BOR1 ( $0.492 \text{ mm decade}^{-1}$ ), WROC ( $0.424 \text{ mm decade}^{-1}$ ), and LAMA ( $0.396 \text{ mm decade}^{-1}$ ) (Figure 3).

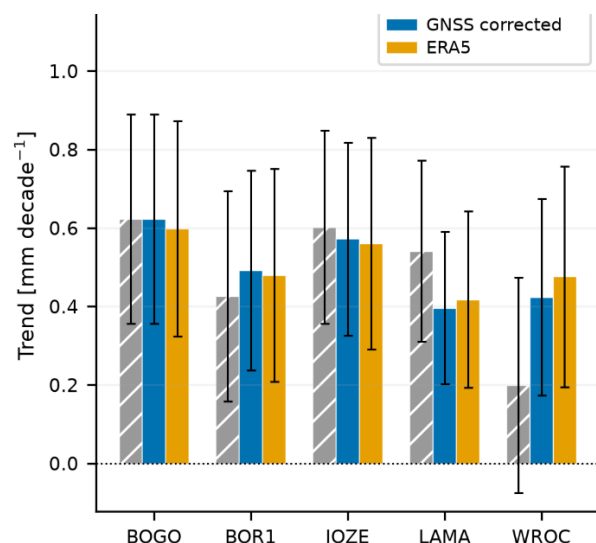


**Figure 3. Long-term PWV trends at the five EPN stations from GNSS observations before homogenisation (GNSS uncorrected), after correction for antenna, radome and eccentricity changes (GNSS corrected), and from ERA5. Bars represent linear trends estimated from monthly mean PWV using regression with annual and semi-annual harmonic terms. Error bars indicate 95% confidence intervals calculated using HAC/Newey–West covariance with 12 monthly lags.**

Removing discontinuities had the strongest effect at WROC, where the GNSS trend increased from  $0.200 \text{ mm decade}^{-1}$  in the uncorrected series (95% confidence interval [CI]:  $-0.075$  to  $0.474$ ;  $p = 0.154$ ) to  $0.424 \text{ mm decade}^{-1}$  after homogenisation (95% CI:  $0.173$  to  $0.674$ ;  $p < 0.001$ ). At BOR1, the trend increased from  $0.426$  to  $0.492 \text{ mm decade}^{-1}$ , whereas at JOZE and LAMA it decreased from  $0.602$  to  $0.572$  and from  $0.541$  to  $0.396 \text{ mm decade}^{-1}$ , respectively. No homogenisation was applied at BOGO, for which the estimated trend was  $0.623 \text{ mm decade}^{-1}$ . At WROC, the correction



225 affected both the magnitude and statistical significance of the estimated trend. ERA5 exhibited significant positive trends at all stations, ranging from  $0.418 \text{ mm decade}^{-1}$  at LAMA to  $0.598 \text{ mm decade}^{-1}$  at BOGO.

The Mann–Kendall test applied to monthly climatological anomalies indicated significant positive trends at all five stations in both datasets ( $p < 0.001$ ). GNSS Sen’s slopes ranged from  $0.414 \text{ mm decade}^{-1}$  at LAMA to  $0.626 \text{ mm decade}^{-1}$  at BOGO, while ERA5 estimates ranged from  $0.432$  to  $0.589 \text{ mm decade}^{-1}$ . Both methods produced similar positive trend estimates  
 230 (Figure 4).

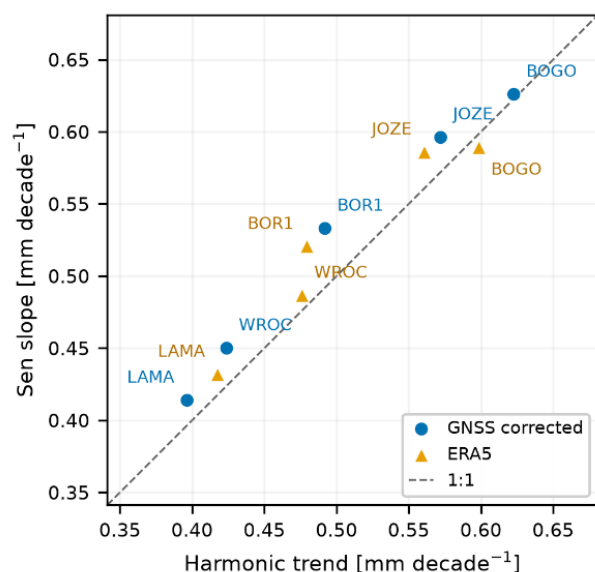
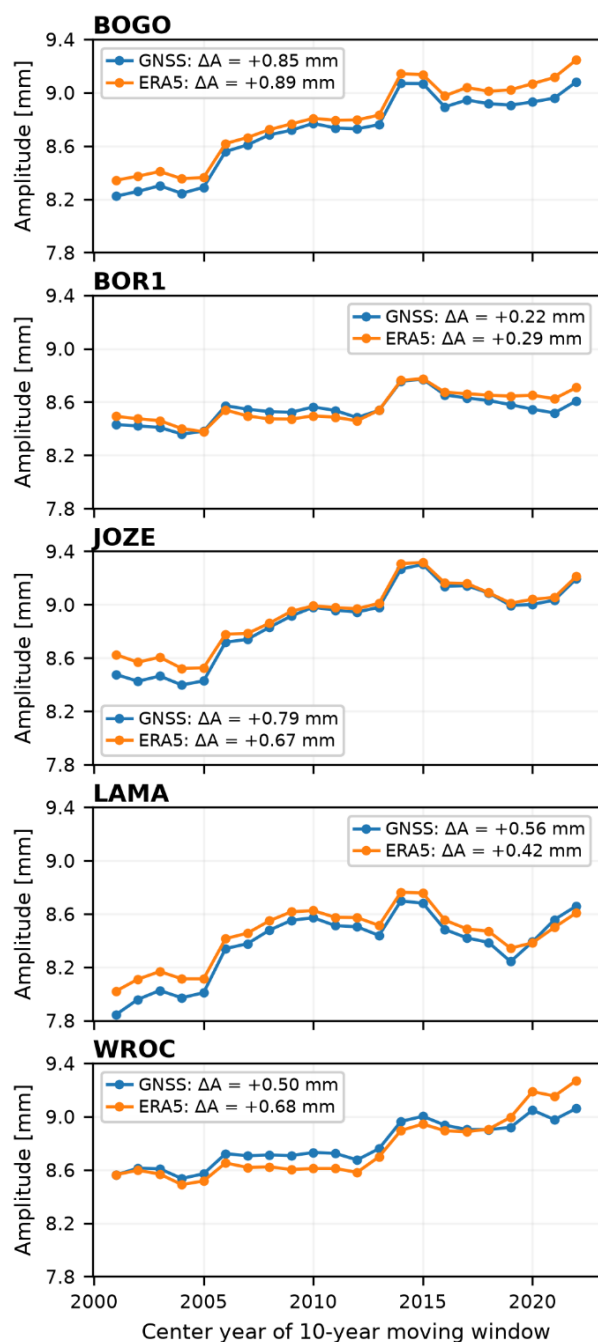


