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1 Spatiotemporal representativeness of ERA5 atmospheric profiles across Cameroon's 2 climatic gradient and clear-sky radiative sensitivity to profile choice

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11 Abstract

12 Vertical atmospheric profiles underpin radiative-transfer modelling, satellite retrievals and climate diagnostics,
13 yet the representativeness of averaged profiles warrants explicit testing across contrasting tropical African
14 environments. We analysed ERA5-derived temperature, humid-air density, water-vapour and ozone
15 concentrations at ten Cameroonian sites spanning coastal, humid-forest, highland, Guinean-savanna, Sudanian
16 and Sudano-Sahelian environments during 2015–2020. Profiles sampled at 06, 09, 12, 15 and 18 UTC on five
17 dates per month were compared across hours, sampled dates, months, seasons, years and sites. Terrain masking
18 established a common 875–1 hPa domain. Temperature and water-vapour contrasts are strongest in the lower
19 troposphere: at 875 hPa, mean site-specific monthly and interannual water-vapour amplitudes are 6.61 and 0.81
20 g m^{-3} , respectively, while the six-year inter-site contrast reaches 5.72 g m^{-3} . Corresponding temperature
21 amplitudes are 5.13 and 0.58 K, with a 4.47 K inter-site contrast. Ozone shows substantial lower-tropospheric
22 spatial variation, but its monthly amplitude reaches 45.96 $\mu\text{g m}^{-3}$ at 50 hPa. Across 720 sampled monthly means,
23 site, month and their interaction account for 29.69%, 38.05% and 26.73% of water-vapour variability at 875 hPa;
24 the shared year effect contributes 0.52%. Clear-sky libRadtran simulations comparing coherent annual, driest-
25 month and wettest-month profiles across 60 site-years yield a mean dry–humid contrast of 34.11 W m^{-2} in
26 downward solar flux and a mean humid–dry contrast of 26.28 W m^{-2} in downward longwave flux at a virtual
27 875-hPa boundary. These findings motivate site- and month-specific profile sensitivity tests for clear-sky
28 radiative applications.

29 Keywords: ERA5 reanalysis; Atmospheric profiles; Cameroon; Spatial and seasonal variability; Clear-sky
30 radiative transfer; Representativeness.

31 1. Introduction

32 Vertical atmospheric profiles are structuring information in atmospheric science because they describe the
33 thermodynamic and compositional state of the air column and therefore control optical properties, radiative
34 exchanges, stability and the capacity to sustain convection. They are used as inputs for radiative-transfer models,
35 satellite retrieval algorithms, data-assimilation systems, numerical weather prediction and climate diagnostics

36 (Clough et al. 2005; Ferreira et al. 2019; Guo et al. 2023; Mashao et al. 2024). The scientific quality of an
37 atmospheric profile therefore depends not only on its internal vertical consistency, but also on its spatio-temporal
38 representativeness with respect to the atmosphere that it is intended to describe.

39 This issue is not merely technical. Classical reference profiles, particularly the AFGL standard atmospheres, have
40 played a foundational role in radiative calculations and spectral simulations, but they were designed as zonal and
41 seasonal archetypes rather than as detailed representations of contemporary regional variability (Anderson et al.
42 1986). Recent work shows that reference-profile databases that are too coarse in space or time can differ
43 substantially from the real atmospheric state. Guo et al. (2023) emphasize the need for representative regional
44 profiles to avoid significant errors in atmospheric modelling and analysis. Santhosh et al. (2024) show, for
45 tropical regions, that standard atmospheres can depart markedly from real-time measurements, with water-vapour
46 biases exerting a particularly strong effect on radiative forcing and heating-rate estimates. For a study focused on
47 averaged profiles, the key question is therefore not only how to calculate a mean profile, but also what this mean
48 retains, and what it suppresses, from the vertical structure that is relevant to meteorology, climatology and
49 radiation.

50 This question is especially relevant in tropical Africa. Despite recent progress in observing systems and satellite-
51 based monitoring, Africa remains under-represented in upper-air observations, creating important gaps for
52 reanalysis evaluation, climate monitoring and the interpretation of vertical structures of temperature and humidity
53 (Mashao et al. 2024). Across West Africa and much of equatorial Africa, both surface and upper-air observations
54 remain sparse, limiting operational analysis and the validation of gridded products (Fink et al. 2011; Ferreira et
55 al. 2019). Hua et al. (2019) further show that rainfall and circulation climatologies over central equatorial Africa
56 remain affected by the scarcity of in situ observations and by substantial disagreements among observational and
57 reanalysis datasets. This scarcity also limits independent evaluation of vertical reference profiles in environments
58 where humidity, deep convection and seasonal cycles vary strongly.

