

Enhancing GNSS Water Vapour Retrieval via Synergistic Microwave Radiometry: Thermodynamic Error Diagnosis and Bias Correction

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Abstract.

The retrieval of Precipitable Water Vapour (PWV) from Global Navigation Satellite Systems (GNSS) in thermodynamically complex environments is fundamentally limited by the accuracy of the weighted mean temperature (T_m). This study evaluates the efficacy of static climatological models versus dynamic ground-based microwave radiometry for T_m determination in the Eastern Mediterranean, a region characterized by sharp refractivity gradients. Using the Cyprus GNSS Meteorology Enhancement research project (CYGMEN) infrastructure in Nicosia, the performance of the ERA5-based HGPT2 model and a co-located Microwave Radiometer (MWR) was assessed against radiosonde (RS) profiles during the 2025 warm season (Spring–Summer). Diagnostic analysis reveals that the static HGPT2 model fails to resolve the diurnal thermodynamic decoupling between the boundary layer and the free troposphere, leading to a systematic overestimation of T_m exceeding 6 K during peak solar insolation. Conversely, the MWR captures short-term thermodynamic variability ($r=0.98$) but exhibits a systematic cold bias of -1.91 K in raw retrievals. It is demonstrated that a site-specific linear bias correction reduces the MWR T_m Root Mean Square Error (RMSE) from 2.32 K to 1.43 K, significantly outperforming the empirical model. Sensitivity analysis confirms that thermodynamic uncertainty dominates the error budget, outweighing uncertainties in refractivity constants by an order of magnitude. Consequently, standard climatological retrievals diverge from the synergistic MWR-GNSS method during extreme hygrometric events, introducing systematic PWV biases exceeding 1.0 mm when moisture levels surpass 45 mm. The synergistic coupling of real-time radiometric T_m with GNSS data is therefore meaningful for generating climate-quality PWV records in semi-arid coastal regions.

1 Introduction

Atmospheric water vapour (WV) is the primary greenhouse gas, contributing approximately 60 % to the natural greenhouse effect and playing a vital role in regulating the Earth's thermodynamic budget (Kiehl and Trenberth, 1997; Trenberth et al., 2005). Furthermore, WV is the main driver of latent heat transport, influencing convective systems and global precipitation patterns. High-frequency variations in Precipitable Water Vapour (PWV) correlate strongly with atmospheric instability and are a key factor in the initiation of severe weather. Specifically, rapid temporal gradients in PWV often precede heavy rainfall

32 and flash floods, acting as a reliable precursor for convective storms (Brenot et al., 2013). Consequently, assimilating high-
33 resolution PWV data into Numerical Weather Prediction (NWP) models significantly improves short-range precipitation "now-
34 casting" (Bennitt and Jupp, 2012). Accurate PWV retrieval is especially crucial for the Eastern Mediterranean, a climate change
35 "hotspot" warming faster than the global average (Giorgi, 2006; Lelieveld et al., 2012). This region is characterized by complex
36 topography and land-sea contrasts, which create sharp atmospheric refractivity gradients. The Eastern Mediterranean faces a
37 hydro-climatic paradox: a long-term drying trend (-0.5 mm/decade) alongside increasing high-intensity, short-duration flash
38 flood events (Zittis et al., 2019; Ziv et al., 2021). GNSS-derived PWV in this region exhibits strong diurnal cycles with
39 amplitudes up to 5 mm, which are closely correlated with atmospheric instability (Ziskin Ziv et al., 2020). Despite this
40 vulnerability, the Eastern Mediterranean currently lacks dense, continuous atmospheric profiling networks. Traditional
41 observation methods, such as radiosondes (RS), fail to resolve these mesoscale events due to low temporal resolution (typically
42 12-hour intervals) and significant spatial gaps (Soden and Lanzante, 1996). While satellite-based passive remote sensing offers
43 global coverage, it is often limited by revisit times, daylight dependence, or data degradation in coastal zones due to land
44 contamination in the microwave footprint (Bennartz and Bauer, 2003).

45 These limitations underscore the necessity for ground-based remote sensing techniques that offer continuous, all-weather
46 operability. Ground-based Global Navigation Satellite Systems (GNSS) meteorology has emerged as a robust technique for
47 atmospheric sounding since the seminal proposal by Bevis et al. (1992). By estimating the Zenith Total Delay (ZTD) of GNSS
48 signals traversing the neutral atmosphere, the Zenith Wet Delay (ZWD) can be isolated by subtracting the Zenith Hydrostatic
49 Delay (ZHD), which is accurately modeled from surface pressure observations (Saastamoinen, 1972). GNSS-derived PWV
50 offers significant advantages, including high temporal resolution (sub-hourly), all-weather availability, and cost-efficiency by
51 leveraging existing geodetic infrastructure (Guerova et al., 2016; Jones et al., 2020).

52 The retrieval of PWV from GNSS ZWD relies on a dimensionless conversion factor, Π , which is a function of the
53 atmospheric weighted mean temperature, T_m . Defined physically as $\int(e/T)dz/\int(e/T^2)dz$ (Askne and Nordius, 1987), T_m
54 encapsulates the thermal state of the atmospheric column. The conversion factor (Π) is nearly linearly proportional to T_m , a 1
55 K error in T_m (assuming standard atmospheric temperatures near 280 K) introduces a relative error of approximately 0.36 %
56 in the final IWV. During severe moisture events with an IWV of 50 kg m^{-2} , this translates to an absolute error of $\sim 0.18 \text{ kg m}^{-2}$.
57 Consequently, a 1 % relative error in T_m translates strictly to a 1 % relative error in IWV. Therefore, alongside the substantial
58 errors inherent in ZTD estimation—such as mapping function inaccuracies and surface pressure interpolation for the ZHD
59 (Ning et al., 2016)—the determination of T_m remains one of the primary sources of uncertainty in GNSS meteorology. In the
60 absence of in-situ profiles, T_m is commonly estimated using empirical regression models or global climatological models.
61 However, earlier studies have demonstrated that empirical T_m regressions, such as the Bevis model (Bevis et al., 1992),
62 introduce relative PWV errors of 1–2 % due to weak T_s – T_m correlations in coastal and equatorial regions, where
63 annual/semiannual variations are not adequately captured (Yao et al., 2014; Lan et al., 2016). Similarly, global grid-based T_m

64 models like GPT2w achieve RMSE <4 K at ~80 % of mid-latitude sites but degrade in data-sparse areas like the Middle East
65 and Africa, where reanalysis quality is limited (Böhm et al., 2015; Jiang et al., 2019). The Hourly Global Pressure and
66 Temperature 2 (HGPT2) model represents a major advancement by providing hourly estimates derived from ERA5 reanalysis
67 (Mateus et al., 2021). Despite recent validation of GPT2w and ECMWF models for Integrated Water Vapour (IWV) retrieval
68 in the Mediterranean (Oikonomou et al. 2018), a critical gap exists: the quantification of vertical interpolation errors in these
69 models, especially over complex coastal terrains. For instance, while recent validation studies in Cyprus demonstrate strong
70 GNSS-PWV correlations (>0.6) with ERA5 during extreme precipitation, persistent reanalysis interpolation errors are
71 highlighted in mountainous areas (Giannadaki et al., 2025). This lack of validation for HGPT2's performance in the complex
72 topography of the Eastern Mediterranean potentially exacerbates PWV biases during extreme events.

73 An alternative approach to deriving T_m is the use of ground-based Microwave Radiometers (MWR). MWRs measure
74 brightness temperatures at multiple frequencies to retrieve continuous vertical profiles of temperature and humidity. Ground-
75 based MWRs have been shown to retrieve T_m with RMSE ~1–2 K in mid-latitudes, outperforming empirical models during
76 synoptic anomalies (Cimini et al., 2010; Crewell and Löhnert, 2007; Löhnert et al., 2012). While multi-site intercomparisons
77 reveal that MWR retrievals can exhibit upper-tropospheric cold biases (up to 5 K at >2 km altitude) (Van Malderen et al.,
78 2014; Steinke et al., 2015), simple linear corrections can reduce RMSE by 20–40 % (Ning and Elgered, 2021). Operational
79 GNSS–MWR synergies for T_m bias correction have documented gains in PWV accuracy (10–30 % RMSE reduction) in
80 European networks (Vaquero-Martínez et al., 2018; Li et al., 2020). However, such applications are rare in the semi-arid
81 Eastern Mediterranean, where MWR could critically mitigate reanalysis uncertainties.

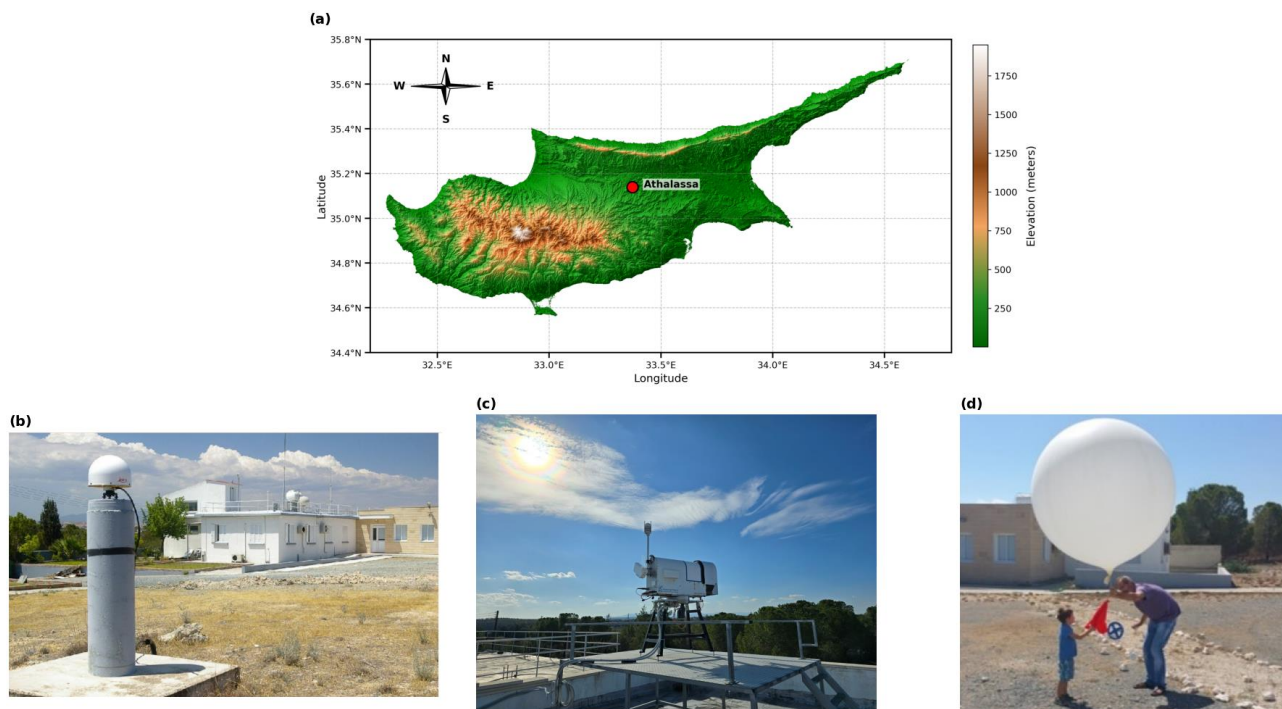
82 This study leverages the infrastructure of the CYGMEN (Cyprus GNSS Meteorology Enhancement) project, which is
83 establishing a dense, multi-sensor meteorological network in Cyprus. The network, termed CyMETEO, integrates a dense
84 array of continuous GNSS stations distributed across the island. Due to the high cost and operational complexity of radiometric
85 profiling, the network currently features a single, centralized thermodynamic 'supersite' at the Athalassa observatory, where a
86 GNSS receiver is strictly co-located with a MWR and a RS launch facility. This unique instrumental setup provides an ideal
87 testbed for inter-comparing atmospheric retrieval techniques in a coastal, semi-arid environment. The primary objective of this
88 manuscript is to evaluate the accuracy of GNSS-derived PWV over the Eastern Mediterranean by assessing the performance
89 of different T_m determination strategies. We specifically investigate the efficacy of the HGPT2 model compared to MWR-
90 derived T_m and RS benchmarks. The study aims to quantify the error budget of GNSS-PWV and determine whether the
91 inclusion of MWR data provides statistically significant improvements over the state-of-the-art HGPT2 model. The manuscript
92 is organized as follows: Section 2 describes the study area and the instrumentation of the CyMETEO network; Section 3 details
93 the methodology for GNSS processing, ZTD estimation, and the mathematical derivation of T_m from different sources; Section
94 4 presents the validation results and statistical analysis against RS reference data; and Section 5 concludes with
95 recommendations for operational PWV monitoring strategies in the region.