**Figure 4: Comparison of long-term PWV trends estimated using harmonic regression and the non-parametric Sen’s slope estimator for GNSS and ERA5 data at the five analysed stations.**

Expressed over a nominal 30-year interval, the fitted harmonic trends correspond to PWV increases of 1.189–1.868 mm for  
 235 GNSS and 1.253–1.795 mm for ERA5. The largest increases occurred at BOGO and the smallest at LAMA in both datasets. At WROC, the corresponding increases were 1.271 mm for GNSS and 1.428 mm for ERA5.

### 3.2 Seasonal Variability and Anomalies

The analysis of moving-window harmonic amplitudes indicated increases in the amplitude of the annual PWV cycle at all stations, although their magnitude varied considerably. The largest fitted increase occurred at BOGO, reaching 0.846 mm for  
 240 GNSS and 0.889 mm for ERA5 over the available window-centre interval. At JOZE, the corresponding increases were 0.790 and 0.667 mm, compared with 0.502 and 0.683 mm at WROC. LAMA exhibited increases of 0.561 and 0.415 mm, while BOR1 showed the smallest changes, at 0.220 and 0.290 mm (Figure 5). Semi-annual amplitudes also increased, with fitted changes ranging from 0.191 to 0.489 mm for GNSS and from 0.257 to 0.528 mm for ERA5. These values represent trend-based changes over the available moving-window interval, with window centres spanning 2001–2022.



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**Figure 5.** Evolution of the annual PWV harmonic amplitude estimated in 10-year moving windows advanced in one-year steps, for homogenised GNSS and ERA5 series at the five stations. Estimates are plotted at the corresponding window centres.



Rising annual amplitudes show that atmospheric moisture increased not only on average but also in terms of seasonal contrast. Summers became progressively more moisture-rich relative to winters. The estimated amplitude changes were positive in both datasets at every station, although differences in magnitude remained.

Monthly PWV anomalies exhibited pronounced interannual variability, with alternating positive and negative departures from the monthly climatology. The homogenised GNSS series closely followed the ERA5 anomaly evolution at all five stations, including WROC. Its corrected GNSS trend was statistically significant, at  $0.424 \text{ mm decade}^{-1}$ , and the monthly GNSS–ERA5 difference trend was not significant at the 5% level ( $p = 0.087$ ). The centred 12-month running means show a similar interannual structure in both datasets (Figure 6).

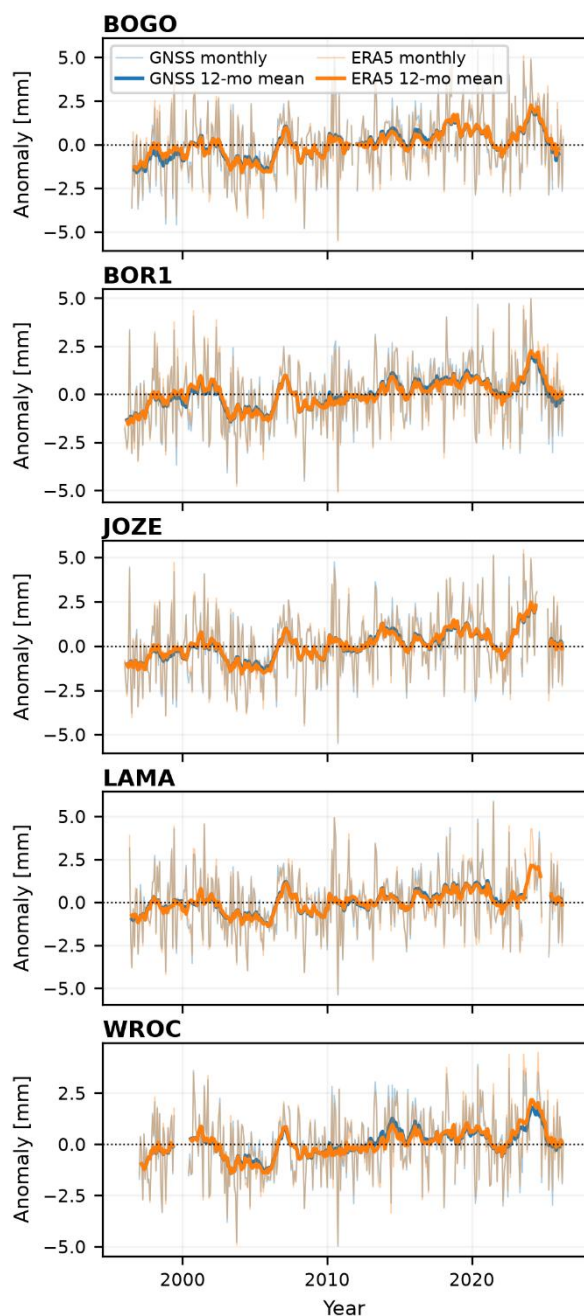


**Figure 6: Monthly PWV anomalies for GNSS and ERA5 at BOGO, BOR1, JOZE, LAMA, and WROC. Anomalies are defined relative to the long-term mean of the corresponding calendar month, thereby removing the mean seasonal cycle. Thin lines denote individual monthly anomalies, whereas thick lines show the centered 12-month running mean, emphasizing interannual variations and persistent wetter- or drier-than-average periods.**



Negative PWV anomalies were prominent during 2003–2006. The interval began with the exceptional European heatwave and drought of 2003, when prolonged precipitation deficits and below-average relative humidity affected large parts of western and central Europe (Rebetez et al., 2006). The negative PWV signal persisted for several years after 2003, so that  
265 event alone cannot account for the full 2003–2006 interval. Around 2007 the smoothed records changed sign for a shorter period, with a positive anomaly visible across the station network.

Positive anomalies were more common in the later part of the record, especially during 2018–2020 and 2023–2024. The shift was not monotonic; near-zero and negative anomalies still occurred after 2015. Over the same broader period, Poland experienced increasing temperatures and changes in hot-day and heatwave occurrence (Wibig, 2021).