59 The present study is framed by this methodological and regional challenge. Its objective is twofold: first, to derive
60 six-year mean vertical profiles of pressure, temperature, air density, water vapour and ozone from ERA5 for ten
61 Cameroonian sites; and second, to explicitly assess, within the sampled ERA5 states, how well mean profiles
62 represent the profiles from which they are formed across temporal and spatial aggregation scales. ERA5 provides
63 a homogeneous, physically constrained and widely used framework for inter-site and interannual comparison
64 (Hersbach et al. 2020). In a tropical context characterized by strong climatic gradients, the scientific value lies
65 not only in the description of mean profiles, but also in the quantification of what an average profile can still
66 represent when it is computed across contrasted atmospheric regimes. A further objective is to identify candidate
67 profile resolutions for application-specific testing in radiative and solar-resource studies. A paired libRadtran
68 experiment additionally examines how coherent within-year profile choices alter clear-sky downward radiative
69 fluxes at the network's common 875-hPa lower boundary.

70 **1.1. Scientific scope and knowledge gap**

71 Vertical profiles are routinely used in radiative and remote-sensing applications because they affect molecular
72 absorption, transmittance, top-of-atmosphere radiances and derived geophysical products (Clough et al. 2005;

73 Guo et al. 2023). These uses motivate examining how much spatial and seasonal variation a generic or annual
74 profile may conceal across sampled tropical sites. In Cameroon, Fotsing Talla et al. (2018) used ECMWF
75 atmospheric profiles over Maroua for simulations of downward global solar radiation, but did not systematically
76 examine how the profiles depend on temporal and spatial aggregation scale. The present study extends this
77 question to ten locations across the sampled Cameroonian gradient.

78 Cameroon is particularly instructive for this purpose. A mean profile over Douala, Ambam or Mamfe is not
79 controlled by the same physical conditions as a profile over Ngaoundere, Garoua or Maroua. Proximity to the
80 ocean, humid Atlantic advection, the orographic influence of the western highlands and Mount Cameroon, the
81 elevation of the Adamawa Plateau, the meridional decline in rainfall and the increasing influence of dry
82 continental air toward the north all modify the vertical structure of the atmospheric column. The implicit
83 assumption that a small number of averaged profiles can represent regional tropical variability must therefore be
84 tested rather than presumed. This study treats vertical profiles as climatological objects in their own right, while
85 recognizing that every average is a reduction operator whose information cost must be quantified.

86 Beyond atmospheric science, this question matters for solar-resource assessment. Inadequate spatial or temporal
87 resolution has been identified as a barrier to the use of climate information in the energy sector (Bartók et al.
88 2019) and, more broadly, in West Africa (Sultan et al. 2020). The present study addresses an upstream element
89 of this problem: it quantifies how temporal and spatial aggregation alters ERA5-derived vertical profiles prepared
90 for radiative-transfer applications, without evaluating end-user uptake.

91 **2. Study area and data**

92 **2.1. Study area and climatic context**

93 Cameroon provides a geographically varied setting for this analysis. Located at the head of the Gulf of Guinea,
94 the country covers approximately 475,650 km² and extends over nearly 1,840 km from south to north. This
95 meridional extent, combined with strong heterogeneity in relief and vegetation cover, explains the coexistence
96 within a single national territory of major agroecological and climatic domains ranging from southern humid
97 forests to the Sudano-Sahelian domain of the Far North (FAO 2026).

98 Relief further reinforces this diversity. Lowlands in the north and southwest are bordered by highlands and
99 mountain massifs, while the Cameroon Volcanic Line and the western highlands form a major orographic barrier.
100 The Adamawa Plateau acts as a transitional highland between the humid forested south and the Sudanian and
101 Sahelian basins of the north. Nlend et al. (2023) emphasize that this geomorphological complexity is directly
102 linked to the main climatic units of the country. Tsalefac et al. (2015) show that the joint influence of the Atlantic
103 coast and coastal relief contributes to extreme rainfall in parts of the southwest, whereas northern domains evolve
104 toward drier regimes with shorter rainy seasons and larger thermal amplitudes. Cameroon is therefore not a simple
105 latitudinal transect, but a combined meridional, altitudinal and maritime gradient.

106 The climatic functioning of the country results from the interaction of several mechanisms. In the south and along
107 the Atlantic façade, humidity advected from the Gulf of Guinea feeds strongly rainy regimes, either bimodal over
108 the southern plateau and forest interior or predominantly monomodal along the coast and southwest under

maritime and orographic influence (Nlend et al. 2023). Farther north, seasonality becomes unimodal and progressively shorter in relation to the seasonal migration of the tropical rain belt, the retreat of humid Atlantic flows and the increasing influence of dry continental air associated with the Harmattan (Tsalefac et al. 2015). This seasonality is not controlled by rain-belt migration alone: thermodynamic structure, shallow meridional circulation, low-level frontal structure and land–ocean thermal contrast also contribute (Nicholson 2018; Son and Seo 2020). Profiles sampled along this Cameroonian gradient may reflect different regional influences, which motivates testing the representativeness of a single mean profile.

