

Article

Constellation-Dependent GNSS PWV Retrieval Under Humid Conditions in Beijing

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Abstract

Noncollocation can obscure small constellation-dependent differences in Global Navigation Satellite System (GNSS) precipitable water vapor (PWV). We assessed five constellation configurations processed with a common precise point positioning strategy at the same four physical station groups surrounding the Beijing radiosonde site during June–September 2023–2025. In the original year-specific matched samples, BeiDou Navigation Satellite System (BDS)-only Root Mean Square Error (RMSE) was 1.3%, 5.4%, and 7.9% lower than GPS-only RMSE in 2023, 2024, and 2025, respectively. Because these percentages were descriptive, we added a direct paired analysis on strict-common samples ($n = 225, 231$, and 216). Paired BDS-minus-GPS RMSE differences were -0.19 mm (95% CI: -0.41 to -0.03), -0.39 mm (-0.61 to -0.16), and -0.44 mm (-0.65 to -0.23), respectively. Fixed-geometry nearest-station, alternative inverse-distance weighting, and elevation-sensitive tests showed that the small constellation difference was not invariant to spatial transfer. Residuals became progressively more negative with increasing radiosonde PWV, and high-moisture (>50 mm) biases were -10.75 mm for BDS and -11.36 mm for GPS. Full-season leave-one-year-out PWV percentile achieved Area Under Curve (AUC) = 0.846, but its transferred threshold yielded False Alarm Ratio (FAR) = 92.2% and Critical Success Index (CSI) = 7.6%. The common five-configuration processing provides a controlled comparison; the rainfall result supports retrospective regional moisture monitoring, not stand-alone operational prediction.

Keywords: GNSS meteorology; BeiDou Navigation Satellite System; precipitable water vapor; spatial representativeness; inverse-distance weighting; block bootstrap; leave-one-year-out evaluation; radiosonde



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1. Introduction

Atmospheric water vapor controls important aspects of cloud formation, precipitation development, and lower-atmospheric energy exchange. Precipitable water vapor (PWV) is the equivalent depth of liquid water obtained by vertically integrating water vapor through an atmospheric column. Radiosondes provide vertical thermodynamic profiles but, with routine twice-daily sampling, cannot resolve rapid moisture variability. Ground-based Global Navigation Satellite System (GNSS) observations complement radiosondes by providing continuous, all-weather estimates of zenith total delay (ZTD), from which zenith wet delay (ZWD) and PWV can be derived [1,2].

GNSS-derived PWV has been used to examine moisture transport, rainfall evolution, and short-term precipitation occurrence. Applications have been reported across a range of climatic settings [3–11]. Many studies report an increase in PWV before or during rainfall and a decrease as the atmospheric column dries. This temporal correspondence is useful for process monitoring; however, high PWV is not sufficient for convection, and PWV alone does not establish forecast skill. Rainfall-oriented applications require both accurate retrieval and explicit characterization of errors at the humid end of the PWV distribution.

Ground-based GNSS meteorology was initially developed using the Global Positioning System (GPS), and many established PWV studies remain GPS-based [1,8,9]. Multi-GNSS processing can improve satellite availability, observation geometry, and solution robustness [12–14]. Following the completion of the BeiDou Navigation Satellite System (BDS)-3 constellation, the independent meteorological performance of BDS warrants evaluation against GPS and combined solutions. Existing BDS studies have often focused on precise point positioning B2b (PPP-B2b) services or have embedded BDS in multi-system comparisons [15–18]. Stand-alone BDS-only PWV performance remains less well-constrained than combined-system performance, particularly under very humid conditions.

This study assesses five constellation configurations processed under a common strategy during the Beijing flood seasons of 2023–2025. The objectives are to (1) retain the original five-configuration comparison under identical PPP processing; (2) quantify BDS–GPS differences with a direct paired analysis on strict-common samples; (3) test whether the small differences persist under fixed-geometry horizontal and elevation-sensitive spatial transfers; (4) characterize the gradual development of negative residuals across the PWV range; and (5) evaluate PWV–rainfall associations over complete June–September seasons using leave-one-year-out construction. Satellite count and Position Dilution of Precision (PDOP) are interpreted descriptively, and neither a causal geometry mechanism nor operational rainfall forecast skill is inferred.

2. Materials and Methods

2.1. Study Area and Observation Network

Beijing lies along the northern margin of the North China Plain (39.4–41.6° N, 115.7–117.4° E), with mountains to the north and west and lower terrain toward the south-east. The analysis was centered on upper-air station 54511 (39.93° N, 116.28° E; 34 m). No continuously operating GNSS receiver was collocated with the radiosonde. The same four physical GNSS station groups (G1–G4) were used throughout 2023–2025. Physical station identity was harmonized by group, and the author-verified 2023–2024 coordinates were applied consistently to all three seasons. Their horizontal distances to station 54511 were 88.2, 146.8, 125.8, and 130.0 km, respectively; station-minus-radiosonde height differences ranged from −15.2 to 1082.6 m (Table 1). Figure 1a shows the fixed regional network, and Figure 1b summarizes the common processing and regional cross-site comparison workflow. The design is therefore a regional spatial comparison rather than a collocated instrument comparison.

Table 1. GNSS precise point positioning strategy and reproducibility settings.

Item	Setting or Status
Processing strategy	Precise point positioning (PPP)
Constellation configurations	BDS-only; GPS-only; GPS+BDS; GPS+BDS+GLONASS; GPS+BDS+GLONASS+Galileo
Study period	June–September 2023–2025
Physical station geometry	Same four groups G1–G4; author-verified 2023–2024 coordinates used for all seasons
ZTD estimation	Stochastic parameter; 60 min interval; PRIDE input values 0.20 and 0.0004 m

Table 1. Cont.

Item	Setting or Status
PWV conversion	ZTD–ZHD separation; ERA5 t2m; $T_m = 0.72T_s + 70.2$ K
Spatial transfer	Baseline four-station IDW, $w_i = d_i^{-2}$; nearest, IDW $p = 1/3$, and elevation-sensitive tests
Regional comparison benchmark	Station 54511 radiosonde; pressure-space specific-humidity integration; exact nominal-hour match
PPP software and version	PRIDE PPP-AR v3.0
Observation sampling interval	10 s
Orbit and clock products	WUM final (FIN) products
Elevation cutoff angle	7°
Troposphere mapping	Global Mapping Function
Ambiguity resolution	LAMBDA; 15° cutoff; minimum ambiguity duration 600 s
Editing and positioning mode	Strict editing; kinematic positioning
BDS-only satellite setting	BDS-2 and BDS-3 enabled; C01–C05 excluded; C18 and C59–C61 downweighted
Observation noise	Pseudorange: 0.30 m; carrier phase: 0.01 cycle
Tide corrections	Solid Earth tide, ocean loading, and pole tide
Tropospheric gradients	Piecewise constant; 720 min interval; PRIDE input values 0.005 and 0.002 m
ERA5 t2m and sp audit	Nearest 0.25° data; sp file covers 39.0–40.5° N, 115.0–117.0° E and is stored in Pa
Pressure-height limitation	Exact sp grids for G1/G3; G2/G4 outside domain; grid geopotential/elevation unavailable
Analysis QC	Original descriptive metrics retained; strict-common paired samples used for inference
Uncertainty	Paired circular moving-block bootstrap; 14 profiles ≈ 7 days