270 The strongest recent positive PWV episode occurred during 2023–2024, alongside exceptionally warm conditions in Poland and Europe. The Polish Institute of Meteorology and Water Management – National Research Institute reported 2024 as the warmest year in Poland’s instrumental record (Poland climate reports), while the European State of the Climate assessment identified 2024 as the warmest year on record for Europe (C3S and WMO, 2025). By 2025 the positive PWV signal had weakened at several stations. That year was still classified as very warm but dry in the national climate assessment (Poland  
275 climate reports). The contrast is useful: temperature and atmospheric moisture did not evolve in lockstep.

The coherent timing of PWV anomalies across the five stations points to a substantial regional component of atmospheric moisture variability. Their long-term evolution also overlaps with the broader warming observed in Poland, where the increase in annual mean air temperature since 1951 exceeds 2°C (Poland climate reports). The temporal correspondence is descriptive, not causal. Attribution of individual PWV anomalies to temperature, drought or atmospheric circulation would  
280 require a separate analysis. The close similarity between homogenised GNSS and ERA5 anomalies is also partly constrained using ERA5 to estimate the instrumental offsets.

No significant trend in the 5-year rolling standard deviation of monthly anomalies was found at any station in either dataset. For the 10-year measure, WROC showed a positive GNSS trend of 0.052 mm decade<sup>-1</sup> ( $p = 0.010$ ), while the corresponding ERA5 trend of 0.067 mm decade<sup>-1</sup> remained just above the 5% significance threshold ( $p = 0.054$ ). Overlapping windows  
285 introduce serial dependence that was not modelled explicitly in this regression. The 10-year WROC estimate is therefore less secure than the main HAC-based trend results.

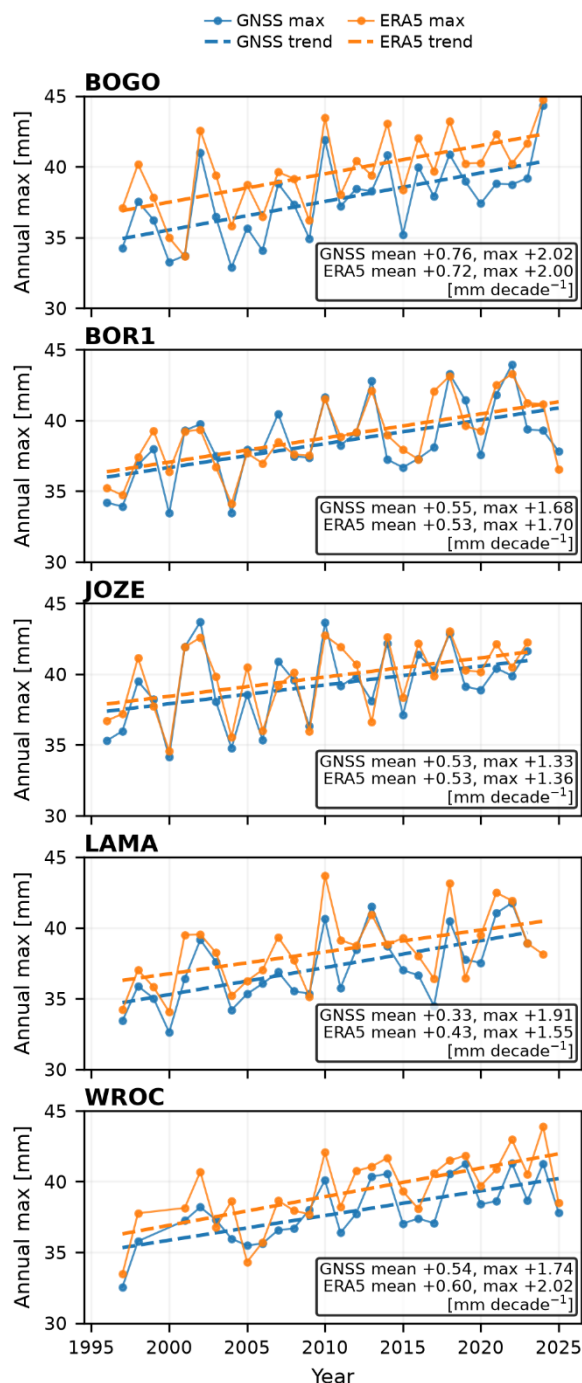
### 3.3 Extreme Events and GNSS-ERA Consistency

Significant positive trends in annual maximum of daily PWV were detected at all five stations in both datasets (Figure 7). For the homogenised GNSS series, trends ranged from 1.328 mm decade<sup>-1</sup> at JOZE to 2.016 mm decade<sup>-1</sup> at BOGO. The  
290 corresponding ERA5 trends ranged from 1.357 mm decade<sup>-1</sup> at JOZE to 2.021 mm decade<sup>-1</sup> at WROC. Relatively large GNSS increases were also observed at LAMA and WROC, reaching 1.906 and 1.743 mm decade<sup>-1</sup>, respectively.

The estimated annual-maximum trends exceeded the corresponding annual-mean trends by factors of approximately 2.5–5.8 for GNSS and 2.6–3.6 for ERA5. These comparisons use annual maxima and annual means calculated from the daily PWV series, rather than the monthly harmonic-regression trends reported in Section 3.1. The separation is substantial. It suggests



295 that the upper end of daily PWV changed faster than the annual background state. The difference between maximum and mean trends was not subjected to a separate significance test, and the PWV analysis alone cannot establish a change in precipitation extremes.



300 **Figure 7:** Annual maximum PWV values and fitted trends for GNSS and ERA5 at the five analysed stations. Solid lines with markers show annual maxima, whereas dashed lines represent their linear trends. The inset in each panel compares trends in annual mean and annual maximum PWV for GNSS and ERA5. Larger trends in annual maxima than in annual means indicate a stronger long-term increase in extreme moisture conditions than in the background mean PWV.



Monthly homogenised GNSS and ERA5 PWV exhibited close agreement at all stations (Figure 8). Pearson correlation coefficients ranged from 0.9991 to 0.9994, while mean GNSS–ERA5 biases ranged from  $-1.491$  mm at BOGO to  $-0.178$  mm at JOZE. MAE values ranged from 0.234 to 1.491 mm, and RMSE ranged from 0.292 mm at JOZE to 1.512 mm at BOGO. The consistently negative biases indicate that homogenised GNSS-derived PWV remained lower than ERA5 PWV on average. These statistics demonstrate close agreement in monthly variability alongside persistent station-dependent mean offsets. Because ERA5 was used to estimate the homogenisation corrections, the resulting agreement represents consistency with the reference dataset rather than independent validation of absolute accuracy.