2.2. Study sites and sampling rationale

The ten-site network was designed to sample Cameroon’s major hydroclimatic environments without changing national context or data source. Based on the ERA5 extraction points used in the study, the sample extends from Ambam (2.38°N) to Maroua (10.47°N), corresponding to 8.09 degrees of latitude, 2.99 degrees of longitude and nearly 960 km of linear distance. It captures the southern humid forest, the central-eastern forest interior, the Atlantic coastal domain, the western highlands, the central interior–Adamawa transition, the Guinean high savanna, and finally the Sudanian and Sudano-Sahelian plains of the north. The sites and their hydroclimatic settings are listed in Table 1 and mapped in Fig. 1. This typology synthesizes the national agroecological zoning and the regional literature; it is a functional classification supporting the sampling strategy rather than a detailed climatic map.

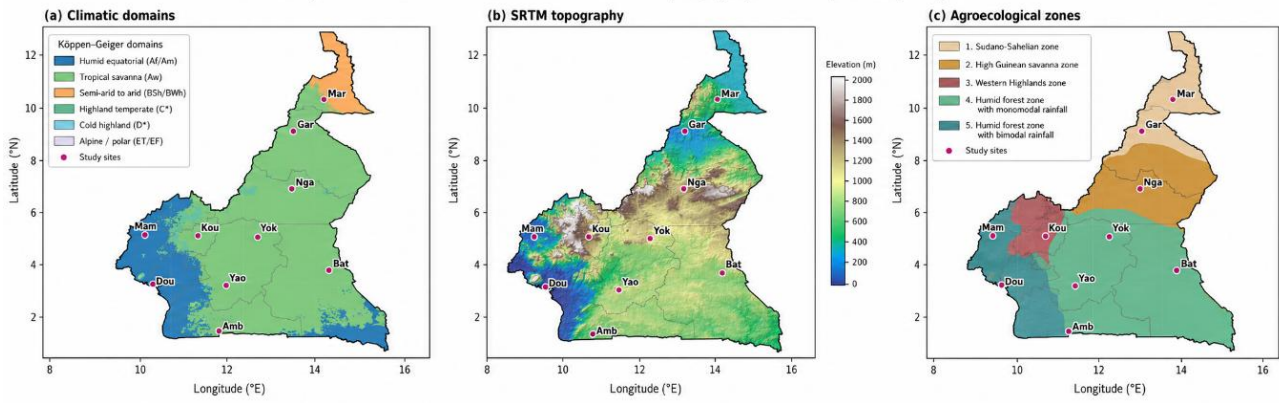
Within this design, Douala and Mamfe represent the humid domain strongly influenced by the ocean and by a long wet season. Ambam, Yaounde and Batouri document the southern and eastern humid forest zones with bimodal or sub-bimodal seasonality. Koutaba captures the cooling and orographic influence of the western highlands. Yoko and Ngaoundere characterize the transition toward the interior high savannas, while Garoua and Maroua describe the warmer, drier and more seasonally contrasted northern atmosphere.

Table 1. Study sites, coordinates and dominant hydroclimatic setting.

Code	Site	Coordinates	Mean ERA5 surface pressure (hPa)	Dominant hydroclimatic setting
Amb	Ambam	2.38°N, 11.28°E	943.62	Southern humid forest
Yao	Yaounde	3.87°N, 11.53°E	934.98	Southern forest plateau
Dou	Douala	4.02°N, 9.73°E	1007.67	Atlantic coast
Bat	Batouri	4.42°N, 14.40°E	938.21	Eastern humid forest
Yok	Yoko	5.55°N, 12.37°E	921.91	Central interior–Guinean savanna transition
Kou	Koutaba	5.62°N, 10.75°E	895.26	Western highlands
Mam	Mamfe	5.72°N, 9.28°E	991.94	Humid southwest
Nga	Ngaoundere	7.28°N, 13.32°E	898.70	Guinean high savanna of Adamawa
Gar	Garoua	9.33°N, 13.38°E	979.74	Sudanian savanna
Mar	Maroua	10.47°N, 14.27°E	961.40	Sudano-Sahelian domain

132

Study-site distribution across Cameroon's climatic, topographic and agroecological gradients