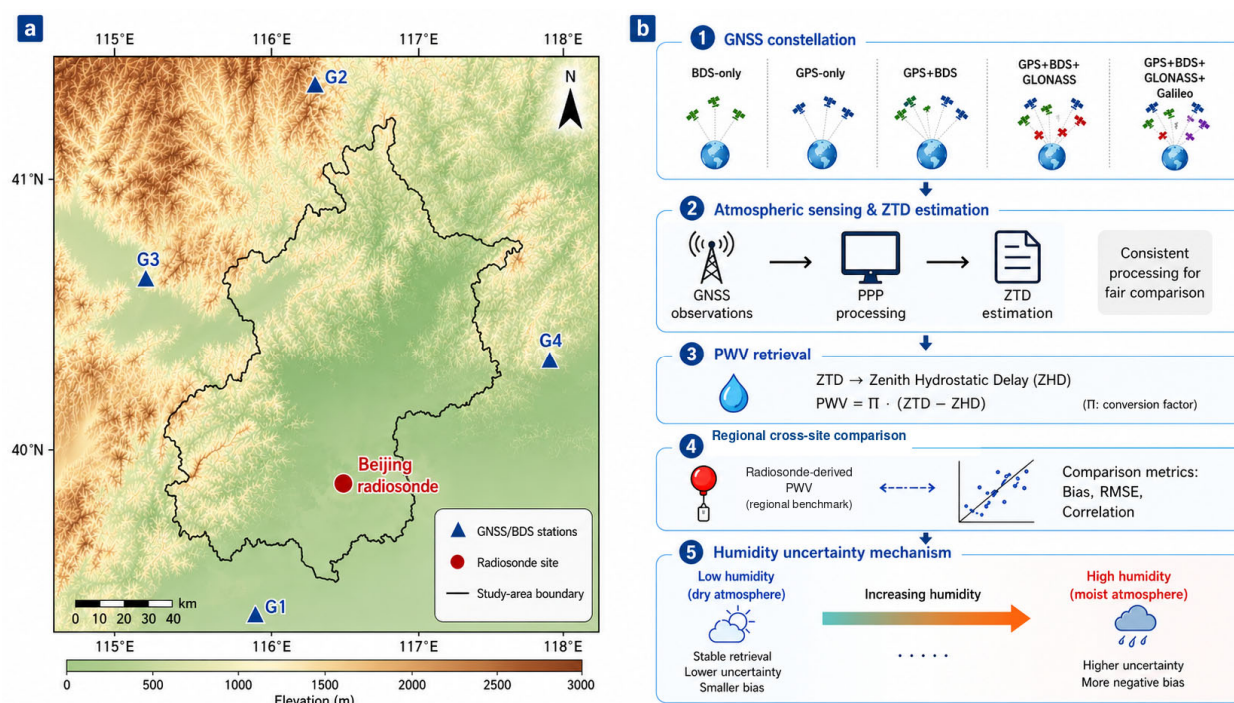


Figure 1. Study area and methodological overview. (a) Locations of the four GNSS station groups (G1–G4) and Beijing radiosonde station 54511; the author-verified 2023–2024 station locations represent all three seasons. (b) Common PPP processing, PWV retrieval, regional cross-site comparison with radiosonde-derived PWV, and moisture-dependence analysis used for the five constellation configurations.

2.2. GNSS Observations and Processing

Dual-frequency carrier-phase and pseudorange observations sampled every 10 s were processed in kinematic mode with PRIDE PPP-AR v3.0 and strict data editing [19]. Five configurations were evaluated: BDS-only, GPS-only, GPS+BDS, GPS+BDS+GLONASS, and GPS+BDS+GLONASS+Galileo. Only the constellation composition differed. The BDS-only solution included BDS-2 and BDS-3, excluded C01–C05, and downweighted C18 and C59–C61 under the original common processing strategy; it was not a BDS-3-only or real-time service. Wuhan University MGEX Analysis Center (WUM) final orbit and clock products distributed through the International GNSS Service were used [20].

The elevation cutoff angle was 7° . Solid-Earth-tide, ocean-tidal-loading, and pole-tide corrections were applied. The second-order ionospheric correction was not applied in the original solutions. Because this omission was common to every configuration and its expected magnitude is small relative to the multi-millimeter PWV residuals, it is unlikely to explain the observed constellation ordering; however, it remains a limitation rather than a proven zero-effect assumption. The complete common PPP strategy and reproducibility settings are summarized in Table 1.

Station PWV was transferred to the radiosonde location using the original baseline inverse-distance weighting (IDW): $PWV_IDW(t) = \sum_i w_i(t)PWV_i(t) / \sum_i w_i(t)$, with $w_i = d_i^{-2}$ and epoch-specific renormalization over available stations. The four distances were fixed to the author-verified 2023–2024 geometry for all seasons. The original year-specific interpolated series were retained for the descriptive five-configuration results. For spatial sensitivity, station-level data were harmonized into the physical groups G1–G4 and rebuilt using the nearest station, IDW powers 1, 2, and 3, and elevation-sensitive transfer [21,22]. For diagnostic sensitivity only, each station PWV series was transformed to the radiosonde height as $PWV_{i,adj} = PWV_i \exp[(h_i - h_0)/H_w]$, with $H_w = 1.5, 2.0$, and 2.5 km [21], before power-2 IDW. These transformed values define uncalibrated sensitivity scenarios; they are not corrected retrievals. Table 2 lists the fixed station geometry and base weights once for each physical station; mean effective BDS weights and availability are reported as 2023/2024/2025 sequences. Complete configuration-specific values are supplied in the Supplementary Data.

Table 2. Fixed GNSS station geometry, baseline IDW weights, BDS effective weights, and availability. Values separated by slashes are ordered as 2023/2024/2025.