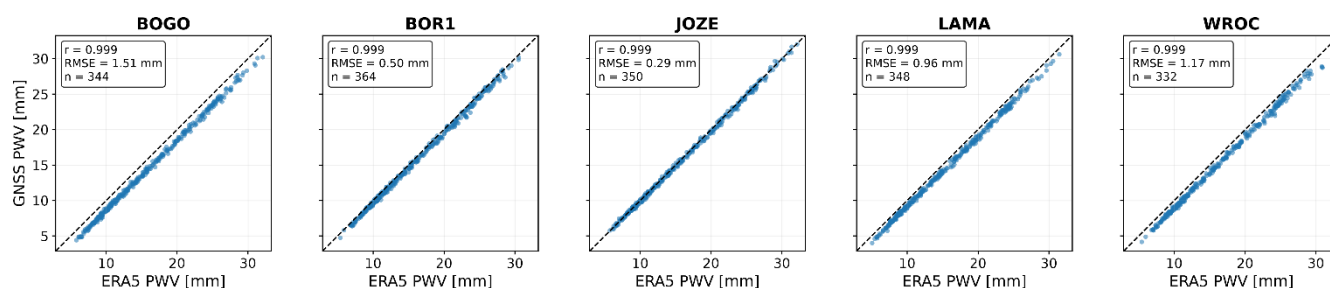


**Figure 8: Comparison of monthly GNSS-derived and ERA5 PWV for the five analysed stations. Each panel shows paired monthly mean PWV values, with ERA5 on the x-axis and GNSS on the y-axis. The dashed line represents perfect 1:1 agreement. Pearson correlation coefficient ( $r$ ), root-mean-square error (RMSE), and the number of paired monthly observations ( $n$ ) are reported separately for each station. Overall correlation and RMSE calculated from the pooled observations of all stations are given below the panels.**

No statistically significant linear trend in the monthly GNSS–ERA5 difference series was detected at any station at the 5% significance level (Figure 9). Estimated  $\Delta$ PWV trends were  $0.026$  mm decade $^{-1}$  at BOGO ( $p = 0.529$ ),  $0.013$  mm decade $^{-1}$  at BOR1 ( $p = 0.754$ ),  $0.011$  mm decade $^{-1}$  at JOZE ( $p = 0.570$ ),  $0.033$  mm decade $^{-1}$  at LAMA ( $p = 0.063$ ), and  $-0.052$  mm decade $^{-1}$  at WROC ( $p = 0.087$ ).

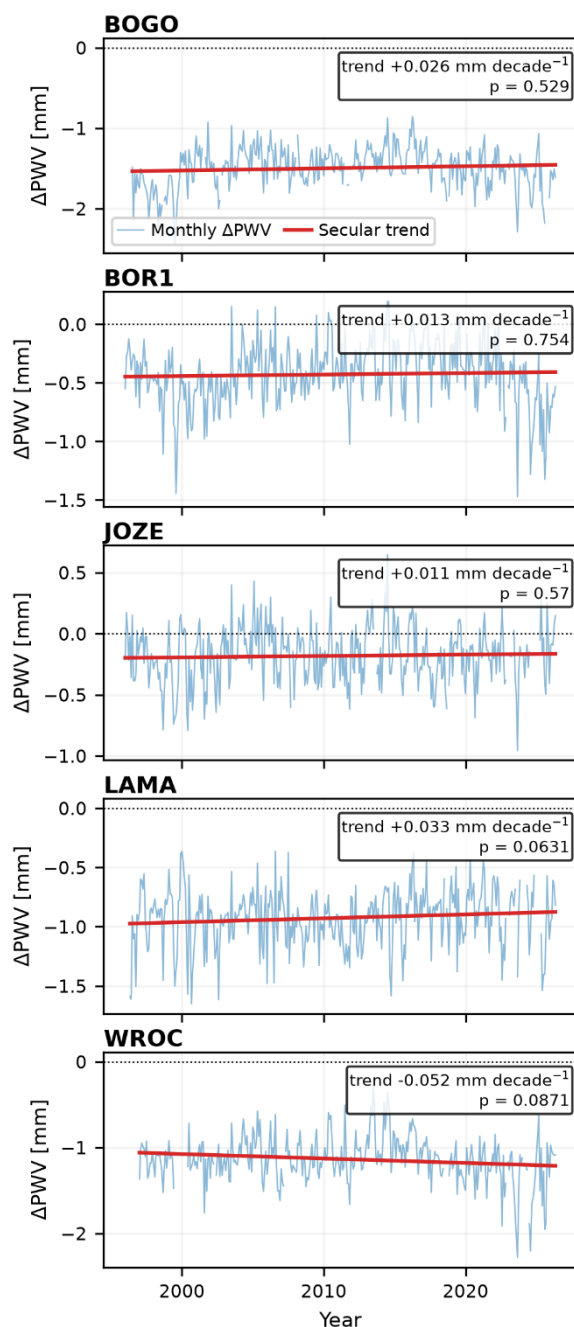


**Figure 9: Temporal evolution of the monthly PWV differences between GNSS and ERA5 for the five analysed stations. Blue lines represent monthly mean differences, while red lines indicate the secular component derived from the harmonic regression model. The estimated long-term trend in  $\Delta PWV$  and its p-value are reported for each station.**

325 The monthly error curves revealed a pronounced seasonal structure (Figure 10). The multi-year mean MAE increased from 0.90 mm in February to 1.54 mm in August. MBE remained negative throughout the mean seasonal cycle, ranging from



–0.68 mm in April to –1.05 mm in September. Thus, the largest absolute discrepancies occurred in late summer, while the strongest systematic underestimation of GNSS PWV relative to ERA5 occurred one month later. The warm-season enhancement may reflect greater atmospheric moisture variability and differences in representativeness between station observations and gridded reanalysis, consistent with the European assessment of Yuan et al. (2023). Among individual year–month values, the highest post-homogenisation network MAE occurred in August 2024 (1.97 mm), whereas the most negative MBE occurred in September 2023 (–1.68 mm). These maxima coincided with the broader positive PWV anomaly episode described in Section 3.2, but do not by themselves establish a causal relationship. The August 2024 estimate included four stations, compared with five in September 2023.