133

134 **Fig. 1** Distribution of the ten study sites across Cameroon's climatic, topographic and agroecological gradients.
 135 The three panels show climatic domains, SRTM topography and agroecological zones. The site network spans
 136 humid coastal and forest domains, western highlands, the Adamawa transition and the Sudanian to Sudano-
 137 Sahelian north

138 2.3. ERA5 data source and variables

139 The atmospheric profiles analysed in this study were derived from ERA5 hourly data on pressure levels for 2015–
 140 2020. ERA5 is the fifth-generation atmospheric reanalysis produced by ECMWF and distributed through the
 141 Copernicus Climate Data Store. It combines a global model with a large set of observations through 4D-Var data
 142 assimilation to produce spatially complete and physically coherent atmospheric fields. The pressure-level product
 143 is provided on a regular latitude-longitude grid of $0.25^\circ \times 0.25^\circ$, at hourly temporal resolution, and on 37 standard
 144 pressure levels from 1000 to 1 hPa. Pressure-level fields are generated from the native 137 hybrid model levels
 145 of the IFS and are well suited to vertical-structure analyses and radiative-transfer applications expressed in
 146 pressure coordinates (Hersbach et al. 2020; Hersbach et al. 2023).

147 Published evaluations support the use of ERA5 as a spatially coherent analysis framework while showing that
 148 accuracy depends on variable, region and height. Relative to ERA-Interim, the global ERA5 assessment found
 149 smaller tropospheric temperature and humidity departures from radiosondes in the assimilation system; these
 150 diagnostics are not independent validation of the ten Cameroonian profiles (Hersbach et al. 2020). At nine GPS
 151 sites in or near Ethiopia, Koji et al. (2022) reported correlations of 0.96–0.99 between ERA5 and GPS
 152 precipitable water vapour, with an overall root-mean-square error of 3.4 mm. This column-integrated
 153 agreement does not establish accuracy at individual pressure levels. Conversely, a tropical-ocean radiosonde
 154 comparison documented ERA5 temperature and humidity differences in the lower and middle troposphere,
 155 including temperature-bias gradients around 700–900 hPa (Virman et al. 2021).

156 Four ERA5 pressure-level fields were used: geopotential (paramId 129; $\text{m}^2 \text{s}^{-2}$), converted to geopotential height
 157 z ; temperature (paramId 130; K); specific humidity (paramId 133; kg kg^{-1}), used to derive water-vapour mass
 158 concentration; and ozone mass mixing ratio (paramId 203; kg kg^{-1}), used to derive ozone mass concentration.
 159 Together, these variables allow reconstruction, for each site and each level, of the minimum thermodynamic and
 160 compositional structure required by the final z - p - T -air- H_2O - O_3 profile files.

161 3. Methods

162 3.1. Site extraction, terrain masking and temporal sampling

163 ERA5-derived pressure-level fields were extracted at the ten site coordinates for each sampled time and level
164 before the derived variables were computed. Values were read directly from an ERA5 grid node when a site
165 coincided with that node; otherwise, they were bilinearly interpolated to the site from the surrounding grid nodes.
166 None of the ten site coordinates in Table 1 coincides with a node of the regular 0.25° ERA5 grid, so bilinear
167 interpolation was applied at every study site. These site-indicative ERA5 grid estimates are not local radiosonde
168 observations. Near elevated terrain, nominal pressure levels may lie beneath the smoothed ERA5 model surface.
169 Such records were excluded using the criterion $p \leq p_s$, where p_s is the ERA5 single-level surface pressure
170 independently bilinearly interpolated to the same site and sampled time; similar masking of extrapolated pressure-
171 level fields was applied by Palarz and Celiński-Mysław (2020). After masking, 875 hPa is the highest-pressure
172 (lowest-altitude) level valid at all ten sites (Table 1) and all sampled times. All full-network comparisons
173 (profiles, amplitudes, deviations and spatial anomalies) are therefore restricted to the common-valid 875–1 hPa
174 domain (32 pressure levels); 900–1000 hPa values remain available only for site-specific analyses when the
175 criterion is satisfied.

176 The processed input contains 1,800 sampled instants per site during 2015–2020. In every calendar month, the
177 same five dates (days 1, 8, 15, 22 and 28) were sampled at 06:00, 09:00, 12:00, 15:00 and 18:00 UTC, yielding
178 25 instants per month, 60 dates per year and 360 dates per site over six years. Intervals between the selected dates
179 within a month are 7, 7, 7 and 6 days. These regularly distributed samples cover different parts of each month
180 but do not constitute a complete daily record or guarantee that brief events are captured. Monthly and annual
181 profiles summarize the sampled dates and hours rather than every atmospheric state in each period. Daily sampled
182 profiles average only the five available hours; hourly comparisons do not span the full 24-hour cycle. Repeated
183 time–level–variable records, when present, were averaged once before aggregation to avoid duplication of
184 weights.