Group/Station	Height (m)	Distance (km)	Δh (m)	Base w	Mean Effective w (2023/24/25)	BDS Availability (%) (2023/24/25)
G1/hbdx	18.8	88.2	−15.2	0.432	0.440/0.430/0.319	93.7/98.9/72.2
G2/hbfn	1116.6	146.8	1082.6	0.156	0.157/0.156/0.178	92.8/98.5/92.4
G3/hbxh	844.5	125.8	810.5	0.213	0.217/0.214/0.260	93.9/98.9/99.6
G4/hbxl	385.9	130.0	351.9	0.199	0.186/0.200/0.244	87.3/98.8/99.6

2.3. Radiosonde and Meteorological Data

Radiosonde profiles for station 54511 were obtained from the University of Wyoming Upper-Air Sounding Archive [23]. Routine profiles were labeled at 00:00 and 12:00 UTC; the median first reported level occurred about 44.5 min before the nominal label. GNSS values were matched to the exact nominal UTC hour (0 min label offset). After removal of flagged or physically invalid levels, pressure was sorted monotonically and duplicate pressure levels were removed. Mixing ratio r was converted to specific humidity $q = r/(1 + r)$, and PWV was integrated in pressure coordinates by the trapezoidal rule, $PWV = -(100/g) \int q dp$, with p in hPa and $g = 9.80665 \text{ m s}^{-2}$. Missing humidity levels were omitted; no extrapolation was made above the highest valid level. Profiles had to extend to at least 300 hPa

(i.e., top pressure ≤ 300 hPa). Median top pressures were 137.2, 138.6, and 147.2 hPa in 2023–2025. The raw June–September audit contained 244, 244, and 243 profiles; 238, 233, and 235 passed the final radiosonde-PWV quality controls, and 225, 231, and 216 remained after strict-common-configuration matching. Reintegrated and supplied radiosonde PWV agreed within 0.04 mm RMSE.

ERA5 supplied hourly 2 m air temperature (t2m) for weighted-mean atmospheric temperature estimation and surface pressure (sp) for the pressure-input audit [24,25]. The uploaded sp file contains 553,392 hourly records for June–September 2023–2025 on 63 grid cells (0.25° spacing; 39.0 – 40.5° N, 115.0 – 117.0° E), with sp stored in pascals. Exact grid coordinates were available for G1 and G3, whereas G2 and G4 lie outside the uploaded pressure domain; no spatial extrapolation was performed. The file does not contain ERA5 grid geopotential or surface elevation. Consequently, the grid-to-receiver height difference and a full four-station pressure-height correction cannot be determined from the supplied data. At the two covered station grids, a hydrostatic sensitivity calculation indicates an absolute PWV change of approximately 3.9–4.3 mm per 100 m of assumed height error. This shows that pressure-height mismatch could be material, but its actual sign and contribution to the observed negative bias cannot be established without grid elevation.

Hourly precipitation was obtained from the China Meteorological Administration Land Data Assimilation System version 2.0 (CLDAS-V2.0) forcing product [26]. One fixed 0.0625° cell, centered at 39.90625° N, 116.28125° E, was used for every season and event. Its center is 2.64 km from radiosonde station 54511. CLDAS precipitation was treated as a gridded fusion estimate rather than a collocated rain-gauge observation.

2.4. PWV Retrieval

For each constellation configuration, ZTD was separated into the zenith hydrostatic delay (ZHD) and ZWD. ZHD was computed with the Saastamoinen formulation [27], ZWD was obtained by subtraction, and ZWD was converted to PWV with the temperature-dependent factor Π [1]. Equations (1)–(5) define the complete conversion:

$$\text{ZTD} = \text{ZHD} + \text{ZWD} \quad (1)$$

$$\text{ZHD} = 0.0022768P / [1 - 0.00266 \cos(2\varphi) - 0.00028H] \quad (2)$$

$$\text{PWV} = \Pi \cdot \text{ZWD} \quad (3)$$

$$\Pi = 10^6 / \{\rho_w R_v [k'_2 + k_3 / T_m]\} \quad (4)$$

$$T_m = 0.72T_s + 70.2 \quad (5)$$

In Equation (2), P is the ERA5 surface-pressure input used during the station PWV retrieval, φ is geodetic latitude in radians, and H is station geodetic height in kilometers; Equation (2) returns ZHD in meters. The newly supplied sp file confirms the pressure unit and temporal coverage, but it does not contain ERA5 grid elevation and does not cover G2 or G4. We therefore retain the original PWV products and report the pressure-height calculation only as an uncalibrated diagnostic sensitivity scenario, not as a corrected retrieval. In Equations (3)–(5), $\rho_w = 1000 \text{ kg m}^{-3}$, $R_v = 461.518 \text{ J kg}^{-1} \text{ K}^{-1}$, $k'_2 = 0.1652 \text{ K Pa}^{-1}$, and $k_3 = 3776 \text{ K}^2 \text{ Pa}^{-1}$. The resulting Π is dimensionless, so PWV and ZWD use the same length unit. Comparable regional BDS-network assessment uses the same ZTD-to-PWV retrieval framework [28].

2.5. Statistical, Sensitivity, and Rainfall Analyses

Two complementary sample definitions were used. First, the original year-specific matched-sample metrics were retained to preserve the reported five-configuration compar-

ison; under this descriptive definition, BDS-only RMSE was 1.3%, 5.4%, and 7.9% lower than GPS-only RMSE. Second, direct inference used only exact-time profiles available for all five configurations in each season ($n = 225$, 231, and 216). Residual was defined as GNSS minus radiosonde PWV. Pearson R, signed bias, Mean Absolute Error (MAE), and RMSE were calculated. A paired circular moving-block bootstrap resampled 14 consecutive twice-daily profile positions (approximately seven days) within each season. The identical index sequence was applied to every configuration in each of 5000 replicates. Percentile 95% Confidence Intervals (CIs) were reported for signed bias, RMSE, and paired $\Delta\text{RMSE} = \text{RMSE}_{\text{configuration}} - \text{RMSE}_{\text{GPS}}$. The original percentages are therefore treated as descriptive, whereas the strict-common block bootstrap supplies the requested paired uncertainty.

Spatial-transfer sensitivity was evaluated on the strict-common profiles using the fixed G1–G4 geometry, nearest-station transfer, IDW powers 1–3, and the three elevation scale heights described above. Moisture dependence was assessed using radiosonde classes <30 mm (low; $n = 208$), 30–50 mm (moderate; $n = 310$), and >50 mm (high; $n = 154$), with block-bootstrap intervals. The five-configuration agreement plot was retained, and residual-versus-radiosonde-PWV regressions were added separately by season for BDS-only and GPS-only. Three descriptive case panels were selected objectively as the highest hourly CLDAS rainfall in each June–September season for which BDS PWV was available; they were not used for inferential forecast evaluation.

The rainfall evaluation used all complete, currently dry hourly windows in June–September. A positive target was any CLDAS rainfall $\geq 1 \text{ mm h}^{-1}$ at $t + 1$, $t + 2$, or $t + 3$; overlapping windows were retained and their dependence was addressed by seven-day calendar-block resampling. In each leave-one-year-out (LOYO) fold, the empirical BDS PWV distribution and a Youden-J threshold were constructed only from the other two years, then applied to the held-out year. Area Under Curve (AUC), probability of detection (POD), false-alarm ratio (FAR), critical success index (CSI), and specificity were reported. The preceding 3 h PWV rate, $[\text{PWV}(t) - \text{PWV}(t-3 \text{ h})]/3$, was evaluated separately. Objective rainfall onset was defined as the first hour with rainfall $\geq 1 \text{ mm h}^{-1}$ after at least six consecutive hours below 1 mm h^{-1} . PWV percentiles at -12 , -6 , -3 , and -1 h were summarized for 86 onsets, and the association between the -1 h percentile and maximum rainfall in the next 3 h used a year-stratified event bootstrap.