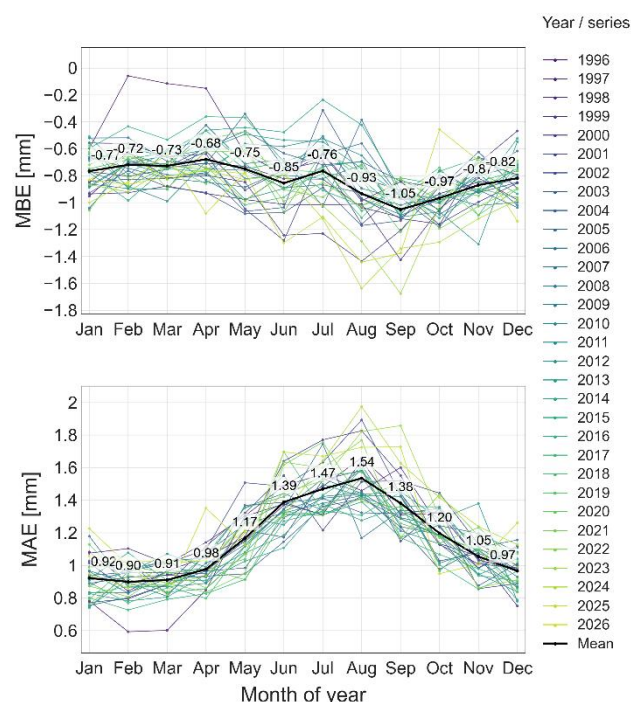


**Figure 10: Monthly mean bias error (MBE; upper panel) and mean absolute error (MAE; lower panel) of GNSS-derived precipitable water vapour relative to ERA5. Coloured lines represent individual years; the black line shows the multi-year mean for each calendar month.**

The WROC diagnostics separate two different effects of homogenisation. On identical valid epochs before monthly aggregation, the standard deviation of GNSS–ERA5 differences decreased from 1.205 to 1.148 mm. At the same time, the mean difference shifted from –0.942 to –1.139 mm, MAE increased from 1.226 to 1.328 mm, and RMSE increased from 1.530 to 1.617 mm. This follows directly from aligning earlier antenna-configuration periods with the most recent period, whose mean ERA5–GNSS difference is retained. Homogenisation reduced dispersion associated with station changes even though the absolute reference offset became larger.



## 345 4 Conclusions

GNSS-derived PWV increased significantly at all five analysed EPN stations over 1996–2026. Harmonic-regression trends ranged from 0.396 to 0.623 mm decade<sup>-1</sup>, compared with 0.418–0.598 mm decade<sup>-1</sup> for ERA5. Sen’s slope estimates were similar, and the Mann–Kendall test indicated positive trends in both datasets. The similar estimates obtained from both methods, together with the positive trend at every station, point to a regional long-term increase in atmospheric moisture.  
 350 Five stations cannot represent the full spatial variability of PWV across Poland, but a station-specific artefact is unlikely to explain a signal observed at every station and in the reanalysis.

The magnitude of the trends obtained in this study is smaller than the 0.078 mm year<sup>-1</sup> reported by Araszkiewicz et al. (2021) for the ASG-EUPOS network over 2009–2020. The earlier analysis covered a 12-year period, whereas the present study spans approximately 30 years, from 1996 to 2026. The length of the analysed time series can affect the estimated  
 355 magnitude of long-term tropospheric trends (Baldysz et al., 2015), while differences in GNSS processing strategy may also influence the resulting estimates (Baldysz et al., 2016). The present analysis is based on the EPN Repro3 solution, in which historical GNSS observations were reprocessed using updated models and a consistent processing strategy. The longer time span and the close agreement between the trends derived independently from GNSS and ERA5 support the reliability of the trend estimates obtained in this work.

360 The influence of instrumental discontinuities was strongly station dependent. WROC provides the clearest example: homogenisation increased the estimated trend from a non-significant 0.200 to a significant 0.424 mm decade<sup>-1</sup>. At JOZE and LAMA, by contrast, the corrections reduced the estimated trends, while BOGO required no homogenisation. The effect of homogenisation was therefore clearly station dependent. The observed differences follow the individual histories of the stations and are consistent with the sensitivity of long-term GNSS atmospheric parameters to processing strategy and  
 365 instrumental changes reported in previous studies. Among the analysed stations, WROC demonstrates that the effect of homogenisation can be large enough not only to modify a trend estimate but also to change its statistical interpretation. For long climate records, station metadata are consequently part of the measurement record rather than merely supplementary information.

The changes were not restricted to mean PWV. Annual-cycle amplitudes increased at all stations, and positive anomalies  
 370 occurred more frequently during the later part of the record. Annual maxima of daily mean PWV also increased substantially, with trends of 1.328–2.016 mm decade<sup>-1</sup> for GNSS and 1.357–2.021 mm decade<sup>-1</sup> for ERA5. These slopes exceeded the corresponding annual-mean trends. At the same time, no significant network-wide trend was detected in the 5-year rolling standard deviation of monthly anomalies. The main long-term change was an increase in atmospheric moisture, accompanied by a stronger seasonal cycle. The upper range of daily PWV also increased faster than the mean, while short-  
 375 term anomaly variability showed no comparable network-wide change.

An interesting aspect of the results is the faster increase in annual PWV maxima. This suggests that the most moisture-rich atmospheric conditions have changed more rapidly than the annual background state. The result cannot by itself be translated



into changes in heavy precipitation, because precipitation depends not only on atmospheric moisture availability but also on circulation, vertical motion and thermodynamic conditions. Establishing whether the observed increase in high-PWV conditions is associated with changes in precipitation extremes would therefore require an analysis combining the present PWV records with precipitation and circulation data.

GNSS and ERA5 showed very similar temporal behaviour. Monthly correlations ranged from 0.9991 to 0.9994, and no significant linear drift was detected in the monthly GNSS–ERA5 differences. Persistent station-dependent offsets remained, however. Agreement also varied seasonally, with the largest mean MAE in August and the strongest negative bias in September. Homogenisation increased MAE and absolute bias in the network seasonal averages, illustrating that alignment to the latest antenna configuration improves continuity without necessarily improving absolute agreement with ERA5. In addition, ERA5 was used as the reference for estimating the homogenisation corrections. The comparison should therefore be regarded as evidence of temporal consistency rather than as an independent validation of absolute GNSS PWV accuracy. The WROC results illustrate this distinction particularly well: homogenisation reduced discontinuities in the record without necessarily reducing its mean offset relative to ERA5.