185 3.2. Derived variables and concentration conversions

186 The vertical coordinate reported in the final files as z (km) was obtained from ERA5 geopotential. ERA5 archives
187 geopotential, Φ , in $\text{m}^2 \text{s}^{-2}$ rather than height directly. Geopotential height was therefore computed as $z = \Phi/g_0$ and
188 then expressed in kilometres. The aggregated z profiles describe the average height of isobaric surfaces rather
189 than a prescribed standard atmosphere.

190 The variable air in the output files was defined as humid-air density in g m^{-3} . It was computed from the equation
191 of state for moist air using the virtual-temperature approximation:

$$192 \quad \rho_{air} = \frac{p}{[R_d T (1 + 0.61q)]}, \quad (1)$$

193 where p is the nominal isobaric pressure in Pa, T is temperature, q is specific humidity and R_d is the gas constant
194 for dry air. The result was converted from kg m^{-3} to g m^{-3} . Water-vapour concentration was then computed
195 directly from the definition of specific humidity, $\rho_{H_2O} = q \rho_{air}$. Because ozone mass mixing ratio is supplied as
196 ozone mass per unit mass of air, ozone concentration was analogously computed as $\rho_{O_3} = r_{O_3} \rho_{air}$. The final air,

197 H₂O and O₃ columns are therefore all expressed as mass concentrations, facilitating vertical comparison and
 198 direct use in radiative-transfer profile files.

199 A key methodological point is that all derived variables were calculated at the instantaneous scale, after site-
 200 coordinate pressure-level fields were assembled and before temporal or spatial aggregation. This sequence is
 201 preferable to reconstructing concentrations a posteriori from already averaged profiles because air density
 202 depends non-linearly on T and q. A mean of instantaneous concentrations is therefore not strictly equivalent to a
 203 concentration derived from mean temperature and humidity profiles. The monthly, seasonal, annual and six-year
 204 mean profiles produced in this study should thus be interpreted as averages of instantaneously derived physical
 205 quantities, not as secondary derivatives of intermediate time averages. The humid-air density calculation does
 206 not explicitly include condensed water or ice contents; this is a secondary uncertainty in very cloudy layers but
 207 is generally acceptable for climatological pressure-level profiles.

208 3.3. Aggregation framework

209 The central objective is to describe mean profiles and quantify differences between sampled ERA5 states and
 210 their temporal or spatial aggregates. This framework is consistent with the broader concept of representativeness
 211 error, in which discrepancies arise whenever atmospheric objects with different spatial or temporal supports are
 212 compared or substituted (Janjić et al. 2018; Schutgens et al. 2017; Boersma et al. 2016). Fig. 2 summarizes the
 213 processing chain from ERA5 extraction to the aggregation-deviation diagnostics.

214 Let $X(s,p,t)$ denote the value of a variable at site s , pressure level p and elementary time t . Each time can be
 215 associated with a date, UTC hour, month, season and year. Aggregation is treated as an arithmetic averaging
 216 operator applied to a homogeneous set of times or sites; the resulting profile hierarchy is summarized in Table 2.
 217 The instantaneous profile is the finest reference available. Hourly climatologies group all times sharing the same
 218 UTC hour over 2015–2020. Daily sampled profiles average the available hours for a given date. Monthly and
 219 seasonal profiles average the sampled instants by calendar month and by DJF, MAM, JJA and SON, respectively.
 220 Annual profiles average the sampled instants within a given year. Six-year monthly, seasonal and hourly sample
 221 composites are then obtained by grouping the corresponding periods across all six years. Finally, the spatial mean
 222 is defined as the unweighted mean of the ten sites at a fixed temporal scale. It represents the mean behaviour of
 223 the site network and should not be interpreted as an area-weighted national mean.

224 Table 2. Profile hierarchy and physical meaning of the aggregation levels.

Aggregation level	Notation	Practical definition	What the aggregation preserves	Mainly suppressed variability
Instantaneous	$X(s,p,t)$	Profile at a given date and UTC hour	Finest available atmospheric state	Nothing
Hourly climatology	$X_h(s,p)$	Mean of all instants at the same UTC hour	Mean signature of a given sampled hour	Day-to-day and seasonal variability

Daily sampled	$X_d(s,p)$	Mean of available hours within one date	Mean sampled daily state	Intraday variability
Monthly	$X_m(s,p)$	Mean of all available instants in a month	Mean monthly state	Daily and intraday variability
Seasonal	$X_k(s,p)$	Mean of all instants in one season	Mean seasonal contrast	Fine monthly variability
Annual	$X_y(s,p)$	Mean of all instants in one year	Annual mean state	Intra-annual variability
Spatial	$X_{sp}(p)$	Unweighted mean of ten sites at fixed temporal scale	Mean network signature	Climatic contrasts among sites