3. Results

3.1. Observation Geometry and Data Availability

BDS-only—here the processed BDS-2+BDS-3 solution with the exclusions and down-weighting stated in Section 2.2—provided more visible satellites (Figure 2a) and lower PDOP (Figure 2b) than GPS-only in every flood season. Mean visible-satellite counts across the three seasons were 13.75 for BDS and 8.61 for GPS; mean PDOP values were 1.83 and 2.49. Data completeness by configuration and season is shown in Figure 2c. Completeness also varied by station group; for example, BDS availability at G1 was 72.2% in 2025, while the other three groups exceeded 92% (Table 2). These availability changes were handled through epoch-specific renormalization of the fixed IDW weights.

Adding BDS to GPS produced the largest PDOP reduction, and additional GLONASS and Galileo observations further improved the geometry. These quantities describe observation availability and geometry only. Formal ZTD uncertainty, ambiguity-fixing rate, and convergence diagnostics were not supplied and therefore cannot be used to explain the PWV error pattern causally.

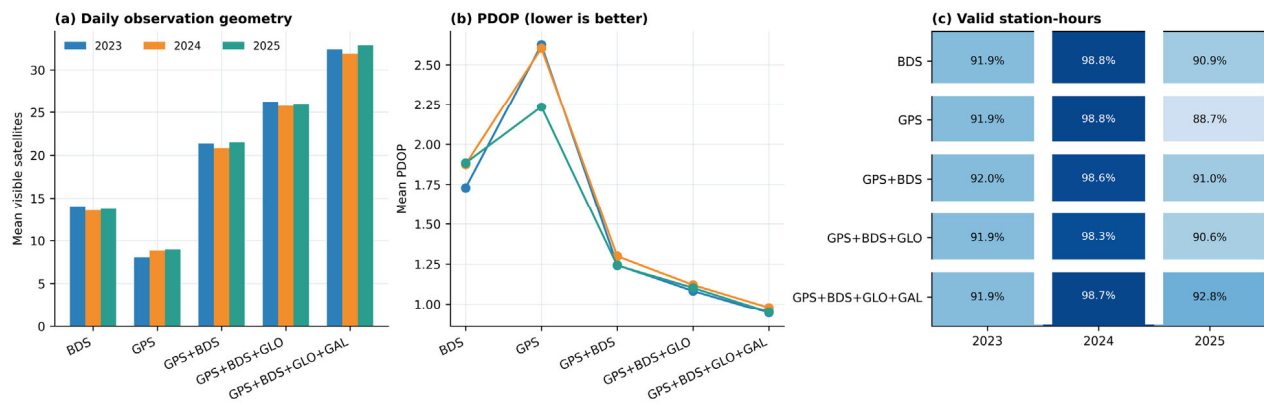


Figure 2. Observation geometry and completeness by flood season. (a) Mean visible satellites; (b) mean PDOP; (c) percentage of valid station-hours aggregated across four stations. Geometry is descriptive and is not treated as a causal proxy for PWV accuracy.

3.2. Regional Cross-Site Comparison with Radiosonde PWV

All five spatially transferred configurations tracked radiosonde-derived PWV in 2023 (Figure 3a), 2024 (Figure 3b), and 2025 (Figure 3c). The original year-specific matched-sample analysis gave $R = 0.945\text{--}0.963$ and $\text{RMSE} = 7.15\text{--}9.28$ mm. In that descriptive analysis, BDS-only RMSE was 1.3%, 5.4%, and 7.9% lower than GPS-only RMSE in 2023, 2024, and 2025, respectively. The five-configuration comparison also showed that adding GLONASS and Galileo did not reduce PWV error monotonically, despite the progressively stronger observation geometry. These percentages are retained because they describe the original analysis population; they are not used as a significance test.

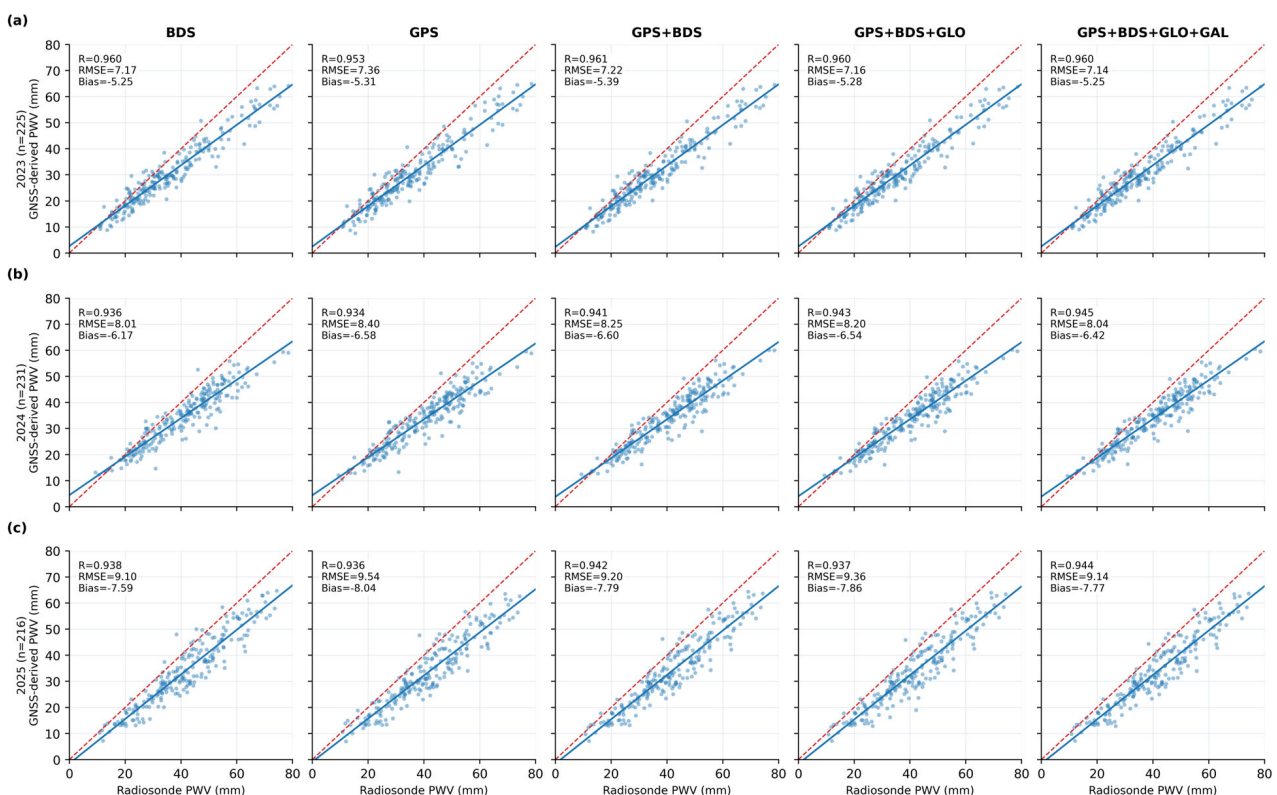


Figure 3. Year-specific regional cross-site comparison of spatially transferred GNSS-derived PWV against radiosonde-derived PWV for five constellation configurations on strict-common samples: (a) 2023; (b) 2024; (c) 2025. Each row contains BDS, GPS, GPS+BDS, GPS+BDS+GLONASS, and