The station-specific findings on long-term PWV trends, seasonal amplitude changes, anomaly variability, annual maxima and GNSS–ERA5 consistency are summarised in Table 1.

**Table 1. Summary of the principal findings for the five analysed EPN stations of the GNSS-derived PWV series.**

| Station     | PWV trend, mm decade <sup>-1</sup> | Annual amplitude change, mm | Anomaly variability          | Annual-max trend, mm decade <sup>-1</sup> | Monthly GNSS–ERA5 drift |
|-------------|------------------------------------|-----------------------------|------------------------------|-------------------------------------------|-------------------------|
| <b>BOGO</b> | 0.623                              | +0.846                      | No significant 5-year trend  | 2.016                                     | Not significant         |
| <b>BOR1</b> | 0.493                              | +0.220                      | No significant 5-year trend  | 1.684                                     | Not significant         |
| <b>JOZE</b> | 0.572                              | +0.790                      | No significant 5-year trend  | 1.328                                     | Not significant         |
| <b>LAMA</b> | 0.396                              | +0.561                      | No significant 5-year trend  | 1.906                                     | Not significant         |
| <b>WROC</b> | 0.424                              | +0.502                      | No significant 5-year trend; | 1.743                                     | Not significant         |

Overall, the three-decade records show a consistent increase in atmospheric moisture over Poland, accompanied by changes in the seasonal cycle and stronger increases in the highest daily mean PWV values. The results also demonstrate that trend estimates from long GNSS series can be materially affected by documented changes in the observing system. Long-running GNSS stations therefore provide valuable information for regional climate studies, but their use requires consistent processing, detailed station metadata and explicit treatment of instrumental discontinuities. The next step should be to extend the analysis to a denser station network and to combine PWV observations with temperature, precipitation and circulation datasets in order to better identify the spatial structure and physical drivers of the observed changes.



## Appendix A

**Table A1. Long-term PWV trends derived from GNSS observations and ERA5. Trends and Sen's slopes are expressed in mm decade<sup>-1</sup>; changes are expressed in mm. Thirty-year changes were calculated by multiplying the fitted harmonic trend by a nominal 30-year interval. GNSS results refer to homogenised series.**

| Station     | GNSS Trend | ERA5 Trend | GNSS Sen Slope | ERA5 Sen Slope | GNSS 30-year change | ERA5 30-year change |
|-------------|------------|------------|----------------|----------------|---------------------|---------------------|
| <b>BOGO</b> | 0.623      | 0.626      | 0.626          | 0.589          | 1.868               | 1.797               |
| <b>BOR1</b> | 0.492      | 0.479      | 0.533          | 0.521          | 1.476               | 1.438               |
| <b>JOZE</b> | 0.572      | 0.561      | 0.596          | 0.586          | 1.716               | 1.683               |
| <b>LAMA</b> | 0.396      | 0.418      | 0.414          | 0.432          | 1.189               | 1.253               |
| <b>WROC</b> | 0.424      | 0.476      | 0.450          | 0.487          | 1.272               | 1.428               |

**Table A2. Long-term changes in seasonal characteristics and variability. All changes are expressed in mm and were calculated as the fitted linear slope multiplied by the available time span of the corresponding estimates. Amplitude changes refer to 10-year moving windows with centres spanning 2001–2022. Variability changes refer to the available span of annual averages of the 5-year rolling standard deviation of monthly anomalies.**

| Station     | GNSS Annual Amplitude Change | ERA5 Annual Amplitude Change | GNSS Semi-Annual Change | ERA5 Semi-Annual Change | GNSS 5-year Variability Change | ERA5 5-year Variability Change |
|-------------|------------------------------|------------------------------|-------------------------|-------------------------|--------------------------------|--------------------------------|
| <b>BOGO</b> | 0.846                        | 0.889                        | 0.489                   | 0.528                   | 0.094                          | 0.142                          |
| <b>BOR1</b> | 0.220                        | 0.290                        | 0.255                   | 0.274                   | -0.027                         | -0.034                         |
| <b>JOZE</b> | 0.790                        | 0.667                        | 0.265                   | 0.293                   | 0.092                          | 0.075                          |
| <b>LAMA</b> | 0.561                        | 0.415                        | 0.266                   | 0.289                   | -0.040                         | 0.077                          |
| <b>WROC</b> | 0.502                        | 0.683                        | 0.191                   | 0.257                   | 0.103                          | 0.157                          |

**Table A3. Extreme PWV events and GNSS-ERA5 consistency. Trends are expressed in mm decade<sup>-1</sup>. Annual maxima are derived from daily mean PWV. Correlation, bias, MAE, RMSE and ΔPWV trends refer to paired monthly values. GNSS results refer to homogenised series.**

| Station     | GNSS Annual-Max Trend | ERA5 Annual-Max Trend | ΔPWV Trend (GNSS–ERA5) | r      | Bias (mm) | MAE (mm) | RMSE (mm) |
|-------------|-----------------------|-----------------------|------------------------|--------|-----------|----------|-----------|
| <b>BOGO</b> | 2.016***              | 2.002***              | 0.026 ns               | 0.9993 | -1.491    | 1.491    | 1.513     |
| <b>BOR1</b> | 1.684***              | 1.705***              | 0.013 ns               | 0.9991 | -0.426    | 0.434    | 0.504     |



|             |          |          |           |        |        |       |       |
|-------------|----------|----------|-----------|--------|--------|-------|-------|
| <b>JOZE</b> | 1.328**  | 1.357**  | 0.011 ns  | 0.9994 | -0.178 | 0.234 | 0.292 |
| <b>LAMA</b> | 1.906*** | 1.547**  | 0.033 ns  | 0.9993 | -0.927 | 0.927 | 0.960 |
| <b>WROC</b> | 1.743*** | 2.021*** | -0.052 ns | 0.9991 | -1.135 | 1.135 | 1.167 |

*ns:  $p \geq 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$*

## 415 Data availability

Zenith path delay (ZPD) products are publicly available from the EPN Regional Data Centre hosted by the Bundesamt für Kartographie und Geodäsie (BKG) at [https://igs.bkg.bund.de/root\\_ftp/EUREF/products/](https://igs.bkg.bund.de/root_ftp/EUREF/products/). The products used in this study followed the naming patterns /GPSW/MUT0EPNE03\*\*\*.TRO.gz and /GPSW/MUT0EPNFIN\*\*\*.TRO.gz for the EPN Repro3 and operational solutions, respectively.