225

226 3.4. Aggregation deviations, anomalies and diagnostic metrics

227 Aggregation deviation, anomaly, amplitude, range and contrast denote related but distinct diagnostics.
 228 Aggregation deviations compare a fine-scale ERA5 state with an ERA5 aggregate at the same level and do not
 229 quantify accuracy against independent observations. Amplitudes and contrasts summarize spread across sampled
 230 states, whereas absolute deviations quantify departures from a specified aggregation.

231 Let $X(s, p, t)$ denote the value of an atmospheric variable X at site s , pressure level p , and elementary time t . The
 232 variable X may represent temperature T , humid-air density ρ_{air} , water-vapour concentration ρ_{H_2O} , or ozone
 233 concentration ρ_{O_3} . Each time t can be associated with a sampled UTC hour h , date d , month m , season k , and
 234 year y . The ten sites are denoted by $s = 1, \dots, N_S$, with $N_S = 10$, and the five sampled UTC hours by:

$$235 \quad H = \{06, 09, 12, 15, 18\} \quad (2)$$

236 An aggregation deviation (or anomaly) is the signed difference, at the same pressure level, between a fine-scale
 237 profile and the aggregate or reference mean chosen to represent it:

$$238 \quad D(i, p) = X_{fine}(i, p) - X_{agg}(p). \quad (3)$$

239

240 Positive values indicate fine-scale values above the aggregate.

241 Four aggregation-deviation families were calculated. Denoting by $X_d(s, p, d)$ the daily sampled profile, i.e. the
 242 mean of the available UTC hours for date d , the daily-to-monthly deviation was defined as:

$$243 \quad D_{d-m}(s, p, d) = X_d(s, p, d) - X_m(s, p, m, y), \quad (4)$$

244

245 where $X_m(s, p, m, y)$ is the monthly profile for month m and year y . The monthly-to-annual deviation was
 246 defined as:

$$247 \quad D_{m-y}(s, p, m, y) = X_m(s, p, m, y) - X_y(s, p, y), \quad (5)$$

249
 248 and the seasonal-to-annual deviation as:

$$250 \quad D_{k-y}(s, p, k, y) = X_k(s, p, k, y) - X_y(s, p, y), \quad (6)$$

254
 251 where X_k is the seasonal profile and X_y the annual profile for the same site and year. The spatial deviation was
 252 defined as the departure of a site profile from the unweighted inter-site mean at the same pressure level and
 253 temporal reference:

$$255 \quad D_{sp}(s, p, \tau) = X(s, p, \tau) - \bar{X}_{sp}(p, \tau), \quad (7)$$

256 with:

$$257 \quad \bar{X}_{sp}(p, \tau) = \frac{1}{N_s} \sum_{s=1}^{N_s} X(s, p, \tau), \quad (8)$$

264
 258 where τ denotes the temporal reference used for the comparison, for example an hourly, monthly, seasonal,
 259 annual or multiannual profile. This definition ensures that spatial aggregation is assessed at a fixed temporal
 260 scale and is not confused with temporal aggregation. Evaluated at 875 hPa for the 2015–2020 multiannual site
 261 means, this quantity defines the spatial anomalies mapped in Section 3.5; 875 hPa is the lowest common-valid
 262 level (Section 3.1) and the level of largest inter-site contrast for T, H₂O and O₃ within the common-valid
 263 domain.

265 For each deviation family, two summary diagnostics were calculated over the N profiles or states included in
 266 the diagnostic. The mean absolute deviation is:

$$267 \quad MAD(p) = \frac{1}{N} \sum_{i=1}^N |D_i(p)|, \quad (9)$$

270
 268 and represents the average absolute departure of the compared sampled states from the specified aggregate
 269 without sign cancellation. The root-mean-square deviation is:

$$271 \quad RMSD(p) = \sqrt{\frac{1}{N} \sum_{i=1}^N D_i^2(p)}, \quad (10)$$

274
 272 and gives greater weight to large deviations. In the results, MAD is the principal summary of within-sample
 273 departures from a specified aggregate; RMSD is reported alongside it.

275 The amplitude is defined as the maximum-to-minimum spread of a variable or diagnostic at a given pressure
 276 level:

$$277 \quad A(p) = \max_i X(i, p) - \min_i X(i, p). \quad (11)$$

281

278 Depending on the index i , this quantity may represent an interannual, monthly, hourly or spatial amplitude. The
279 term contrast denotes the difference between two specified states (for example two sites); the maximum inter-
280 site contrast is therefore the spatial amplitude.