96

97 **2 Data and Methodology**

98 **2.1 Observational Site and CYGMEN Infrastructure**

99 The observational campaign was conducted at the Athalassa atmospheric observatory in Nicosia, Cyprus (35.15°N, 33.40°E,
100 160 m a.s.l.), situated in the central Mesaoria plain. The site is characterized by complex topography, bounded by the Troodos
101 Mountain to the southwest and the Pentadaktylos Mountain to the north, as shown in Fig. 1a. This study presents the first
102 comprehensive analysis of radiometric data acquired under the CYGMEN infrastructure project, established to monitor the
103 thermodynamic state of the Eastern Mediterranean atmosphere. To ensure robust thermodynamic profiling and validation,
104 three primary datasets were collated, as shown in Table 1:



105 **Figure 1.** Location and instrumentation at Athalassa, Cyprus. (a) Site location on the island's elevation map. (b) GNSS reference station.
106 (c) RPG-HATPRO radiometer. (d) Radiosonde balloon launching.
107

108

109 **Table 1:** Summary of Instrumentation and Datasets

Parameter	Microwave Radiometer (MWR)	Radiosonde (RS)	GNSS Station
Instrument Model	HATPRO-Gen5 (RPG)	Vaisala RS41-SGP	GNSS Receiver LEICA GR50 (Collocated)
Role in Study	Synergistic thermodynamic profiling (temperature and humidity) and IWV estimation	<i>In-situ</i> "Ground Truth" Reference	ZTD Source for PWV Retrieval

Observation Type	Passive remote sensing (22–58 GHz)	<i>In-situ</i> vertical profile (balloon-borne)	Continuous satellite signal delay
Key Variables	Brightness Temp (T_B), $T(z)$, $\rho_v(z)$, IWV	$P(z)$, $T(z)$, $RH(z)$, Geopotential Height	Zenith Total Delay (ZTD)
Vertical Range	Surface to 10 km (94 levels)	Surface to burst altitude (~30 km)	Column-integrated (single value)
Temporal Resolution	High frequency (~1 s raw, resampled to 15 min)	Periodic (launch dependent)	Continuous (high rate)
Accuracy / Noise	T_B noise < 0.11 K (K-band), < 0.32 K (V-band)	T : 0.3 K, RH : 4 % (Manufacturer spec)	ZTD precision ~mm level
Auxiliary Data	Vaisala WXT536 (Rain, Surface Met)	GPS position/height	Surface Pressure

110

111 **2.2 Instrumentation and Data Processing**112 **2.2.1 Microwave Radiometry (MWR)**

113 The RPG-HATPRO radiometer observes downwelling atmospheric brightness temperatures (T_B) across 14 channels: seven in
114 the K-band (22–31 GHz) sensitive to water vapour, and seven in the V-band (51–58 GHz) sensitive to oxygen for temperature
115 profiling. This instrument enables the continuous retrieval of temperature (T) and absolute humidity (ρ_v) profiles on a
116 standardized grid of 94 vertical levels from the surface up to 10 km. The vertical resolution is optimized for the planetary
117 boundary layer (PBL), ranging from 10–30 m up to 500 m, and decreasing to 100–500 m in the free troposphere. For this
118 study, high-frequency MWR observations were resampled to 15-minute intervals to align with GNSS processing epochs. It is
119 a well-documented limitation of passive microwave radiometry that retrieval accuracy degrades significantly during
120 precipitation, as liquid water on the instrument's radome heavily contaminates the measured brightness temperatures. Because
121 this study focused on the warm, dry season in the Eastern Mediterranean (March–October 2025), rainfall events were naturally
122 sparse. Nevertheless, to ensure data integrity, real-time precipitation flags generated by the co-located Vaisala WXT536
123 surface weather transmitter were utilized as a strict quality-control filter. Any MWR profiles retrieved during active
124 precipitation events were excluded from the dataset to prevent wet-radome anomalies from artificially skewing the
125 thermodynamic bias analysis. To diagnose potential biases in the MWR-derived T_m , the dataset was split into a training Set
126 (April–June 2025) for regression modeling and a validation Set (July–October 2025) for independent testing. In addition to
127 thermodynamic profiling, the MWR's native retrieval algorithm possesses the capacity to directly estimate IWV from its K-
128 band brightness temperatures.

129

130 2.2.2 Radiosonde Data Processing

131 To establish a rigorous validation dataset, IWV was derived from high-resolution vertical profiles obtained from collocated
 132 radiosonde launches. A strict collocation window was applied, where MWR profiles were averaged within ± 30 minutes of the
 133 balloon launch time. The raw telemetry data, comprising pressure (P), temperature, and dew point temperature (T_d), were
 134 processed to derive the total columnar water vapour content (in kg m^{-2}) through the vertical integration of specific humidity,
 135 assuming the atmosphere is in hydrostatic equilibrium. The determination of the necessary moisture variables relied on the
 136 Magnus-Tetens approximation, which provides a widely accepted empirical relationship for saturation vapour pressure. First,
 137 the actual vapour pressure (e , in hPa) was computed directly from the dew point temperature (T_d , in $^{\circ}\text{C}$). This calculation
 138 utilized the coefficients defined by Bolton (1980), which are optimized for saturation vapour pressure over liquid water in the
 139 meteorological temperature range, as shown in Eq. (1):

$$140 \quad e = 6.112 \cdot \exp\left(\frac{17.67 \cdot T_d}{T_d + 243.5}\right) \quad (1)$$

141 Subsequently, the specific humidity (q , in kg kg^{-1}) was derived via Eq. (2), representing the mass mixing ratio of water vapour
 142 to the total moist air parcel:

$$143 \quad q = \frac{\epsilon \cdot e}{P - (1 - \epsilon) \cdot e} \quad (2)$$

144 where P is the static pressure (hPa) and $\epsilon \approx 0.622$ represents the ratio of the molecular weight of water vapour to that of dry
 145 air. Once the specific humidity profile was established, the IWV was calculated by integrating q with respect to pressure. The
 146 retrieval algorithm employed the trapezoidal rule for numerical integration, which approximates the integral as the sum of
 147 discrete atmospheric layers (Eq. 3):

$$148 \quad IWV = \frac{1}{g} \sum_{i=0}^{N-1} \frac{q_i + q_{i+1}}{2} \cdot |P_{i+1} - P_i| \quad (3)$$

149 where g is the gravity dependent on altitude, $g(\phi, h)$, where ϕ represents the Geodetic latitude and h is the orthometric height.
 150 P is converted to Pascals (Pa) prior to integration and N represents the total number of vertical levels in the RS profile. It
 151 should be noted that IWV, representing the mass column integral in kg m^{-2} , is physically and numerically equivalent to PWV
 152 expressed as a depth in millimeters (mm), assuming the standard density of liquid water (1000 kg m^{-3}). While the term IWV
 153 is frequently used when discussing direct profile integration from the MWR and RS, this study uses PWV (mm) as the
 154 standardized final retrieval metric to align with operational meteorological and forecasting conventions. It is important to note
 155 that while the nominal manufacturer uncertainty for the Vaisala RS41 humidity sensor is stated as 4 % for individual profile
 156 measurements, the uncertainty of the resulting IWV is significantly lower. Because IWV is computed by integrating hundreds
 157 of discrete measurements across the vertical column (Eq. 3), uncorrelated random sensor noise is largely suppressed through
 158 statistical cancellation. Consequently, the integrated variables derived from the radiosonde, such as IWV and the T_m , possess
 159 the requisite precision to serve as a robust 'ground truth' standard for evaluating the finer relative uncertainties (1–2 %)
 160 associated with the GNSS and MWR retrievals. To ensure a rigorous, 'apples-to-apples' intercomparison with the active MWR,
 161 the radiosonde integration was strictly confined to a maximum altitude of 10 km Above Ground Level (AGL). This vertical

162 cutoff was deliberately chosen to exactly match the 10 km ceiling of the standard RPG-HATPRO retrieval grid. While GNSS
163 integrates delays through the entire atmosphere, bounding the in-situ reference data is mathematically necessary to isolate
164 profiling performance. It is well established that this 10 km threshold does not introduce a systematic dry bias when comparing
165 against total-column GNSS. Based on the mean radiosonde H_v of 1.51 km observed in this study, moisture decays exponentially
166 (Eq. 12) such that the absolute humidity above 10 km is nearly zero. Furthermore, ambient temperatures at this altitude range
167 from -40 °C to -50 °C, strictly limiting the saturation vapour pressure. Consequently, the residual water vapour between 10
168 km and the tropopause is thermodynamically constrained to fractions of a millimeter, falling well below the nominal 4 %
169 measurement uncertainty of the Vaisala RS41 sensor itself.

170

171 **2.2.3 GNSS Data Processing**

172 ZTD estimates were derived from the collocated Leica GR50 receiver (station NICO) using the Tefnut PP software (Douša et
173 al., 2014). The processing employed a Precise Point Positioning (PPP) strategy with an elevation cutoff angle of 10° . To
174 account for tropospheric mapping errors, the Vienna Mapping Function 1 (VMF1) was applied. Station coordinates were
175 constrained to the IGS14 reference frame, and satellite orbits and clock corrections were utilized from IGS Ultra-Rapid
176 products. While IGS Final products are the gold standard for historical climate reprocessing due to their minimal orbital
177 uncertainty, this study deliberately utilized IGS Ultra-Rapid products to evaluate the proposed synergistic retrieval architecture
178 under near real-time operational constraints. Because a primary application of continuous GNSS-PWV is its assimilation into
179 short-range NWP for severe weather 'nowcasting', it is crucial to assess system performance using the satellite orbits and clocks
180 actually available during active forecasting. Although Ultra-Rapid products introduce a slight degradation in ZTD precision
181 compared to Final products, this uncertainty (typically fractions of a millimeter in PWV) remains negligible compared to the
182 massive, multi-millimeter systematic errors introduced by static thermodynamic modeling, which is the primary focus of this
183 investigation. To isolate the ZWD, the ZHD was precisely calculated using continuous, co-located surface pressure
184 observations obtained directly from the Vaisala WXT536 weather transmitter installed at the site, rather than relying on
185 interpolated pressure fields. ZTD values were estimated at 15-minute intervals, directly aligning with the temporal resolution
186 of the MWR. It must also be noted that the computation of ZHD is fundamentally dependent on the assumed value of the dry
187 refractivity constant, k_1 . As established by Bevis et al. (1994) and further evaluated by Healy (2011), while k_1 is known to a
188 high degree of relative accuracy, its residual fractional uncertainty introduces a persistent systematic bias into the ZHD
189 estimation. Because ZWD is isolated by subtracting ZHD from the total delay, this k_1 -induced bias directly propagates into the
190 final IWV error budget, acting alongside the conversion uncertainties analyzed later in this study.