420 ERA5 and ERA5-Land data were accessed through the Copernicus Climate Data Store (CDS). Hourly surface pressure and 2-m air temperature were obtained from the ERA5-Land time-series dataset, while hourly Total Column Water Vapour (TCWV) fields were obtained from the ERA5 single-level reanalysis. ERA5-Land data were retrieved for the individual GNSS station locations, whereas ERA5 TCWV fields were downloaded for a domain covering Poland and subsequently interpolated to the station coordinates. All ERA5 and ERA5-Land data used in this study are publicly available through the  
 425 Copernicus Climate Data Store.

## Competing interests

The author declares no conflicts of interest.

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#### **Review statement**

445 The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

#### **References**

- Araszkiewicz, A., Kiliszek, D., Mierzwia, M., Nowak Da Costa, J., and Szolucha, M. (2021). GPS-based multi-temporal variation in precipitable water over the territory of Poland. *Remote Sensing*, 13(15), Article 2960.  
450 <https://doi.org/10.3390/rs13152960>.
- Bai, J., Lou, Y., Zhang, W., Zhou, Y., Zhang, Z., Shi, C., and Liu, J. (2023). Impact analysis of processing strategies for long-term GPS zenith tropospheric delay (ZTD). *Atmospheric Measurement Techniques*, 16(21), 5249–5259.  
<https://doi.org/10.5194/amt-16-5249-2023>.
- Baldysz, Z., Nykiel, G., Figurski, M., Szafrank, K., and Kroszczyński, K. (2015). Investigation of the 16-year and 18-year  
455 ZTD time series derived from GPS data processing. *Acta Geophysica*, 63(4), 1103–1125. <https://doi.org/10.1515/acgeo-2015-0033>.
- Baldysz, Z., Nykiel, G., Araszkiewicz, A., Figurski, M., and Szafrank, K. (2016). Comparison of GPS tropospheric delays derived from two consecutive EPN reprocessing campaigns from the point of view of climate monitoring. *Atmospheric Measurement Techniques*, 9(9), 4861–4877. <https://doi.org/10.5194/amt-9-4861-2016>.
- 460 Baldysz, Z., Nykiel, G., Figurski, M., and Araszkiewicz, A. (2018). Assessment of the impact of GNSS processing strategies on the long-term parameters of 20 years IWB time series. *Remote Sensing*, 10(4), Article 496.  
<https://doi.org/10.3390/rs10040496>.



- Bevis, M., Businger, S., Herring, T. A., Rocken, C., Anthes, R. A., and Ware, R. H. (1992). GPS meteorology: Remote sensing of atmospheric water vapor using the global positioning system. *Journal of Geophysical Research: Atmospheres*, 97(D14), 15787–15801. <https://doi.org/10.1029/92JD01517>.
- Bevis, M., Businger, S., Chiswell, S., Herring, T. A., Anthes, R. A., Rocken, C., & Ware, R. H. (1994). GPS meteorology: Mapping zenith wet delays onto precipitable water. *Journal of Applied Meteorology*, 33(3), 379–386. [https://doi.org/10.1175/1520-0450\(1994\)033%3C0379:GMMZWD%3E2.0.CO;2](https://doi.org/10.1175/1520-0450(1994)033%3C0379:GMMZWD%3E2.0.CO;2)
- Boehm, J., B. Werl, and H. Schuh (2006), Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data, *J. Geophys. Res.*, 111, B02406, <https://doi.org/10.1029/2005JB003629>.
- Bruyninx, C., Legrand, J., Fabian, A., Pottiaux E., GNSS metadata and data validation in the EUREF Permanent Network, *GPS Solut* (2019) 23: 106. <https://doi.org/10.1007/s10291-019-0880-9>.
- Chen, G., and T. A. Herring (1997), Effects of atmospheric azimuthal asymmetry on the analysis of space geodetic data, *J. Geophys. Res.*, 102(B9), 20489–20502, <https://doi.org/10.1029/97JB01739>.
- Collaud Coen, M., Andrews, E., Bigi, A., Martucci, G., Romanens, G., Vogt, F. P. A., and Vuilleumier, L. (2020). Effects of the prewhitening method, the time granularity, and the time segmentation on the Mann–Kendall trend detection and the associated Sen's slope. *Atmospheric Measurement Techniques*, 13, 6945–6964. <https://doi.org/10.5194/amt-13-6945-2020>.
- Copernicus Climate Change Service (C3S) and World Meteorological Organization (WMO): European State of the Climate 2024: Temperature, 2025, <https://climate.copernicus.eu/esotc/2024/temperature>.
- Fabian, A., Bruyninx, C., Miglio, A., Legrand, J. (2021): M3G - Metadata Management and Distribution System for Multiple GNSS Networks, <https://doi.org/10.24414/ROB-GNSS-M3G>.
- Gocic, M., and Trajkovic, S. (2013). Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. *Global and Planetary Change*, 100, 172–182. <https://doi.org/10.1016/j.gloplacha.2012.10.014>.
- Guerova, G., Jones, J., Douša, J., Dick, G., de Haan, S., Pottiaux, E., Bock, O., Pacione, R., Elgered, G., Vedel, H., & Bender, M. (2016). Review of the state of the art and future prospects of the ground-based GNSS meteorology in Europe. *Atmospheric Measurement Techniques*, 9(11), 5385–5406. <https://doi.org/10.5194/amt-9-5385-2016>.
- Held, I. M., & Soden, B. J. (2000). Water vapor feedback and global warming. *Annual Review of Energy and the Environment*, 25, 441–475. <https://doi.org/10.1146/annurev.energy.25.1.441>.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>.
- Poland climate reports. Institute of Meteorology and Water Management – National Research Institute. <https://imgw.pl/en/edukacja/raporty-klimatyczne-dla-polski/>, last access: 10 September, 2026.