282 The hourly anomaly heatmaps were constructed from the inter-site mean at each sampled UTC hour and
283 pressure level:

$$284 \quad \bar{X}_S(h, p) = \frac{1}{N_S} \sum_{s=1}^{N_S} X_h(s, p), \quad (12)$$

287

285 where $X_h(s, p)$ is the hourly climatological profile for site s . The hourly anomaly was then computed as the
286 departure from the mean of the five available UTC hours:

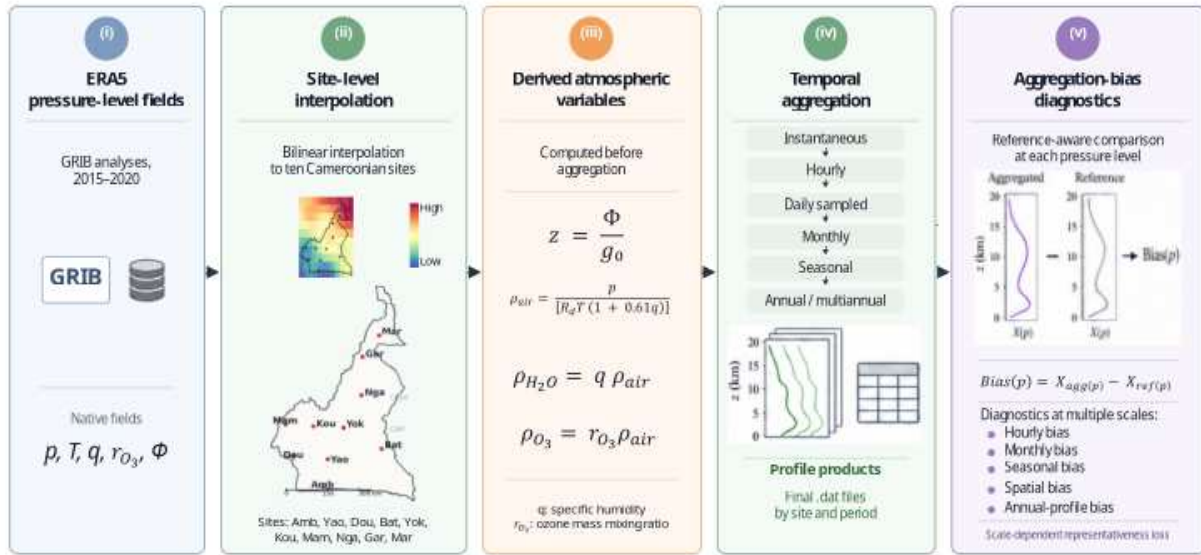
$$288 \quad X'_h(h, p) = \bar{X}_S(h, p) - \frac{1}{N_H} \sum_{h \in H} \bar{X}_S(h, p), \quad (13)$$

291

289 with $N_H = 5$. These anomalies describe partial intradiurnal departures from the five-hour daytime mean, not a
290 complete 24-hour diurnal cycle.

292 For a like-for-like comparison of spatial, seasonal and year-to-year variability, a complete balanced array of
293 site-specific monthly means was formed at each of 875 and 850 hPa: ten sites $\times$ twelve calendar months $\times$ six
294 years = 720 values per variable and level. The total sum of squared departures from its grand mean was
295 partitioned orthogonally into main effects of site, calendar month and year and their two- and three-factor
296 interactions; each reported percentage is 100 times a component sum of squares divided by the total. This fixed-
297 factor, descriptive decomposition gives each site–year–month mean equal weight; at both pressure levels
298 analysed, every cell is based on the same 25 sampled instants. It does not quantify within-month variability,
299 sampling uncertainty or variation beyond the six sampled years. The year main effect captures a common
300 interannual shift; variation in the site $\times$ year and month $\times$ year interactions must also be considered.

Workflow for deriving ERA5-based site-specific atmospheric profiles and aggregation biases



Note: Air, H₂O and O₃ concentrations are derived from ERA5 p-T-q-rO₃ fields and are not native ERA5 output variables.