191

192 **2.3 Thermodynamic Modeling and Synergistic Retrieval Strategy**

193 The conversion of GNSS-derived ZWD to PWV is governed by a proportionality factor, Π , whose accuracy is largely dictated

194 by the T_m . To assess the fidelity of thermodynamic inputs for GNSS meteorology, we evaluated three distinct T_m derivation
 195 strategies. For profile-resolving instruments (MWR and RS), T_m values were computed by integrating the vertical profiles of
 196 physical temperature, $T(z)$ (K), and absolute humidity, $\rho_v(z)$ (kg m^{-3}). Consistent with Bevis et al. (1992), T_m is defined as the
 197 mean temperature of the atmosphere weighted by the water vapour partial pressure, which can be expressed in terms of vapour
 198 density as shown in Eq. (4):

$$199 \quad T_m = \frac{\int_{z_{surf}}^{z_{top}} \rho_v(z) dz}{\int_{z_{surf}}^{z_{top}} \frac{\rho_v(z)}{T(z)} dz} \quad (4)$$

200 In practice, the continuous integrals were discretized using the trapezoidal rule from the surface (z_{surf}) to the highest available
 201 profile level (z_{top}). This approach assumes linear variation of T and ρ_v between measurement levels. For standalone GNSS
 202 retrieval (where no dynamic profiles are available), T_m was derived from the HGPT2 (Hourly Global Pressure and Temperature
 203 2) model (Mateus et al., 2021). HGPT2 is an advanced 'blind' empirical model, meaning its outputs are independent of the
 204 specific observational year. While dynamic NWP models provide superior real-time meteorological data, 'blind' models like
 205 HGPT2 remain heavily utilized in standard geodetic GNSS processing where real-time meteorological or NWP data streams
 206 are unavailable. It is constructed from a comprehensive 20-year historical baseline of atmospheric data from the ERA5 global
 207 reanalysis. Unlike standard static climatologies, HGPT2 leverages the full ERA5 spatial resolution ($0.25^\circ \times 0.25^\circ$) and provides
 208 temporal resolution at 1-hour intervals for any given Day of Year (DOY). It achieves this by employing a time-segmentation
 209 concept, modeling thermodynamic variables via long-term mean values combined with annual, semi-annual, and quarterly
 210 periodic functions.

211 To mitigate T_m errors in MWR, a supervised linear regression model was developed to calibrate the MWR observations. For
 212 robust independent validation, the collocated dataset was separated into two distinct temporal subsets: the training Set (April
 213 – June 2025), which was used to derive the regression coefficients, and the validation Set (July – October 2025), which was
 214 used exclusively to test the correction's performance on unseen data. A simple linear correction model was fitted to the training
 215 data using Ordinary Least Squares (OLS) minimization. The relationship is defined in Eq. (5) as:

$$216 \quad T_{m,corr} = \alpha \cdot T_{m,MWR} + \beta \quad (5)$$

217 where $T_{m,corr}$ is the corrected MWR temperature, $T_{m,MWR}$ is the raw T_m derived from the radiometer and α (slope) and β
 218 (intercept) are the learned coefficients minimizing the residual sum of squares between the MWR and RS values. Based on
 219 our training Set (April–June 2025), the derived coefficients applied to the validation Set were $\alpha = 1.0623$ and $\beta = -15.6062$ K.
 220 To quantify the benefits of sensor synergy in integrated water vapour estimation, this study defines and contrasts two distinct
 221 GNSS PWV retrieval architectures. The first, “Standard Retrieval” which is a control method utilizes the ZTD_{GNSS} combined
 222 with the T_m derived empirically from the HGPT2 climatological model (Böhm et al., 2015). Second “Synergistic Retrieval”
 223 which proposed method couples ZTD_{GNSS} with a physical T_m derived directly from a collocated MWR. For the synergistic
 224 approach, the dimensionless conversion factor (I) was calculated dynamically using the MWR-derived T_m following Eq. (6)

225 and Eq. (7).

$$226 \quad PWV = \Pi \cdot ZWD \quad (6)$$

$$227 \quad \Pi = \frac{10^6}{\rho_w R_v [k_2' + (k_3/T_m)]} \quad (7)$$

228

229 where ρ_w represents the density of liquid water (1000 kg m^{-3}) and R_v is the specific gas constant for water vapour (461.52 J
 230 $\text{kg}^{-1}\text{K}^{-1}$). To assess the sensitivity of the Π to the choice of thermodynamic coefficients, three widely used formulations were
 231 employed in this study, following Davis (1985)/Thayer (1974), Bevis et al. (1994), and Rüeiger (2002), as shown in Table 2:

232 **Table 2.** Refractivity constants used in the sensitivity analysis of the Π factor, based on three commonly adopted formulations.

Method	k_2 (K hPa ⁻¹)	k_3 (K ² hPa ⁻¹)	k_2' (K hPa ⁻¹)
Davis (1985) / Thayer (1974)	64.79	3.776×10^5	16.52
Bevis et al. (1994)	70.40	3.739×10^5	22.13
Rüeiger (2002)	71.295	3.7546×10^5	22.97

233

234 To rigorously quantify the uncertainty in the final IWV (which is numerically equivalent to PWV) retrieval and avoid
 235 fragmented error attributions, standard error propagation must be applied to the fundamental conversion Eq. 6. Assuming the
 236 uncertainties in the wet delay and the conversion factor are uncorrelated, the variance of the final IWV (σ_{IWV}^2) is expressed
 237 using partial derivatives as in Eq. (8):

$$238 \quad \sigma_{IWV}^2 = \left(\frac{\partial IWV}{\partial ZWD}\right)^2 \sigma_{ZWD}^2 + \left(\frac{\partial IWV}{\partial \pi}\right)^2 \sigma_{\pi}^2 \quad (8)$$

239 Evaluating these primary partial derivatives yields the proportional contributions of the geodetic and thermodynamic
 240 components as shown in Eq. (9):

$$241 \quad \sigma_{IWV}^2 = \pi^2 \sigma_{ZWD}^2 + ZWD^2 \sigma_{\pi}^2 \quad (9)$$

242 The uncertainty in the conversion factor (σ_{π}^2) is itself a compound term driven by the T_m and the static atmospheric refractivity
 243 constants (k_2' and k_3). Its variance is defined via partial derivatives as shown in Eq. (10):

$$244 \quad \sigma_{\pi}^2 = \left(\frac{\partial \pi}{\partial T_m}\right)^2 \sigma_{T_m}^2 + \left(\frac{\partial \pi}{\partial k_2'}\right)^2 \sigma_{k_2'}^2 + \left(\frac{\partial \pi}{\partial k_3}\right)^2 \sigma_{k_3}^2 \quad (10)$$

245 The sensitivity of the conversion factor strictly to T_m (the dynamic thermodynamic variable evaluated in this study) is quantified
 246 by its partial derivative and it represented as Eq. (11):

$$247 \quad \frac{\partial \pi}{\partial T_m} = \pi \left[\frac{k_3}{T_m^2 (k_2' + \frac{k_3}{T_m})} \right] \quad (11)$$

248 This consolidated formulation establishes the exact mathematical limits of thermodynamic error propagation. As demonstrated
249 in the sensitivity analysis (Section 3.4), this framework accurately isolates the dynamic uncertainties driven by T_m from the
250 baseline static biases introduced by the chosen refractivity constants.

251

252 **2.4 Diagnostic Parameters and Error Analysis**

253 The vertical structure of the atmosphere was analyzed by segregating the dataset into two regimes: the PBL (0–2 km), where
254 water vapour is concentrated, and the Free Troposphere (> 2 km). Additionally, the scale height (H_v) was calculated to quantify
255 the vertical distribution of moisture. This parameter is crucial because it provides a single, representative value for the rate at
256 which water vapour decreases with altitude, which is a key factor in understanding atmospheric stability, cloud formation, and
257 radiative transfer processes. H_v was derived for both RS and MWR by fitting an exponential decay function (Eq. 12) to the
258 absolute humidity profile (ρ_v). This curve fitting was deliberately restricted to the lowest 4 km of the atmosphere because this
259 layer contains the vast majority (>90 %) of the tropospheric water vapour mass. As established in climatological studies (e.g.,
260 Trenberth et al., 2005; Weaver and Ramanathan, 1995), atmospheric water vapour decays exponentially with a typical scale
261 height of 1.5 to 2.5 km. Above 4 km, moisture levels approach the noise floor of both the MWR and the RS sensors, and the
262 profile frequently deviates from a standard exponential decay due to complex layering or subsidence inversions. Forcing an
263 exponential fit over the entire 10 km column causes the algorithm to heavily weight near-zero, noisy upper-tropospheric values,
264 which mathematically degrades the curve fit for the boundary layer where the bulk mass actually resides (Tomasi, 1984).
265 Therefore, the 4 km limit is a necessary mathematical boundary to ensure a physically meaningful fit.

$$266 \quad \rho_v(z) = \rho_{v,0} \cdot \exp\left(-\frac{z}{H_v}\right) \quad (12)$$

267 where $\rho_v(z)$ is the absolute humidity at height z , and $\rho_{v,0}$ is the surface humidity. Furthermore, the scale height metric
268 fundamentally assumes the atmosphere conforms to a well-behaved exponential decay. During complex meteorological
269 states—such as deep convective mixing, strong elevated moist layers, or severe shallow inversions—the true vertical moisture
270 distribution breaks this exponential assumption. Forcing a mathematical fit onto these non-exponential profiles yields
271 physically meaningless artifacts. Therefore, a Quality Assurance filter was applied, bounding the analysis to the physically
272 realistic range of $0.1 \text{ km} < H_v < 4.0 \text{ km}$. Profiles yielding values outside this range were discarded because they indicate the
273 underlying exponential model itself is invalid for that specific atmospheric profile, preventing artificial statistical skewing in
274 the instrument intercomparison. Profiles yielding H_v values outside the physically realistic range of 0.1 to 4.0 km were excluded
275 from the statistical analysis. To evaluate the performance limitations of standard climatological models under varying
276 hygrometric conditions, the systematic error (ΔPWV) was defined as the residual between the synergistic and standard
277 approaches (Eq. 13):

$$278 \quad \Delta PWV = PWV_{Synergistic} - PWV_{Standard} \quad (13)$$

279 The dataset was stratified into discrete bins of 5 mm PWV to isolate regimes of moisture abundance. Within each bin, the
 280 mean bias and $\pm 1\sigma$ uncertainty were computed. These statistics were utilized to determine the "Systematic Bias Threshold,"
 281 defined herein as the specific hygrometric threshold where the systematic model error exceeds 1 mm. Finally, the propagation
 282 of thermodynamic uncertainty into the moisture retrieval was quantified via linear regression analysis. This compared the
 283 relative error in T_m (HGPT2 vs. MWR) against the resulting relative error in PWV, serving as an empirical verification of the
 284 theoretical sensitivity approximation given in Eq. (14):

$$285 \quad \frac{\Delta PWV}{PWV} \approx \frac{\Delta T_m}{T_m} \quad (14)$$

286 **3 Results** 287

288 The following evaluation follows a top-down diagnostic approach. First, the macroscopic baseline performance of the final
 289 derived moisture products is established. Subsequently, the underlying thermodynamic variables driving these discrepancies
 290 are isolated, culminating in the development of a targeted calibration scheme to mitigate the identified biases.

291 **3.1 Temperature and Humidity Profile Validation**

292 MWR-retrieved temperature T and ρ_v profiles were validated against collocated RS observations at 00:00 UTC and 12:00 UTC
 293 during March–October 2025. Profiles were stratified into the planetary boundary layer (PBL; 0–2 km) and free troposphere
 294 (>2 km), as shown in Figs. 2 and 3. Mean vertical temperature profiles show agreement between MWR and RS (Fig. 2a–b).
 295 In the boundary layer (0–2 km), MWR retrieves temperature with high precision ($r > 0.98$, $RMSE < 1.5$ K). Above 2 km, a cold
 296 bias is observed in the MWR retrieval, reaching -5.16 K at 12 UTC (Fig. 2f). Despite this bias, the linearity remains strong
 297 ($r \approx 0.97$), indicating the sensor captures relative thermal variations aloft despite the absolute offset. This confirms the trend
 298 observed in the mean profiles, where the MWR underestimates temperatures in the mid-to-upper troposphere. Consequently,
 299 the RMSE increases substantially to approximately 6.4–6.7 °C. The stark contrast in accuracy between the lower and upper
 300 troposphere is a known characteristic of ground-based microwave radiometry (Parde et al., 2025; Pakkattil et al., 2025). The
 301 high accuracy below 2 km is attributed to the high information content of the opaque V-band channels (51–58 GHz), whose
 302 weighting functions peak near the surface. Above 2 km, these weighting functions broaden significantly, reducing vertical
 303 resolution and causing a "smearing" effect where the instrument provides a volume-averaged temperature rather than a precise
 304 point measurement. The observed cold bias is likely a result of the retrieval algorithm (e.g., neural network) relying heavily
 305 on a climatological *a priori* dataset that does not perfectly represent the thermal conditions of the transition season observed,
 306 or systematic offsets in the radiative transfer model (absorption coefficients) used for training.