GPS+BDS+GLONASS+Galileo panels. The red dashed and blue solid lines denote the 1:1 relationship and fitted regression, respectively. R, RMSE, and signed bias are shown in each panel. The conventional axis order (radiosonde-derived PWV on the *x*-axis) makes negative GNSS bias appear below the 1:1 line.

On strict-common samples, BDS/GPS RMSE values were 7.17/7.36 mm in 2023, 8.01/8.40 mm in 2024, and 9.10/9.54 mm in 2025. The paired BDS-minus-GPS Δ RMSE was -0.19 mm (95% CI: -0.41 to -0.03), -0.39 mm (-0.61 to -0.16), and -0.44 mm (-0.65 to -0.23), respectively (Table 3). Within this strict-common subset, the corresponding relative reductions were 2.6%, 4.6%, and 4.6%. The intervals exclude zero under the baseline transfer, but the absolute differences are small relative to the overall RMSE and to spatial-transfer sensitivity. We therefore describe BDS and GPS as broadly comparable, with a small baseline numerical advantage for BDS in this regional dataset.

Table 3. Paired BDS-only versus GPS-only RMSE comparison under baseline IDW power 2.

Flood Season	n	BDS RMSE (mm)	GPS RMSE (mm)	Δ RMSE (mm)	95% CI (mm)
2023	225	7.17	7.36	-0.19	-0.41 to -0.03
2024	231	8.01	8.40	-0.39	-0.61 to -0.16
2025	216	9.10	9.54	-0.44	-0.65 to -0.23

3.3. Error Distributions and Moisture Dependence

Residuals became more negative as radiosonde PWV increased in 2023 (Figure 4a), 2024 (Figure 4b), and 2025 (Figure 4c). BDS-only residual slopes were -0.23 , -0.26 , and -0.15 mm per mm in 2023–2025; GPS-only slopes were -0.22 , -0.27 , and -0.17 mm per mm. Thus, the high-moisture discrepancy developed gradually across the PWV range and was not confined to a small number of upper-tail observations.

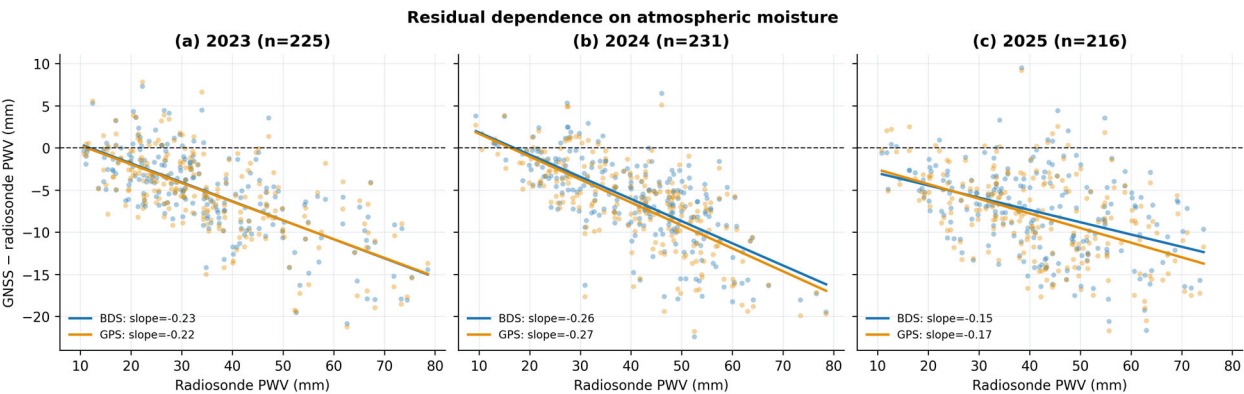


Figure 4. Regional cross-site residual (spatially transferred GNSS PWV minus radiosonde-derived PWV) versus radiosonde-derived PWV for BDS-only and GPS-only: (a) 2023; (b) 2024; (c) 2025. Each flood-season panel shows strict-common samples and linear residual slopes. The horizontal dashed line marks zero residual; the fitted slopes show that negative bias develops gradually with atmospheric moisture.

Figure 5a retains the original year-specific descriptive BDS improvement, while Figure 5b shows that negative residuals dominate the regional cross-site error distribution. Moisture-stratified correlation remained high across all configurations (Figure 5c). For low, moderate, and high radiosonde PWV, BDS-only RMSE was 4.30, 7.82, and 11.80 mm (Figure 5d), with signed biases of -2.72 , -6.53 , and -10.75 mm (Figure 5e). GPS-only RMSE was 4.51, 8.11, and 12.36 mm, with signed biases of -2.85 , -6.80 , and -11.36 mm. All five configurations exhibited the same progressive moisture-dependent degradation.

The direction of error is displayed directly, and MAE remains reported separately in the Supplementary Data.