- 495 Jones, J., Guerova, G., Douša, J., Dick, G., de Haan, S., Pottiaux, E., Bock, O., Pacione, R., & van Malderen, R. (Eds.). (2020). Advanced GNSS tropospheric products for monitoring severe weather events and climate: COST Action ES1206 final action dissemination report. Springer. <https://doi.org/10.1007/978-3-030-13901-8>.
- Lee S-J, Kim J-S, Yun H-S. GNSS Determination of Vertical Movements from Ocean Tide Loading at Palmido, Korea's Largest Tidal Range Site. *Applied Sciences*. 2026; 16(1):32. <https://doi.org/10.3390/app16010032>.
- 500 Lyard, F. H., Allain, D. J., Cancet, M., Carrère, L., and Picot, N. (2021). FES2014 global ocean tide atlas: design and performance, *Ocean Sci.*, 17, 615–649, <https://doi.org/10.5194/os-17-615-2021>.
- Mann, H. B. (1945). Nonparametric Tests Against Trend. *Econometrica*, 13(3), 245–259. <https://doi.org/10.2307/1907187>.
- Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., et al. (2021). ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, 13, 4349-4383.
- 505 <https://doi.org/10.5194/essd-13-4349-2021>.
- Newey, Whitney K & West, Kenneth D, 1987. "A Simple, Positive Semi-definite, Heteroskedasticity and Autocorrelation Consistent Covariance Matrix," *Econometrica*, Econometric Society, vol. 55(3), pages 703-708, May. <https://doi.org/10.2307/1913610/>.
- Nguyen, K. N., Quarello, A., Bock, O., & Lebarbier, E. (2021). Sensitivity of change-point detection and trend estimates to
- 510 GNSS IWV time series properties. *Atmosphere*, 12(9), Article 1102. <https://doi.org/10.3390/atmos12091102>.
- Ning, T., Wickert, J., Deng, Z., Heise, S., Dick, G., Vey, S., & Schöne, T. (2016). Homogenized time series of the atmospheric water vapor content obtained from the GNSS reprocessed data. *Journal of Climate*, 29(7), 2443–2456. <https://doi.org/10.1175/JCLI-D-15-0158.1>.
- Ojrzyska, H., Błaś, M., & Kryza, M. (2022). Precipitable water content climatology over Poland. *Atmosphere*, 13(6),
- 515 Article 988. <https://doi.org/10.3390/atmos13060988>.
- Pacione, R., Araszkiewicz, A., Brockmann, E., & Dousa, J. (2017). EPN-Repro2: A reference GNSS tropospheric data set over Europe. *Atmospheric Measurement Techniques*, 10(5), 1689–1705. <https://doi.org/10.5194/amt-10-1689-2017>.
- Parracho, A. C., Bock, O., & Bastin, S. (2018). Global IWV trends and variability in atmospheric reanalyses and GPS observations. *Atmospheric Chemistry and Physics*, 18(21), 16213–16237. <https://doi.org/10.5194/acp-18-16213-2018>.
- 520 Rebetez, M., Mayer, H., Dupont, O., Schindler, D., Gartner, K., Kropp, J. P., & Menzel, A. (2006). Heat and drought 2003 in Europe: A climate synthesis. *Annals of Forest Science*, 63(6), 569–577. <https://doi.org/10.1051/forest:2006043>.
- Rebischung, P., Villiger, A., Masoumi, S., & Herring, T. (2022). Upcoming switch to IGS20/igs20.atx and repro3 standards (IGSMail-8238). International GNSS Service. <https://lists.igs.org/pipermail/igsmail/2022/008234.html>, last access: 16 September 2026.
- 525 Sen, P. K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association*, 63(324), 1379–1389. <https://doi.org/10.1080/01621459.1968.10480934>.



- Su, H., Yang, T., Wang, K., Sun, B., & Yang, X. (2021). Evaluation of precipitable water vapor retrieval from homogeneously reprocessed long-term GNSS tropospheric zenith wet delay, and multi-technique. *Remote Sensing*, 13(21), Article 4490. <https://doi.org/10.3390/rs13214490>.
- 530 Van Malderen, R., Pottiaux, E., Klos, A., Domonkos, P., Elias, M., Ning, T., Bock, O., Guijarro, J., Alshawaf, F., Hoseini, M., Quarello, A., Lebarbier, E., Chimani, B., Tornatore, V., Zengin Kazancı, S., & Bogusz, J. (2020). Homogenizing GPS integrated water vapor time series: Benchmarking break detection methods on synthetic data sets. *Earth and Space Science*, 7(5), Article e2020EA001121. <https://doi.org/10.1029/2020EA001121>.
- Völksen, C. et al. (2026). EPN-Repro3: Improved Maintenance of Regional Reference Frames Through Standardized and  
 535 Complete Reprocessing of all Available GNSS Data (1996-Present). In: *International Association of Geodesy Symposia*. Springer, Berlin, Heidelberg. [https://doi.org/10.1007/1345\\_2026\\_371](https://doi.org/10.1007/1345_2026_371).
- Wahl, T. and NG Plant (2015), Changes in erosion and flooding risk due to long-term and cyclic oceanographic trends. *Geophys. Res. Lett.*, 42, 2943–2950. <https://doi.org/10.1002/2015GL063876>.
- Waring, A. M., Ghent, D., Perry, M., Anand, J. S., Veal, K. L., & Remedios, J. (2023). Regional climate trend analyses for  
 540 Aqua MODIS land surface temperatures. *International Journal of Remote Sensing*, 44(16), 4989–5032. <https://doi.org/10.1080/01431161.2023.2240522>.
- Wibig, J. (2021). Hot Days and Heat Waves in Poland in the Period 1951–2019 and the Circulation Factors Favoring the Most Extreme of Them. *Atmosphere*, 12(3), 340. <https://doi.org/10.3390/atmos12030340>.
- Wong, M. S., Jin, X., Liu, Z., Nichol, J., and Chan, P. W. (2015). Multi-sensors study of precipitable water vapour over  
 545 mainland China. *International Journal of Climatology*, 35, 3146–3159. <https://doi.org/10.1002/joc.4199>.
- Yuan, P., Hunegnaw, A., Alshawaf, F., Awange, J., Klos, A., Teferle, F. N., & Kutterer, H. (2021). Feasibility of ERA5 integrated water vapor trends for climate change analysis in continental Europe: An evaluation with GPS (1994–2019) by considering statistical significance. *Remote Sensing of Environment*, 260, Article 112416. <https://doi.org/10.1016/j.rse.2021.112416>.
- 550 Yuan, P., Van Malderen, R., Yin, X., Vogelmann, H., Jiang, W., Awange, J., Heck, B., & Kutterer, H. (2023). Characterisations of Europe’s integrated water vapour and assessments of atmospheric reanalyses using more than 2 decades of ground-based GPS. *Atmospheric Chemistry and Physics*, 23(6), 3517–3541. <https://doi.org/10.5194/acp-23-3517-2023>.
- Zhu, D., Zhang, K., Shen, Z., Wu, S., Liu, Z., & Tong, L. (2021). A new adaptive absolute method for homogenizing GNSS-derived precipitable water vapor time series. *Earth and Space Science*, 8(7), Article e2021EA001716.  
 555 <https://doi.org/10.1029/2021EA001716>.