307 The mean ρ_v profiles (Figs. 3a–b) show the expected exponential decrease of moisture with height. At 00 UTC, the profiles
 308 align reasonably well. However, at 12 UTC, the MWR profile exhibits a structural deviation between 1–2 km, failing to capture
 309 the smooth moisture gradient recorded by the RS. This discrepancy may be attributed to the MWR's limited vertical resolution

310 during periods of active daytime mixing or complex humidity layering. The retrieval of humidity in the lower atmosphere
311 shows moderate agreement but is less accurate than the temperature retrievals. Performance is notably better at night (00 UTC)
312 with r of 0.878 and RMSE of 1.98 g m^{-3} . At 12 UTC, the correlation drops to 0.744, and the scatter increases (RMSE = 2.31 g
313 m^{-3}). A negative bias persists at both times (-0.51 g m^{-3} at 00 UTC and -0.91 g m^{-3} at 12 UTC), indicating a tendency for the
314 MWR to underestimate moisture content in the boundary layer, particularly during the day. Surprisingly, the statistical linearity
315 for ρ_v improves slightly or remains stable above 2 km, likely due to the lower overall magnitude of humidity at these heights.
316 The correlation coefficients remain stable (~ 0.87). In contrast to the lower levels, the bias shifts to slightly positive values
317 (0.23 g m^{-3} at 00 UTC and 0.46 g m^{-3} at 12 UTC), suggesting a slight moist bias in the MWR retrievals aloft. The linear fits
318 (Figs. 3e–f) align closely with the 1:1 line, with slopes near unity (0.90 and 1.00), indicating that the MWR effectively captures
319 the free tropospheric humidity trends despite the lower absolute values. The difficulty in retrieving accurate ρ_v profiles,
320 particularly at 12 UTC, stems from the limited vertical resolution of the K-band channels (22–31 GHz). Unlike temperature
321 profiling, humidity profiling offers very few independent degrees of freedom (typically < 3), making it difficult for the MWR
322 to resolve sharp vertical gradients often present at the top of the convective boundary layer during the daytime. The structural
323 deviation and underestimation are common issues linked to the "smoothing" error inherent in passive radiometry, where sharp
324 moisture inversions are averaged out. Furthermore, the persistent bias suggests potential uncertainties in the water vapour
325 absorption models (spectroscopic parameters) or non-representative training data used in the retrieval algorithm.
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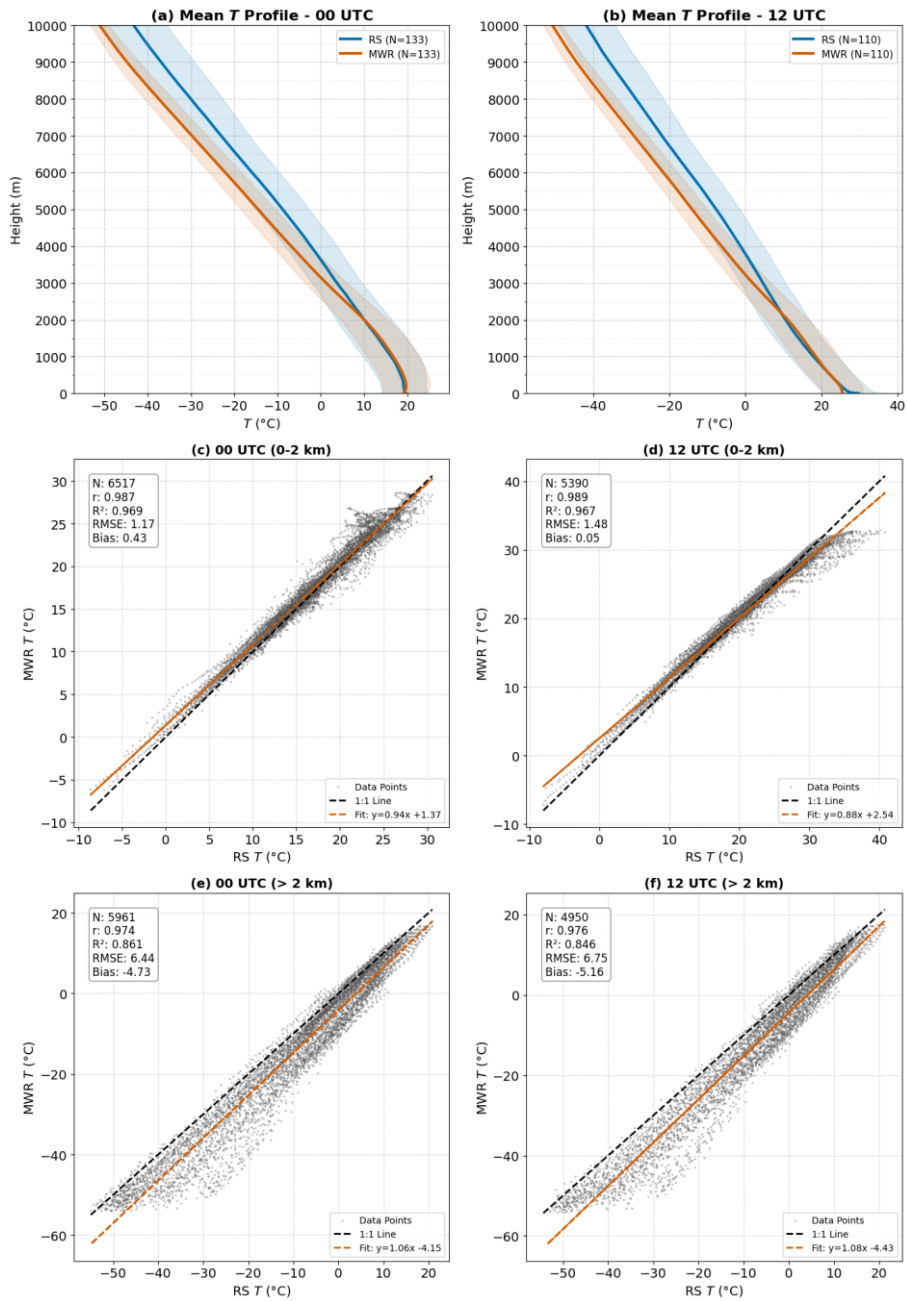


Figure 2. Comparison of radiosonde and microwave radiometer (MWR) temperature profiles: (a–b) Mean vertical temperature (T) profiles at 00 and 12 UTC with variability shading; (c–f) Scatter comparisons for the lower (0–2 km) and upper (>2 km) atmosphere at both times.

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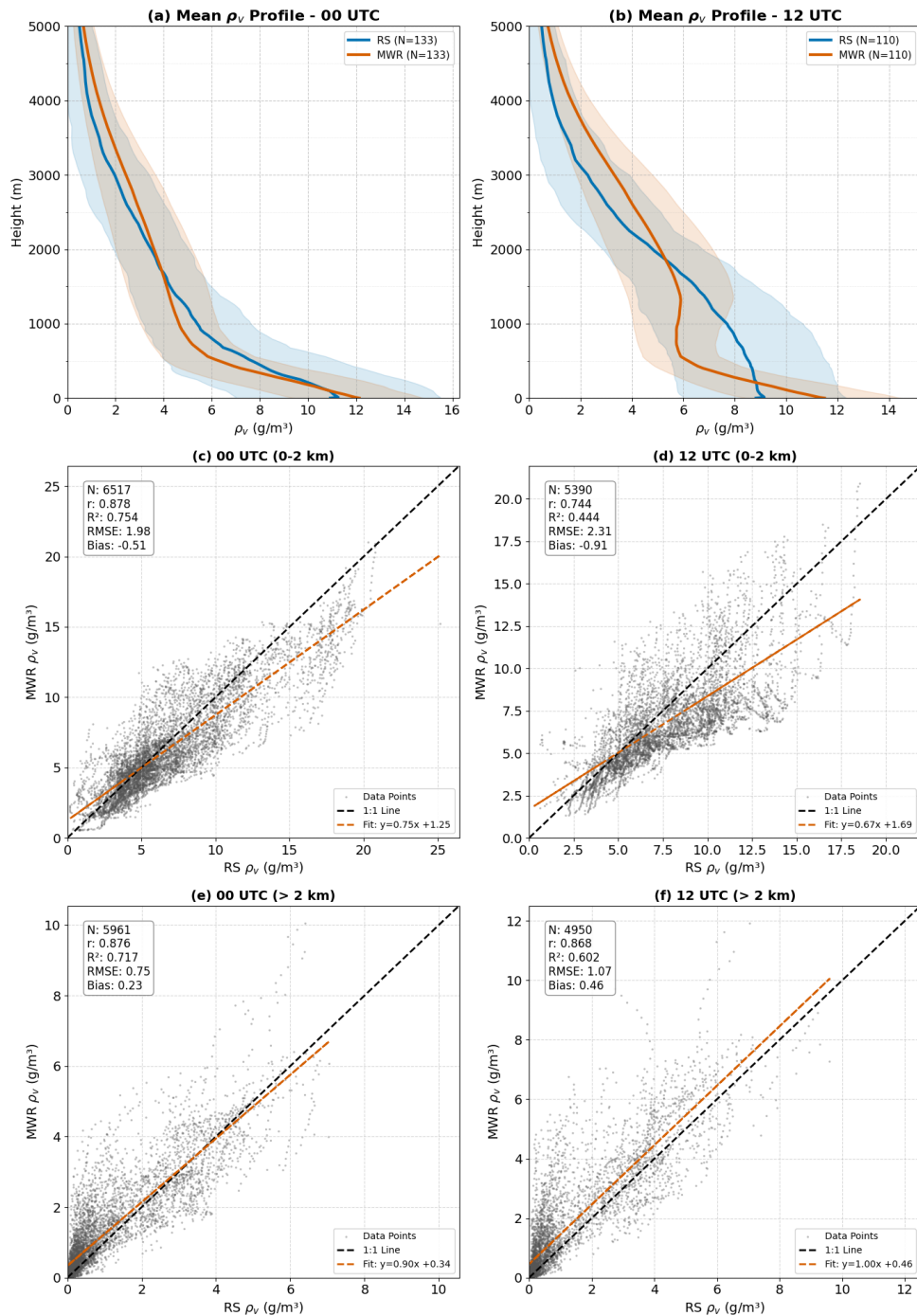
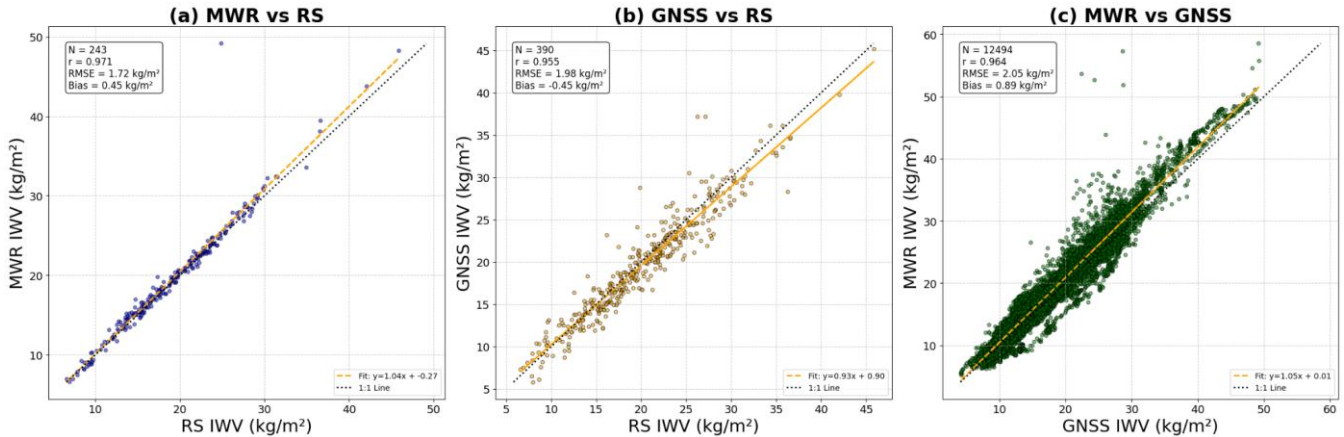


Figure 3. Comparison of radiosonde and microwave radiometer (MWR) absolute humidity (ρ_v) profiles: (a–b) Mean vertical ρ_v profiles at 00 and 12 UTC with variability shading; (c–f) Scatter comparisons for the lower (0–2 km) and upper (>2 km) atmosphere at both times.