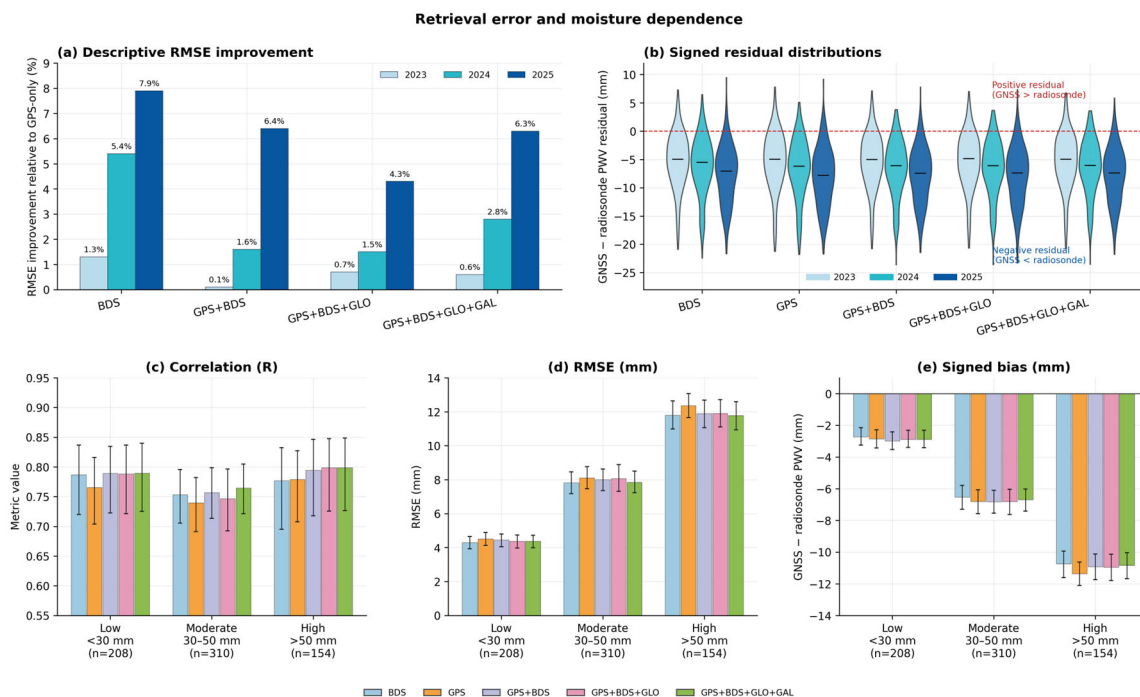


Figure 5. Regional comparison residuals and moisture dependence. (a) Original year-specific descriptive BDS-only RMSE improvement relative to GPS-only; (b) signed spatially transferred GNSS-minus-radiosonde-derived PWV residual distributions; (c–e) moisture-stratified correlation, RMSE, and signed bias for all five configurations. Error bars in (c–e) are year-stratified moving-block-bootstrap 95% confidence intervals. In (b), positive and negative indicate the sign of the retrieval residual, not the moisture classes shown in (c–e).

The paired baseline comparison is summarized in Figure 6a. Spatial treatment materially affected absolute error and the apparent configuration ordering (Figure 6b). Using the same fixed G1–G4 geometry, nearest-station, IDW powers 1–3, and elevation-sensitive transfers changed BDS RMSE by several millimeters. In 2024, BDS-minus-GPS Δ RMSE ranged from -0.41 mm under IDW power 1 to $+0.37$ mm under the 1.5 km elevation sensitivity; in 2025 it ranged from approximately -0.40 to -0.03 mm. The small baseline difference is therefore not invariant to assumptions about regional spatial transfer.

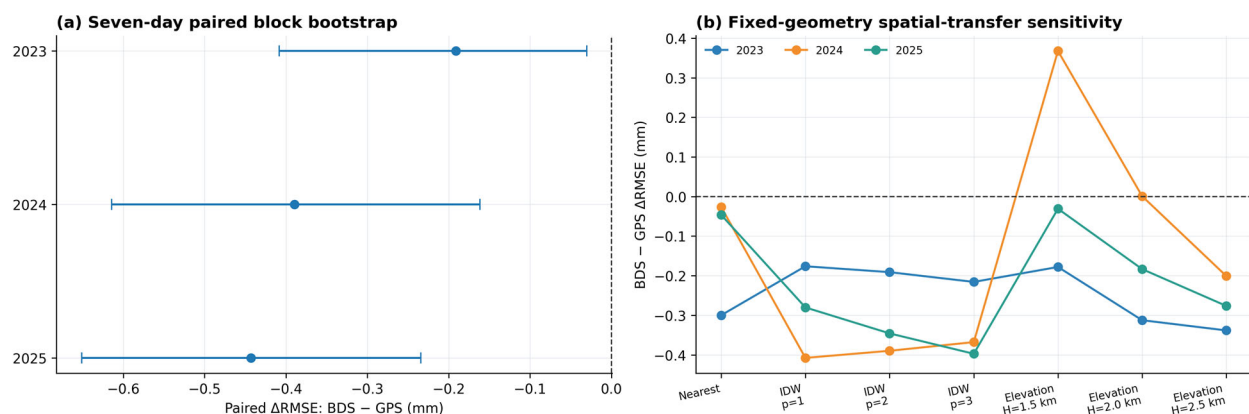


Figure 6. Paired constellation comparison and fixed-geometry spatial sensitivity. (a) BDS-minus-GPS Δ RMSE with paired seven-day moving-block-bootstrap 95% confidence intervals on strict-common

samples; (b) BDS-minus-GPS Δ RMSE under nearest-station, IDW, and elevation-sensitive transfer assumptions. The zero line indicates equal RMSE; elevation-scale sensitivity scenarios are uncalibrated diagnostics rather than corrected retrievals.

3.4. Full-Season PWV Evolution During Representative Rainfall Cases

Figure 7 shows the highest hourly CLDAS rainfall case with valid BDS PWV in 2023 (Figure 7a), 2024 (Figure 7b), and 2025 (Figure 7c). Peak rainfall was 30.7, 32.8, and 24.3 mm h⁻¹, respectively. The corresponding out-of-year PWV percentiles at the rainfall peak were 99.6%, 96.3%, and 95.4%. All three right-hand rainfall axes use the same 0–35 mm h⁻¹ range, allowing for direct comparison without clipping the 2024 maximum.

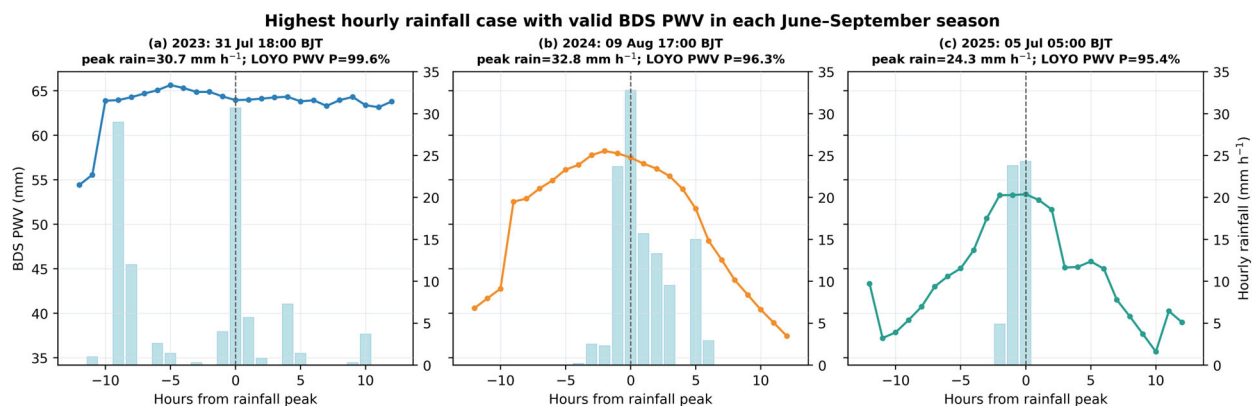


Figure 7. BDS-only PWV and CLDAS hourly rainfall for the highest hourly rainfall case with valid BDS PWV in each June–September season: (a) 2023; (b) 2024; (c) 2025. Time is relative to the rainfall peak. All right-hand rainfall axes use an identical 0–35 mm h⁻¹ range. PWV percentiles were constructed from the other two years and are shown for context only.