3.2 Integrated Water Vapour (IWV) and Scale Height (H_v) Validation

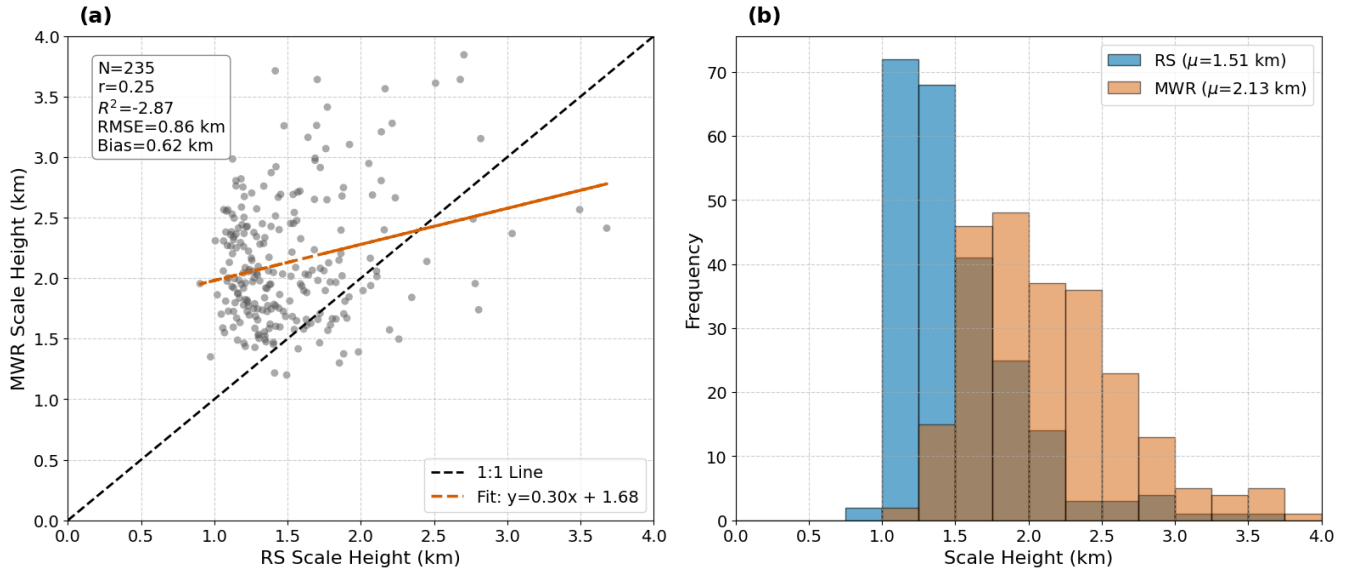
336 Unlike vertical profiling, the MWR excels in measuring total column quantities. The comparison with RS yields an excellent
 337 correlation ($r=0.971$) and a low RMSE of 1.72 kg m^{-2} . This performance disparity—superior IWV versus degraded profiles—
 338 confirms that while the sensor cannot resolve vertical structural details due to smoothing error, the radiometric brightness
 339 temperature in the K-band remains strictly proportional to the total precipitable water mass. The GNSS-derived IWV shows a
 340 slight negative bias relative to RS (-0.45 kg m^{-2}), whereas it relative to the MWR exhibits a positive bias ($+0.45 \text{ kg m}^{-2}$). The
 341 cumulative offset observed in the MWR-GNSS intercomparison ($+0.89 \text{ kg m}^{-2}$) highlights the systematic differences in
 342 calibration and retrieval assumptions between active (GNSS) and passive (MWR) techniques. The GNSS underestimation is
 343 likely driven by errors in the T_m derived from the static HGPT2 model, a hypothesis further explored in Section 3.4. The
 344 derivation of the H_v is admittedly a crude, single-parameter representation of the complex atmospheric moisture profile.
 345 However, it is utilized in this study specifically as a diagnostic metric to quantify the structural limitations of passive
 346 microwave remote sensing. The comparison of H_v calculated from RS and MWR profiles is shown in Fig. 5. Unlike the high-
 347 fidelity IWV retrievals, the MWR-derived scale height shows negligible correlation with RS observations ($r=0.25$, $R^2=-2.87$)
 348 and a massive systematic positive bias of 0.62 km . The histograms (Fig. 5b) further elucidate this discrepancy: while the RS
 349 scale heights follow a narrow, physically realistic distribution centered around a mean (μ) of 1.51 km , the MWR distribution
 350 is artificially broad and shifted to significantly higher values ($\mu=2.13 \text{ km}$).



351
 352 **Figure 4.** Intercomparison of integrated water vapour (IWV) retrieved from Microwave Radiometer (MWR), GNSS, and Radiosonde
 353 observations. (a) MWR IWV versus radiosonde IWV, (b) GNSS IWV (derived using HGPT2 T_m) versus radiosonde IWV, and (c) MWR
 354 IWV versus GNSS IWV (derived using HGPT2 T_m).

355 The large scatter and ambiguity in the MWR estimates—which completely dwarf the individual least-squares fit
 356 uncertainties of the exponential regression—are a direct consequence of the instrument's physical limitations. H_v is highly
 357 sensitive to the sharp vertical gradient of humidity at the top of the planetary boundary layer. However, the K-band channels
 358 (22–31 GHz) utilized for humidity profiling possess broad weighting functions, restricting the vertical degrees of freedom to
 359 typically fewer than three. Because the MWR lacks the vertical resolution to capture sharp moisture inversions, the retrieval
 360 algorithm mathematically smears the moisture mass upward. This inherent 'smoothing error' artificially elongates the vertical

361 moisture profile, effectively inflating the calculated e-folding depth. Therefore, the inclusion of this H_v analysis serves to
 362 transparently demonstrate a critical operational boundary: while the MWR is an excellent standard for IWV, it is fundamentally
 363 unreliable and mathematically unsuited for characterizing vertical moisture compactness. The significant deviations observed
 364 in these macroscopic retrieval products necessitate a deeper investigation into the intermediate thermodynamic variables
 365 driving the conversion process. Consequently, the isolated performance of the T_m is evaluated in Section 3.3, followed by the
 366 introduction of a post-retrieval MWR calibration scheme in Section 3.4 designed to mitigate these native biases.



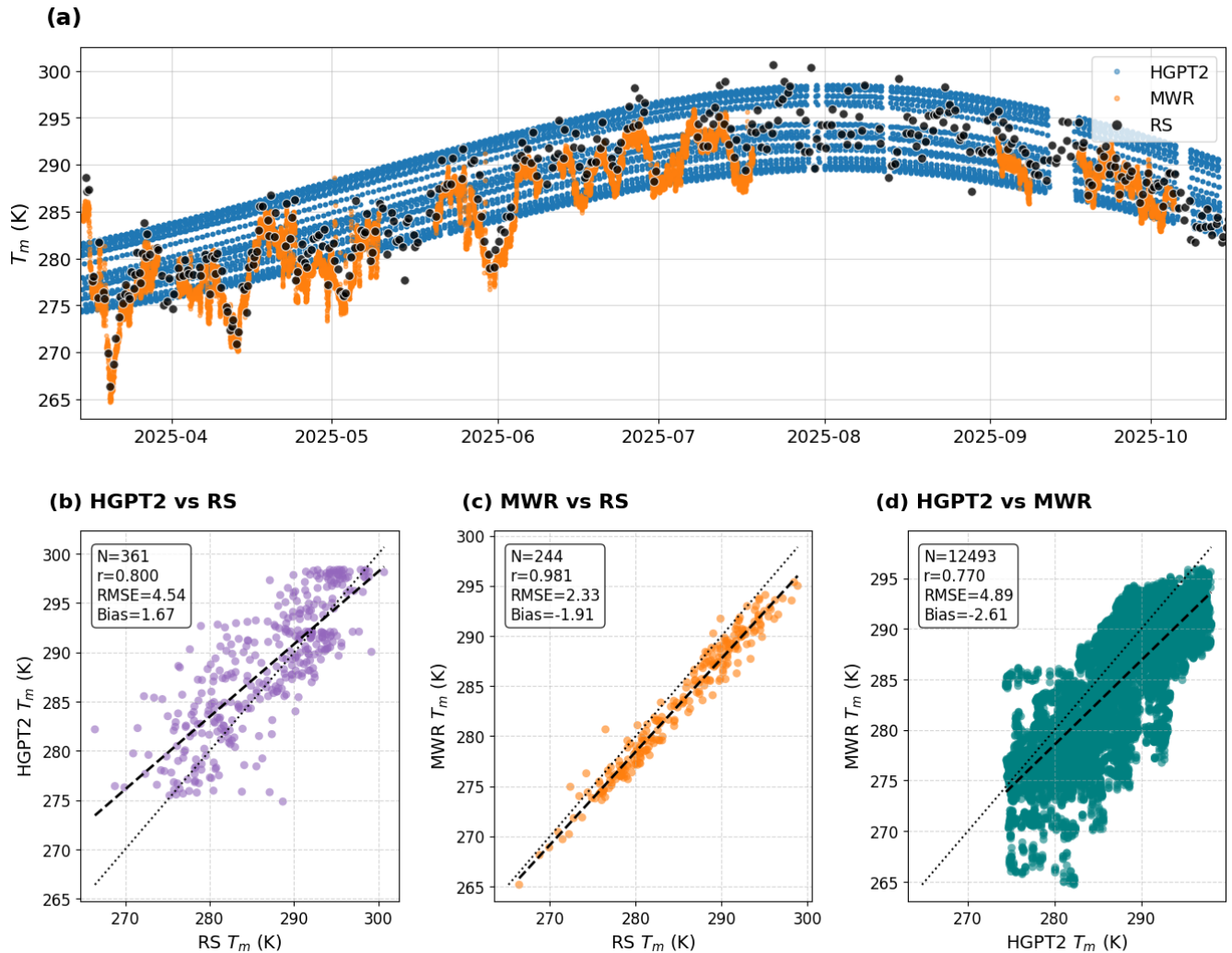
367 **Figure 5:** Comparison of scale height from radiosonde (RS) and microwave radiometer (MWR): (a) Scatter plot with 1:1 line and linear fit,
 368 including summary statistics; (b) Frequency distributions showing mean scale heights for RS and MWR.
 369

370

371 3.3 Weighted Mean Temperature (T_m) Validation

372 The accurate estimation of the T_m is critical for converting GNSS-derived ZWD into PWV. The performance of T_m derived
 373 from the MWR and the empirical GPT2w model (HGPT2) was evaluated against RS measurements, which serve as the "ground
 374 truth." The results are presented in Fig. 6. The time series (Fig. 6a) illustrates the seasonal evolution of T_m from April to October
 375 2025. The Radiosonde observations (black dots) show significant variability, capturing synoptic-scale weather fluctuations.
 376 The MWR-derived T_m (orange dots) tracks these fluctuations with remarkable precision, overlaying the RS points almost
 377 perfectly. In stark contrast, the HGPT2 model (blue dots) provides a smooth, climatological curve. While it captures the general
 378 seasonal trend, it completely misses the day-to-day thermodynamic variability, often overestimating T_m during cooler transient
 379 events and underestimating it during warmer anomalies. The empirical model shows only moderate performance ($r=0.800$)
 380 with a substantial spread ($RMSE = 4.54$ K). A systematic positive bias of 1.67 K indicates that HGPT2 generally overestimates
 381 the atmospheric temperature profile in this region. The scatter plot reveals a diffuse, "cloud-like" distribution, confirming its
 382 inability to capture real-time atmospheric dynamics. The MWR demonstrates superior performance, achieving a near-perfect

383 correlation ($r=0.981$). The RMSE is significantly reduced to 2.33 K, which is nearly half the error of the empirical model.
384 Interestingly, the MWR exhibits a negative bias of -1.91 K, suggesting a systematic underestimation of T_m . Crucially, this bias
385 does not originate in the free troposphere, but rather in the planetary boundary layer (0–3 km). Since T_m is weighted by water
386 vapour pressure, this "cold bias" indicates the MWR is underestimating the intense near-surface heating or the sharp lapse
387 rates characteristic of the Nicosia environment. Despite this offset, the tight linearity indicates that MWR is an excellent source
388 for capturing real-time T_m variations. Comparing the large dataset of MWR against HGPT2 ($N=12,493$) confirms the
389 discrepancy between dynamic and static modeling. The correlation is lower ($r=0.770$) and the scatter is large (RMSE = 4.89
390 K), further proving that static empirical models are insufficient for high-precision GNSS meteorology compared to dynamic
391 radiometer measurements. While errors in ZTD estimation contribute significantly to the overall uncertainty budget, the
392 specific error introduced during the conversion from delay to water vapour is linearly dependent on the accuracy of T_m .
393 Assuming a given ZTD, a standard rule of thumb states that a 1 % relative error in T_m translates to roughly a 1 % relative error
394 in the resulting PWV. By switching from a static model (HGPT2, ~ 4.5 K error) to a dynamic sensor (MWR, ~ 2.3 K error),
395 the uncertainty in the GNSS water vapour product is effectively halved. This validates the "synergistic" approach of using
396 collocated MWR thermal data to process GNSS signals.



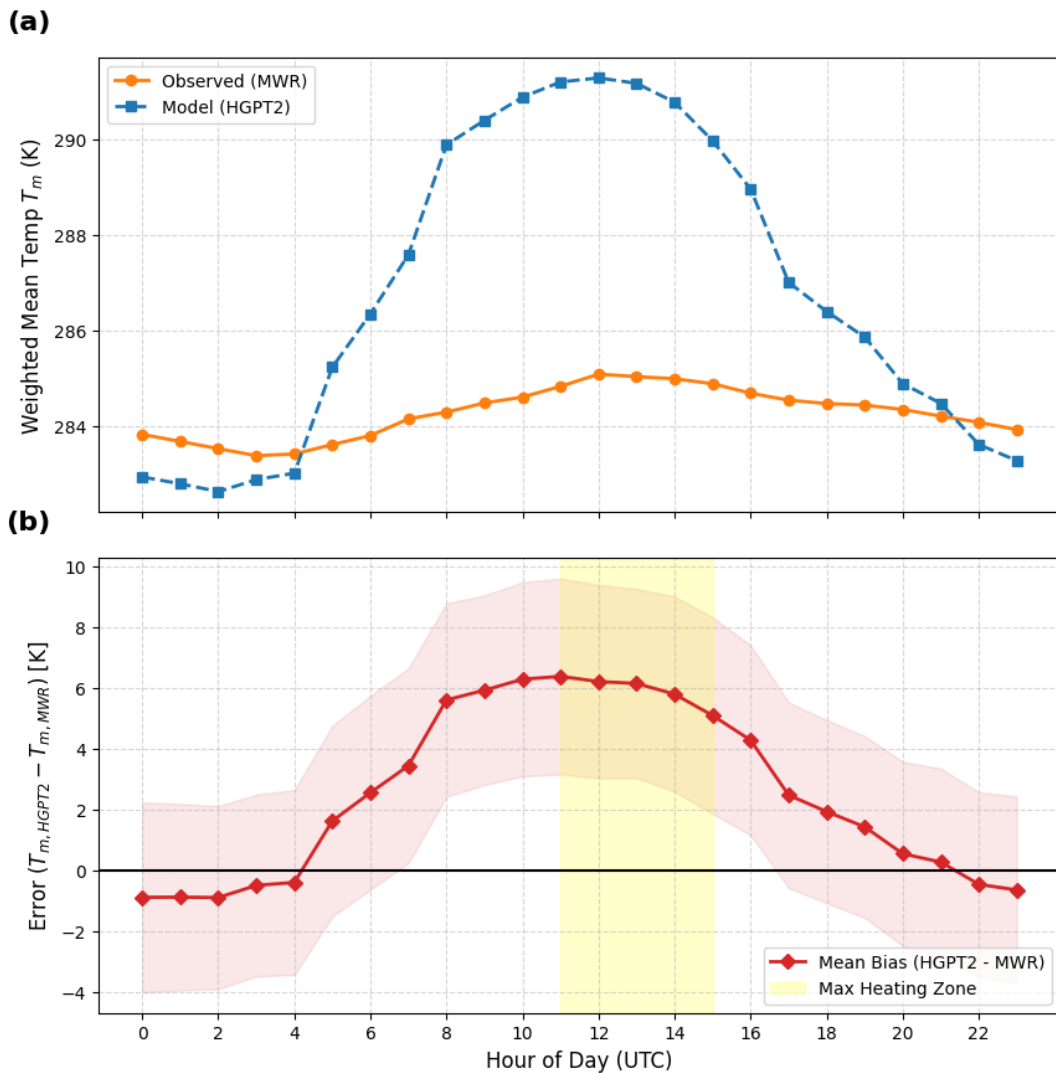
397
 398 **Figure 6.** Comparison of weighted mean temperature (T_m) derived from HGPT2, MWR, and Radiosonde (RS) during March–November
 399 2025. (a) Time series of T_m estimates from all three sources. (b–d) Scatter plots showing statistical comparisons between: (b) HGPT2 vs.
 400 RS, (c) MWR vs. RS, and (d) HGPT2 vs. MWR.

401 3.4 Diagnostic Analysis of Thermodynamic Conversion Uncertainty

402 3.4.1 Diurnal Bias Amplification in Static Models

403 To pinpoint the physical origin of the HGPT2 model's deficiency, a diurnal cycle analysis was performed (Fig. 7). While the
 404 previous statistical metrics indicated a general positive bias, the temporal breakdown in Fig. 7a reveals that this error is not
 405 uniform, but is driven by a fundamental misrepresentation of atmospheric thermodynamics. The MWR-derived T_m (orange
 406 line) exhibits a physically realistic, dampened diurnal amplitude of approximately 1.5 K. This stability reflects the high thermal
 407

408 inertia of the tropospheric column, which does not heat rapidly in response to surface insolation. In stark contrast, the HGPT2
409 model (blue line) displays an exaggerated diurnal wave with an amplitude exceeding 8.5 K, peaking synchronously with solar
410 noon (12:00 UTC). As previously documented in the literature (Wang, 2005; Bock, 2021), deriving T_m via empirical regression
411 on surface skin temperature (T_s) is known to introduce spurious diurnal cycles. Our observations confirm this intrinsic
412 limitation: because the empirical model's periodic functions are overly sensitive to T_s , it assumes intense skin-level heating
413 propagates uniformly through the column, failing to capture the true thermodynamic decoupling between the turbulent
414 planetary boundary layer and the stable free troposphere. During the hours of peak solar insolation (11:00–14:00 UTC), the
415 coastal environment experiences active convective mixing and the onset of the sea breeze, which dramatically alters the vertical
416 distribution of water vapour. If the underlying reanalysis climatology fails to adequately resolve the sharp moisture capping
417 inversion at the top of the daytime planetary boundary layer (PBL), it will misrepresent the T_m weighting function. Specifically,
418 if the model traps too much moisture near the intensely heated surface—or fails to capture the thermodynamic decoupling
419 between the turbulent PBL and the stable free troposphere — the integral will disproportionately weight the hottest atmospheric
420 layers. This coupled temperature-humidity mechanism physically manifests as the severe diurnal bias peak effect observed in
421 Fig. 7b, where the systematic bias surges to over +6 K. This demonstrates that high-precision GNSS meteorology requires
422 synergistic MWR data to capture both the true thermal stability and the dynamic vertical moisture weighting of the atmosphere.
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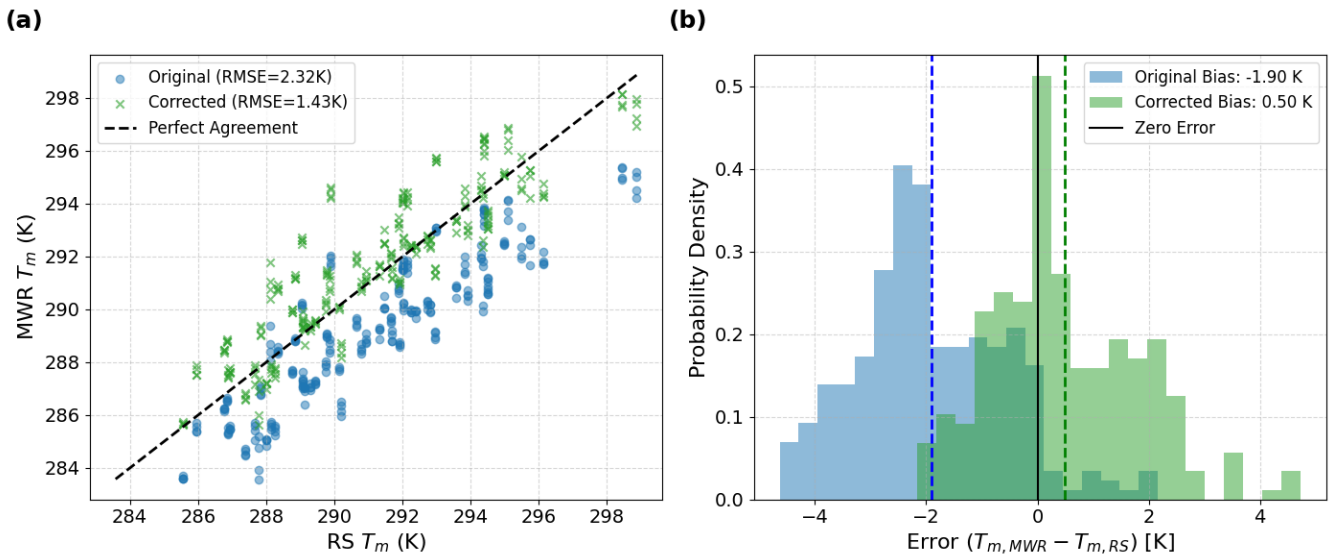
Figure 7. Diurnal variation of weighted mean atmospheric temperature T_m derived from microwave radiometer (MWR) observations and HGPT2 model simulations (top panel). The bottom panel shows the corresponding hourly mean bias ($T_{m,HGPT2} - T_{m,MWR}$), with shaded envelopes indicating variability. The yellow shaded region highlights the period of maximum daytime heating.

429 3.4.2 Calibration and Bias Correction of MWR T_m

430 Fig. 8 presents a statistical validation of the MWR derived T_m against co-located RS observations. The analysis highlights the
431 necessity and efficacy of a linear bias correction scheme to improve GNSS-PWV conversion accuracy. The scatter plot (Fig.
432 2a) reveals a distinct systematic deviation in the original MWR retrieval relative to the RS reference. The data points
433 consistently fall below the 1:1 identity line, indicating a negative bias in the raw MWR T_m product. The original RMSE is 2.32
434 K. This error is largely driven by the systematic offset rather than random scatter, as evidenced by the high linearity (R^2) of

435 the relationship. The thermodynamic profiles were retrieved using the manufacturer's standard Neural Network (NN)
436 algorithm, trained on Region historical RS data.