PWV evolution was not uniform across the cases. The 2023 series rose sharply before the peak and then remained high; the 2024 series rose more gradually and declined after the peak; the 2025 series showed a shorter increase and a marked postpeak reduction. These panels illustrate moisture evolution but are not an independently sampled event population.

3.5. Full-Season Out-of-Year PWV–Rainfall Associations

Figure 8 summarizes the complete out-of-year rainfall analysis: leave-one-year-out discrimination (Figure 8a), subsequent rainfall frequency by PWV percentile (Figure 8b), pre-onset PWV evolution (Figure 8c), and event-level intensity association (Figure 8d). Across 86 objectively defined rainfall onsets, the median out-of-year PWV percentile increased from 79.4% at –12 h to 81.5% at –6 h, 85.5% at –3 h, and 88.0% at –1 h (Figure 8c). Interquartile ranges were broad, indicating substantial event-to-event variability.

Out-of-year next-3 h rainfall frequency increased from 1.2% (71/6095) at $\leq$ P75 to 5.7% (70/1237) at P75–90, 16.3% (48/295) at P90–95, 16.8% (29/173) at P95–97.5, and 29.3% (36/123) above P97.5 (Figure 8b). Seven-day block-bootstrap intervals were wide in the upper bins because heavy rainfall remained uncommon.

Held-out-year AUC values for PWV percentile were 0.906, 0.814, and 0.845 in 2023–2025. The pooled out-of-year AUC was 0.846 (seven-day block-bootstrap 95% CI: 0.806–0.885), compared with 0.641 (0.592–0.695) for the preceding 3 h PWV rate (Figure 8a). However, thresholds selected from the two training years transferred poorly: pooled POD was 81.9%, FAR 92.2%, CSI 7.6%, and specificity 67.8%. AUC discrimination, therefore, did not translate into a useful stand-alone decision threshold.

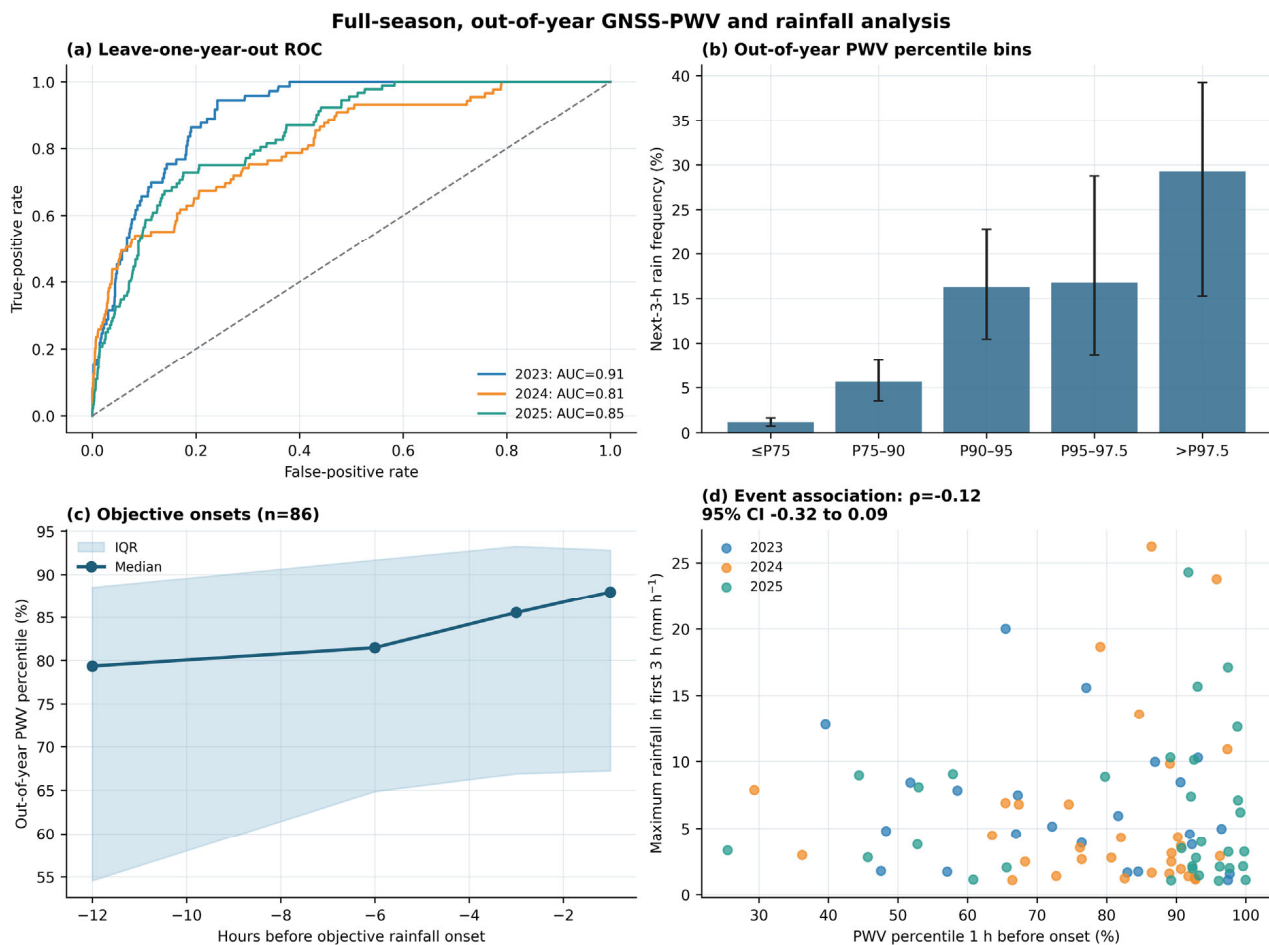


Figure 8. Full-season out-of-year PWV-rainfall analysis. (a) Leave-one-year-out ROC curves; (b) subsequent 3 h rainfall frequency by out-of-year PWV percentile, with seven-day block-bootstrap 95% CIs; (c) median and interquartile range of PWV percentile before 86 objective onsets; (d) event-level association between the -1 h percentile and maximum rainfall in the next 3 h. These retrospective metrics do not establish stand-alone operational forecast skill.

At the event level, the -1 h PWV percentile was not associated with maximum rainfall during the next 3 h (Spearman $\rho = -0.12$; $n = 86$; year-stratified event-bootstrap 95% CI: -0.32 to 0.09 ; Figure 8d). The original positive $\rho = 0.50$ interpretation based on seven selected onsets is therefore not retained.