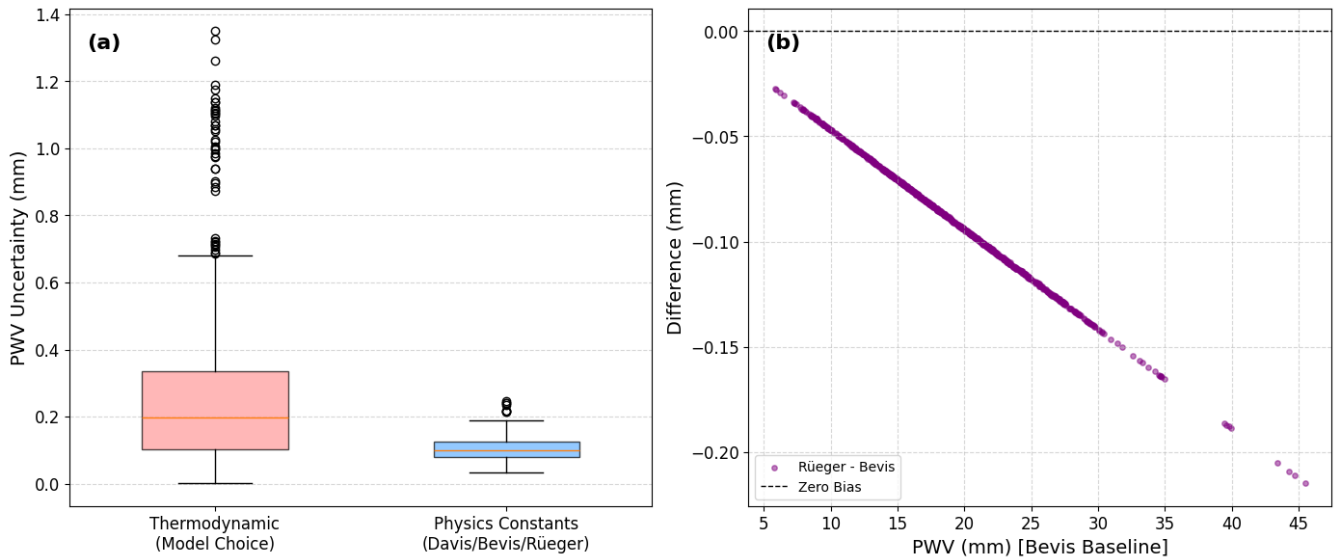
437 The Probability Density Function (PDF) of the errors ($T_{m,MWR}-T_{m,RS}$) in Fig. 8b clearly visualizes the bias shift. The pre-
438 correction distribution is non-Gaussian and shifted significantly to the negative domain, with a mean bias (μ) of -1.90 K. In
439 the context of GNSS meteorology, a T_m error of ≈ 2 K translates to a relative PWV error of approximately 0.7–1.0 %. For
440 climate monitoring, this represents a significant systematic dry bias. Applying the linear correction model ($T_{m,corr}=\alpha T_{m,raw}+\beta$)
441 successfully re-centers the error distribution. The post-correction bias is reduced to 0.50 K, and the histogram aligns
442 symmetrically around the zero-error line. The correction reduces the RMSE to 1.43 K, which is consistent with the theoretical
443 accuracy limit of ground-based radiometric profiling (typically 1–2 K). The remaining spread (width of the green histogram)
444 represents the random error component, likely attributable to instrumental noise and the imperfect spatiotemporal matching
445 between the instantaneous MWR zenith view and the drifting radiosonde balloon. The correction methodology effectively
446 removes the systematic instrumental bias without artificially compressing the natural variability of the atmosphere. The
447 reduction of RMSE by ~ 38 % (from 2.32 K to 1.43 K) confirms that site-specific calibration of T_m is a mandatory processing
448 step for generating climate-quality GNSS-PWV datasets.



449 **Figure 8.** Evaluation of weighted mean temperature T_m correction against Radiosonde (RS) observations. (a) scatter plots of original and
450 bias-corrected MWR-derived T_m versus RS T_m , with the dashed line indicating perfect agreement. (b) presents the probability density of
451 errors ($T_{m,MWR}-T_{m,RS}$) before and after correction, demonstrating a substantial reduction in cold bias and RMSE.
452
453

454 3.4.3 Uncertainty Budget Analysis

455



456 **Figure 9.** (a) PWV uncertainty attributed to thermodynamic assumptions and to the choice of refractivity constants. (b) Difference in GNSS-
 457 derived PWV resulting from the use of alternative refractivity constant formulations relative to Bevis et al. (1994).
 458

459
 460 In standard GNSS network processing, the largest source of PWV uncertainty is often the interpolation or modeling of
 461 surface pressure required to calculate the ZHD (Van Malderen et al., 2022). However, the CYGMEN observatory setup
 462 mitigates this spatial interpolation error by utilizing the co-located Vaisala WXT536 sensor, which has a stated pressure
 463 accuracy of ± 0.5 hPa. A 0.5 hPa pressure uncertainty propagates to approximately 1.15 mm of error in the ZHD. After applying
 464 the Π conversion factor, this restricts the pressure-induced PWV uncertainty to roughly ± 0.17 mm. Because this high-precision
 465 localized pressure data effectively minimizes ZHD uncertainty, the accuracy of the T_m parameterization emerges as the
 466 dominant remaining variable in the PWV error budget for this site.

467 It is important to note that the complete error budget for GNSS-derived PWV encompasses significant uncertainties
 468 originating from the ZTD estimation phase itself. These include geodetic errors such as satellite orbit and clock uncertainties,
 469 mapping function inaccuracies, and site-dependent electromagnetic effects like signal scattering and multipath. While these
 470 geodetic factors are critical, the following component-wise uncertainty analysis (Fig. 9) specifically isolates the errors
 471 introduced during the subsequent conversion step (Π). To decouple these retrieval contributions, two primary sources of
 472 uncertainty were isolated: the thermodynamic parameterization of T_m and the selection of atmospheric refractivity constants
 473 (k_2' , k_3). When decoupling these retrieval contributions, it is critical to distinguish between the statistical nature of the
 474 underlying error sources. As demonstrated by Healy (2011), uncertainties in the atmospheric refractivity constants (k_2' , k_3) act
 475 strictly as static systematic biases; selecting a different set of published constants permanently shifts the baseline of the Π by
 476 a fixed margin. Conversely, the uncertainty originating from the T_m parameterization is a dynamic, compound error. As
 477 highlighted by Wang et al. (2005) and Bock et al. (2021), empirical T_m models derived from surface temperatures often fail to

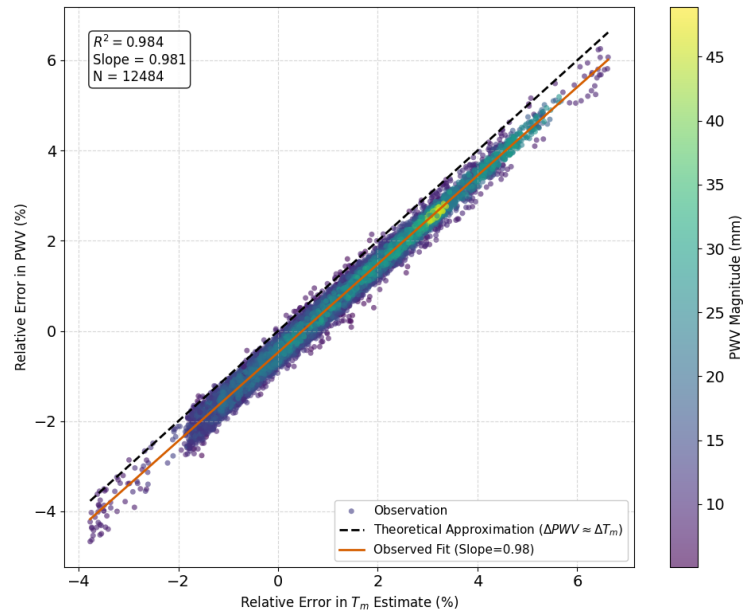
478 capture the true profile variance, introducing both a systematic bias (the model's mean regional offset) and a substantial random
479 error component (the statistical scatter, or RMSE, driven by real-time thermodynamic variability and diurnal decoupling).
480 While Fig. 9 juxtaposes these two distinct sources to illustrate their relative bounding magnitude on the final IWV product,
481 their fundamentally different statistical behaviors—static bias versus dynamic scatter—must be acknowledged. As illustrated
482 in Fig. 9(a), the uncertainty introduced by the T_m estimation strategy significantly outweighs the influence of the physical
483 constants. Specifically, the stochastic variability from modeling T_m (comparing HGPT2 climatology against direct radiometric
484 observation) results in a retrieval error of approximately 1–2 mm. In contrast, the uncertainty associated with the choice of
485 refractivity coefficients—defined here as the maximum divergence between the historical Davis et al. (1985), the standard
486 Bevis et al. (1994), and the updated Rüeiger (2002) formulations—remains an order of magnitude smaller. Fig. 9(b) further
487 resolves the impact of the refractivity constants, showing the differential bias between the oldest (Davis) and newest (Rüeiger)
488 standards. The relationship is linear and proportional to the total water vapour content, consistent with a scaling of the Π factor.
489 While the transition to the Rüeiger (2002) constants introduces a systematic positive shift, the magnitude of this correction
490 (typically <0.2 mm for standard loading) is negligible for synoptic meteorological applications compared to the noise induced
491 by T_m errors. However, for long-term climatological trend analysis where stability is paramount, consistent adherence to the
492 Rüeiger (2002) standard is recommended to eliminate this small, but persistent systematic bias. Overall, the correction of the
493 T_m is 2.5 times more important than selection of the constant.

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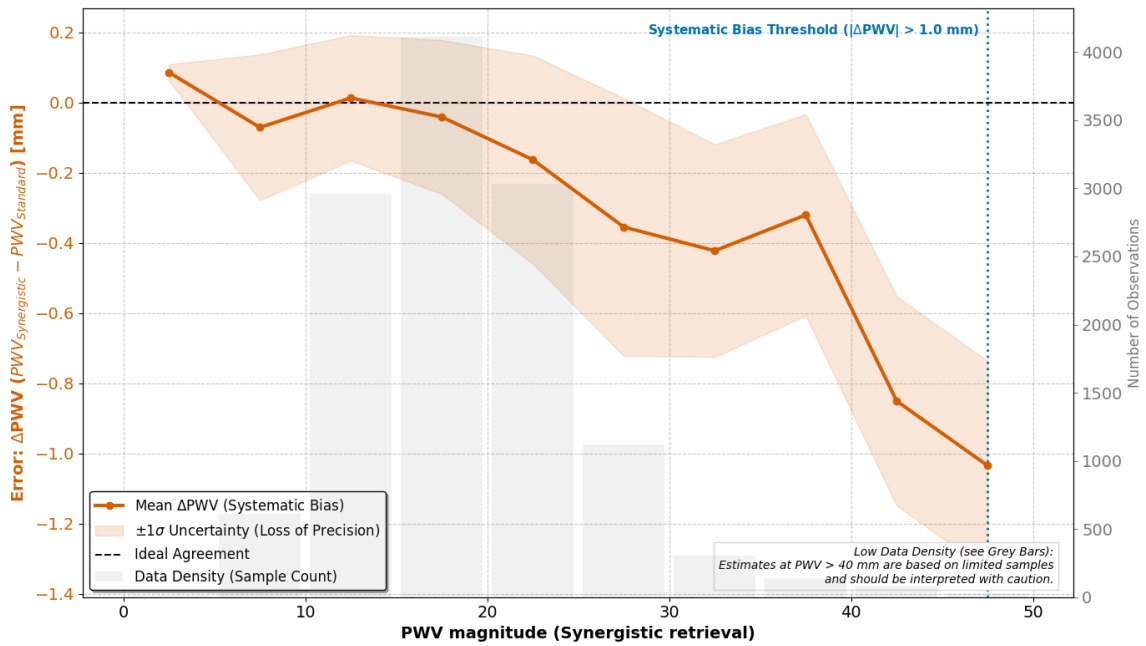
495 **3.5 Error Propagation and Synergistic Retrieval Assessment**

496 In this section, the PWV was derived using bias-corrected mean temperature (T_m) and constant values based on the study by
497 Rüeiger (2002), as mentioned in the Sect. 3.4. The impact of T_m errors on the final PWV product was analyzed to quantify the
498 benefits of the synergistic retrieval method. Fig. 10 visualizes the direct relationship between the relative error in T_m and the
499 resulting relative error in PWV. The plot reveals a strictly linear relationship ($R^2=0.984$) with a slope of 0.981. This confirms
500 the theoretical approximation that $(\Delta PWV/PWV) \approx (\Delta T_m/T_m)$. The color gradient indicates that this linear error propagation
501 holds true across all PWV magnitudes (from <10 mm to >45 mm). This implies that temperature errors propagate directly into
502 moisture errors regardless of the humidity level, making accurate T_m crucial at all times. Fig. 11 investigates the systematic
503 difference (ΔPWV) between the synergistic retrieval (using MWR T_m) and a standard retrieval (using empirical T_m) as a function
504 of moisture abundance (PWV magnitude). For drier conditions (PWV < 25 mm), the difference is minimal (near zero), and
505 the uncertainty (shaded region) is low. This suggests that for low humidity, the choice of T_m source is less critical. As
506 atmospheric moisture increases (> 25 mm), a significant negative bias emerges. The curve dips sharply, reaching nearly -1.0
507 mm at extreme humidity (45+ mm). The 'Systematic Bias Threshold' marker indicates that beyond 45 mm, the discrepancy
508 exceeds 1.0 mm. The fact that the bias magnitude scales directly with total PWV provides physical confirmation that the error
509 source is located in the boundary layer, where the bulk of the water vapour resides. The growing negative bias demonstrates

510 that standard GNSS processing (using static models like HGPT2) systematically overestimates water vapour during extreme
 511 events compared to the more accurate synergistic method. Rather than extrapolating these localized errors to regional
 512 hydrological impacts, we emphasize the primary empirical observation: the systemic deviation of the standard empirical model
 513 scales proportionally with the magnitude of the PWV regime. Crucially, this systematic overestimation of moisture during
 514 extreme events is deeply intertwined with the diurnal cycle of the local atmosphere. This analysis quantifies the specific
 515 operational penalty of utilizing static climatological models in this region, demonstrating that HGPT2 incurs an IWV error
 516 exceeding 1.0 kg m^{-2} during severe thermodynamic events. As previously established (Fig. 7), the static HGPT2 model
 517 displays an exaggerated diurnal wave with an amplitude exceeding 8.5 K. Because the static model fails to account for the
 518 thermodynamic decoupling between the heated boundary layer and the cooler free troposphere during the day, this T_m error
 519 artificially inflates the amplitude of the GNSS-derived PWV diurnal cycle during peak solar insolation. By utilizing the
 520 synergistic retrieval approach, this spurious daytime moisture amplification is effectively mitigated. While further multi-site,
 521 long-term studies are required to assess the broader impacts on regional operational forecasting, our localized dataset clearly
 522 indicates that integrating real-time MWR thermal data successfully removes diurnal artifacts and reduces systematic
 523 measurement biases at this site.



524
 525 **Figure 10.** Driver of model failure: Impact of weighted mean temperature (T_m) accuracy on PWV retrieval.
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528
529 **Figure 11.** Systematic breakdown and instability of the Standard GNSS model under extreme thermodynamic conditions.
530

531 **4 Discussions**

532 The results of this study necessitate a fundamental re-evaluation of how T_m parameterization errors are parameterized in GNSS
533 meteorology, particularly within thermodynamically complex, semi-arid coastal environments like the Eastern Mediterranean
534 (EM). The pronounced failure of the static HGPT2 model to capture the diurnal T_m cycle reveals a structural limitation inherent
535 to empirical modeling. The observed "diurnal bias peak" effect is not merely a statistical anomaly; it represents a physical
536 disconnect. Static empirical models rely heavily on T_s , effectively assuming that intense skin-level heating propagates
537 uniformly through the atmospheric column. This assumption critically breaks down during the daytime in the EM, where the
538 turbulent planetary boundary layer (PBL) aggressively decouples from the stable free troposphere. Evidence for this severe
539 decoupling is explicitly documented in the high-vertical-resolution RS profiles collected during the campaign. Because the
540 passive MWR struggles to effectively capture this sharp boundary—a direct result of the broad weighting functions and
541 degraded vertical resolution inherent to its K-band observations—the instrument exhibits a 'smoothing error' across the
542 inversion layer. This structural limitation highlights exactly why applying a site-specific bias correction to the MWR's native
543 output is a necessary prerequisite for precision GNSS meteorology. Furthermore, the failure of the reanalysis climatology to
544 properly resolve the sharp moisture capping inversion during the onset of the daytime sea-breeze fundamentally corrupts the
545 moisture-weighted T_m integral. Ground-based microwave radiometry overcomes this structural blindness by directly measuring
546 the integrated thermal emissions of the column.

547 However, the performance of the MWR in this study highlights the duality of passive microwave remote sensing: it is highly
548 proficient at retrieving integral quantities but degrades severely when resolving differential or gradient-based parameters. The
549 successful reduction of the T_m RMSE via site-specific linear correction confirms that the MWR's K-band and V-band channels
550 effectively capture the true thermal inertia of the troposphere. The initial systematic cold bias observed aloft is a known artifact
551 of ill-posed neural network retrievals (Cimini et al., 2006; Löhnert and Maier, 2012). Because the vertical resolution of passive
552 microwave observations degrades rapidly with height, the retrievals become heavily constrained by historical training datasets
553 (the climatological prior), which often fail to capture localized, transition-season lapse rates in the free troposphere.
554 Conversely, the complete failure of the MWR to derive a physically realistic water vapour scale height (H_v) exposes the
555 "smoothing error" inherent to passive radiometry. Because the broad weighting functions of the K-band channels cannot
556 resolve sharp boundary layer moisture inversions, the retrieval algorithm mathematically smears the moisture mass upward.
557 This confirms that while MWR serves as a robust standard for total column mass, researchers must exercise extreme caution
558 when utilizing its smoothed profiles to characterize vertical moisture compactness.

559 While this study relies on a single-site, multi-month dataset, the physical mechanisms identified have broad relevance beyond
560 the Nicosia region. The Eastern Mediterranean serves as a highly representative climatic hotspot for semi-arid coastal
561 environments experiencing enhanced warming and intensified hydrological cycles. It is important to note that the specific
562 threshold of >45 mm identified here is characteristic of the climatological moisture capacity of the Eastern Mediterranean
563 during extreme summer anomalies. While the exact numerical value of this 'Systematic Bias Threshold' will vary
564 geographically depending on local atmospheric dynamics and latitude, the underlying physical principle remains universal:
565 empirical T_m models systematically degrade proportionally to the total atmospheric moisture mass during severe local
566 extremes. The core vulnerability exposed in this research—that static global models are structurally blind to sharp boundary
567 layer thermodynamic decoupling during peak insolation—is a fundamental physics problem, not a local anomaly. Therefore,
568 the proposed synergistic MWR-GNSS retrieval architecture provides a universally applicable solution for mitigating
569 systematic dry biases in any complex terrain or coastal environment globally. While the simple linear regression applied in
570 this study proved highly effective at correcting systematic T_m biases for operational GNSS conversions, there remains room
571 for algorithmic improvement. As the CYGMEN infrastructure accumulates a multi-year climatological database of high-
572 resolution radiosonde profiles, future work should focus on complementary Neural Network (NN) training. By retraining the
573 MWR retrieval algorithms using site-specific radiative transfer modeling rather than relying on the manufacturer's regional
574 historical priors, the native temperature and humidity profiles can be further optimized at the retrieval level.

575 Finally, our component-wise uncertainty analysis clarifies the error propagation chain in the GNSS-PWV conversion
576 process, shifting the paradigm of where optimization efforts should be focused. Historically, significant effort within the
577 geodetic community has been expended on refining atmospheric refractivity constants. However, we demonstrate that the error
578 induced by transitioning from the historical Davis et al. (1985) formulations to the modern Rüeiger (2002) constants is

579 practically negligible (<0.2 mm) for synoptic meteorological applications. The true "weak link" in the retrieval chain is
580 unequivocally the thermodynamic parameterization, which introduces errors an order of magnitude larger.

581

582 **5 Conclusion**

583 This study demonstrated that the accuracy of GNSS-derived Precipitable Water Vapour (PWV) in the Eastern Mediterranean
584 region, is significantly affected by the thermodynamic rigidity of static climatological models. By implementing a synergistic
585 retrieval strategy that couples GNSS delays with real-time ground-based microwave radiometry (MWR), we successfully
586 quantified and mitigated these limitations. The investigation yielded three primary methodological conclusions. First, we
587 established that standard empirical models (e.g., HGPT2) are structurally incapable of resolving the diurnal thermodynamic
588 decoupling between the boundary layer and free troposphere. This deficiency leads to severe systematic errors (the "diurnal
589 bias peak" effect) exceeding 6 K in weighted mean temperature (T_m) during peak solar insolation, which directly propagates
590 into a PWV bias >1.0 mm during extreme hygrometric events. Second, the MWR proved to be a superior source for T_m
591 parameterization errors, provided that site-specific calibration is applied. The development of a linear bias correction scheme
592 reduced the MWR T_m root-mean-square error from 2.32 K to 1.43 K. This correction substantially reduces the conversion-
593 related uncertainty in the GNSS water vapour product compared to standard climatological approaches. Third, the component-
594 wise sensitivity analysis confirmed that thermodynamic parameterization is a highly significant source of uncertainty that
595 exacerbates existing geodetic ZTD errors, outweighing uncertainties in refractive index constants by an order of magnitude.
596 Consequently, the proposed combined retrieval represents a highly valuable architectural upgrade for monitoring severe
597 weather in complex coastal environments like the Eastern Mediterranean. However, it must be acknowledged that there are
598 many sites worldwide where the deployment of microwave radiometers may not be justified. Given the high capital and
599 operational costs of radiometric hardware, the presence of other unmitigated geodetic uncertainties, and the adequate
600 performance of static T_m models in less thermodynamically complex regions, this synergistic approach is best reserved for
601 targeted deployments in highly vulnerable climatic hotspots.

602 For the climate-sensitive Eastern Mediterranean region, relying on static models for GNSS processing risks systematically
603 masking moisture trends during heatwaves and deep convection. We therefore recommend the operational integration of
604 collocated MWR observations into national GNSS processing chains. Where collocation is not feasible, future work should
605 focus on assimilating MWR-derived diurnal shape functions into static models to bridge the gap between climatology and
606 reality. This study establishes the "Corrected Synergistic Method" as a robust benchmark for generation of climate-quality
607 water vapour datasets in complex thermodynamic environments.

608

609 **Data availability**

610 The MWR and GNSS data used in this study are available from the CYGMEN project archive upon request. High resolution
611 Radiosonde data available from the Department of Meteorology (DoM), Cyprus. The ERA5 reanalysis data can be downloaded
612 from the Copernicus Climate Change Service (C3S) Climate Data Store.

613

614 **Author contributions**

615 ANP carried out the GNSS, MWR, and Radiosonde data processing, performed the synergistic PWV retrievals and error
616 diagnosis, and wrote the initial version of the paper. CO and HH conceptualized the study, acquired the funding and resources
617 for the CYGMEN infrastructure, and supervised the investigation. All authors discussed the results, edited, and proofread the
618 paper.

619

620 **Competing interests**

621 All authors declare that they have no conflict of interest.

622

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627

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631

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