4. Discussion

4.1. Constellation Dependence of Regional GNSS-PWV Retrieval

The five-configuration comparison remains a strength because constellation composition was changed while the PPP strategy was held constant. In the original year-specific samples, BDS-only RMSE was descriptively 1.3%, 5.4%, and 7.9% lower than GPS-only. The direct strict-common analysis also produced negative BDS-minus-GPS Δ RMSE with block-bootstrap intervals below zero. Nevertheless, the differences were only 0.19–0.44 mm and were not invariant to spatial transfer; one 2024 elevation-sensitive case reversed the BDS–GPS order. Improved satellite count and PDOP likewise did not yield a monotonic reduction in PWV error as constellations were added. The evidence supports BDS–GPS comparability and a small regional baseline advantage, not universal BDS superiority or a causal geometry explanation.

4.2. High-Moisture Bias

The gradual negative residual slope and the approximately -11 mm high-PWV bias are the strongest shared pattern, but they cannot be assigned uniquely to GNSS processing. Potential contributors include ZTD estimation, surface-pressure and T_m inputs, radiosonde humidity and upper-profile treatment, large station-height differences, and horizontal moisture gradients [21,25,29,30]. The supplied ERA5 sp file confirms hourly pressure values but covers only G1 and G3 and does not provide grid elevation. At those two grids, a 100 m assumed height error corresponds to an absolute PWV sensitivity of approximately 3.9–4.3 mm. This is large relative to the constellation differences, but the missing grid elevation prevents determination of the actual pressure-effect sign or attribution of the observed negative bias to ERA5 pressure.

Resolving the high-moisture regime requires collocated GNSS–radiosonde or microwave-radiometer observations, pressure measurements at receiver height, archived PPP formal uncertainties and ambiguity statistics, and a locally validated vertical PWV model. The elevation-scale scenarios in this revision are uncalibrated diagnostic sensitivity tests and should not be interpreted as corrected retrievals.

4.3. Atmospheric Water Vapor Evolution Around Rainfall

The full-season LOYO analysis shows that the relative PWV level contains out-of-year information about subsequent rainfall occurrence, whereas a stand-alone 3 h PWV tendency is less discriminative. Nevertheless, the transferred threshold generated 2473 false alarms for 208 detections, yielding FAR = 92.2% and CSI = 7.6%. High AUC is therefore insufficient evidence for an operational rule when the positive class is rare and thresholds are not calibrated with additional meteorological predictors.

The three peak-centered panels retain value as atmospheric process illustrations, but they are not an inferential event sample. Prior studies likewise show that PWV level, tendency, and multivariate or machine learning combinations can contribute to precipitation analysis, but performance is strongly dependent on event definition, sampling, and evaluation design [31–35]. More importantly, expansion from seven selected onsets to 86 objective onsets removed the apparent positive relationship with subsequent rainfall intensity. The present evidence supports retrospective regional moisture monitoring and prioritization of periods for multivariate meteorological analysis; it does not establish a stand-alone operational rainfall forecast rule.

4.4. Limitations and Reproducibility

The principal limitations are the absence of a collocated GNSS receiver, the single radiosonde site, 88–147 km station-to-radiosonde separations, large elevation contrasts, and only three flood seasons. The same four physical station groups were assumed throughout, using the author-verified 2023–2024 geometry. The elevation-sensitive transfer is an uncalibrated diagnostic. The uploaded ERA5 pressure domain excludes G2 and G4 and lacks grid geopotential/elevation, so a full receiver-height pressure correction remains unavailable. Formal PPP quality indicators were also unavailable. Twice-daily radiosondes limit temporal sampling; hourly rainfall windows overlap; CLDAS is a gridded estimate; and leave-one-year-out testing has only three annual folds. These restrictions preclude a universal constellation ranking, component-level attribution of the negative bias, or operational precipitation claims.

Reproducibility was strengthened by separating the original descriptive sample definition from the strict-common paired analysis, harmonizing physical station groups to a fixed geometry, reporting distances and effective weights, using block resampling, documenting radiosonde integration, and auditing the newly supplied ERA5 pressure file. The Supple-

mentary Data include reported baseline metrics, strict-common samples, paired bootstrap results, spatial-transfer sensitivity, station availability and weights, ERA5 pressure coverage and theoretical height sensitivity, rainfall results, figures, and analysis code.

5. Conclusions

In the Beijing June–September 2023–2025 case study, the common PPP processing of five constellation configurations enabled a controlled regional comparison. In the original year-specific samples, BDS-only RMSE was descriptively 1.3%, 5.4%, and 7.9% lower than GPS-only. On strict-common paired samples, BDS-minus-GPS Δ RMSE was -0.19 , -0.39 , and -0.44 mm, with seven-day block-bootstrap intervals below zero. The differences were statistically distinguishable under the baseline IDW power-2 spatial-transfer assumption because the paired block-bootstrap intervals excluded zero. However, the constellation ordering was not robust across all tested transfer methods and reversed in one 2024 elevation-sensitive diagnostic scenario. The small regional differences therefore do not support a universal BDS ranking; BDS and GPS should be regarded as broadly comparable.

More importantly, the moisture-dependent negative bias was substantially larger than the BDS–GPS differences: BDS-only and GPS-only biases reached -10.75 and -11.36 mm above 50 mm radiosonde PWV. This high-moisture underestimation is the most robust and practically consequential finding of the study. The vertical-PWV and pressure-height calculations are uncalibrated diagnostic sensitivity scenarios, not corrected retrievals. Full-season leave-one-year-out PWV percentile achieved AUC = 0.846, yet FAR = 92.2%, CSI = 7.6%, and the 86-event intensity association was not significant. The rainfall analysis supports retrospective regional moisture monitoring, but it does not establish a stand-alone operational rainfall-prediction tool. Collocated observations, complete ERA5 pressure and grid-elevation inputs, receiver-height pressure measurements, PPP quality diagnostics, and regional evaluation across additional climates are needed before system ranking or operational use.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/atmos17090880/s1>, Data S1: GNSS PWV, radiosonde comparison, satellite geometry, precipitation case series, and descriptive statistics for Beijing (2023–2025).

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Abbreviations

AUC, area under the receiver operating characteristic curve; BDS, BeiDou Navigation Satellite System; BJT, Beijing Time; CI, confidence interval; CLDAS-V2.0, China Meteorological Administration Land Data Assimilation System version 2.0; ERA5, European Centre for Medium-Range Weather Forecasts fifth-generation reanalysis; GNSS, Global Navigation Satellite System; GPS, Global Positioning System; IDW, inverse-distance weighting; LAMBDA, least-squares ambiguity decorrelation adjustment; MAE, mean absolute error; PDOP, position dilution of precision; PPP, precise point positioning; PPP-AR, precise point positioning with ambiguity resolution; PWV, precipitable water vapor; RMSE, root-mean-square error; STO, stochastic option; WUM, Wuhan University Multi-GNSS Experiment; ZHD, zenith hydrostatic delay; ZTD, zenith total delay; ZWD, zenith wet delay.

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