301

302 **Fig. 2** Workflow used to derive ERA5-based site-specific atmospheric profiles and aggregation-deviation
 303 diagnostics. ERA5 pressure-level fields are bilinearly interpolated to the ten study sites; derived variables are
 304 computed before aggregation; temporal products are then generated; and aggregation deviations are finally
 305 quantified at multiple temporal and spatial scales. Air, H₂O and O₃ concentrations are derived quantities, not
 306 native ERA5 output variables

307 3.5. Spatial anomaly mapping

308 The site anomalies at 875 hPa (Section 3.4) are the quantitative basis of the spatial analysis. To facilitate
 309 visualization of their broad geographical organisation, a continuous background surface was generated using
 310 inverse distance weighting (IDW) interpolation. At any map location x , the interpolated anomaly was estimated
 311 as

$$312 \quad X'(x) = \frac{\sum_{i=1}^{10} w_i(x) X'_i}{\sum_{i=1}^{10} w_i(x)}, \quad w_i(x) = d_i(x)^{-2}, \quad (14)$$

313

314 where $d_i(x)$ is the geographic distance between location x and site i . An IDW power of 2 and a raster resolution
 315 of 0.05° were used, and the resulting surface was clipped to the Cameroon national boundary. Diverging colour
 316 scales centred on zero were applied so that negative and positive anomalies could be distinguished consistently.

317 Because the interpolation is constrained by only ten sites, the continuous surfaces are intended solely as
 318 cartographic aids for visualizing broad spatial organisation and not as independently resolved atmospheric fields.
 319 Quantitative interpretation is consequently based on the labelled site anomalies and associated inter-site contrasts
 320 rather than on interpolated values between sites.

321 3.6. Clear-sky radiative-transfer sensitivity experiment

322 For each of the 60 site-year pairs (ten sites, 2015–2020), three vertically coherent profiles were selected: the
 323 annual mean and the individual monthly mean profiles with the minimum and maximum integrated water-vapour

column between 875 and 1 hPa. Monthly extrema were selected by the trapezoidal integral of H₂O mass concentration over the complete geometric-height profile; g m⁻³ integrated over kilometres is numerically equivalent to millimetres of precipitable water. The resulting dry and humid cases are real monthly-mean profiles from the same site and year, not independent level-by-level envelopes. Each profile retains the 32 common-valid ERA5 pressure levels from 875 to 1 hPa. The twelve available monthly mean profiles in each site–year were all eligible for end-member selection, but only the two selected months were simulated radiatively. The dry and humid labels refer to extrema among the five-date monthly profiles, rather than to all calendar days of the year.

Radiative calculations were performed with libRadtran version 2.0.6 (Mayer and Kylling 2005; Emde et al. 2016). ERA5 geopotential height $H = \Phi/g_0$ was converted approximately to geometric altitude $h = RH/(R - H)$, with $R = 6371$ km and heights expressed in consistent units. Pressure and temperature set air number density through the ideal-gas law; H₂O and O₃ mass concentrations were converted to molecules cm⁻³. The dry-air O₂ and CO₂ mole fractions were fixed at 0.20946 and 410 ppm, respectively, and NO₂ was set to zero. The lowest atmospheric level, at 875 hPa, defined a virtual lower boundary for each profile; the output option zout 0 sampled the radiation there, rather than at mean sea level or the physical ground at each site.

We ran 180 clear-sky atmospheres with the uvspec radiative-transfer solver of libRadtran, separately for solar and thermal radiation (360 runs). The radiative-transfer equation was solved with the discrete-ordinate solver DISORT (Stamnes et al. 1988) using eight streams. Gaseous absorption was represented by correlated-k parameterizations: the kato2 scheme in the solar range (Kato et al. 1999), with a solar zenith angle of 30° and day of year 75, and the Fu and Liou (1992) scheme in the thermal range, using bands 7–18. The solar fluxes were spectrally summed and the downward global, direct-horizontal and diffuse components extracted. Thermal bands were summed to obtain downward longwave flux. Clouds and aerosols were omitted, the solar albedo was set to zero, and the virtual lower boundary emitted at the 875-hPa temperature of the corresponding profile. Within each site–year pair, the same solar geometry was used for all three profiles. We report paired dry-minus-annual and humid-minus-annual differences, as well as dry-minus-humid solar and humid-minus-dry longwave differences. Means across site-years are descriptive; an annual-mean profile simulation is not an annual mean of radiative fluxes. These two selected monthly profiles are purposeful end members rather than a representative sample of month-by-month flux departures from the annual profile.

3.7 Use of AI-assisted tools and other software

OpenAI’s ChatGPT was used to assist with coding of the analysis scripts and with language editing. All code, numerical results and text were checked by the authors, who take full responsibility for the content of the manuscript. QGIS software, Excel and Python were also used.

4. Results

4.1. Vertical structure of the multiannual profiles

The 2015–2020 mean vertical structure (Fig. 3; Tables 3–6) is strongly stratified within the terrain-valid network domain. Mean temperature decreases from 294.78 K at 875 hPa to 193.05 K at 100 hPa, then increases to 205.90 K at 50 hPa, 230.30 K at 10 hPa and 264.18 K at 1 hPa. This reversal of the thermal gradient above 100 hPa is

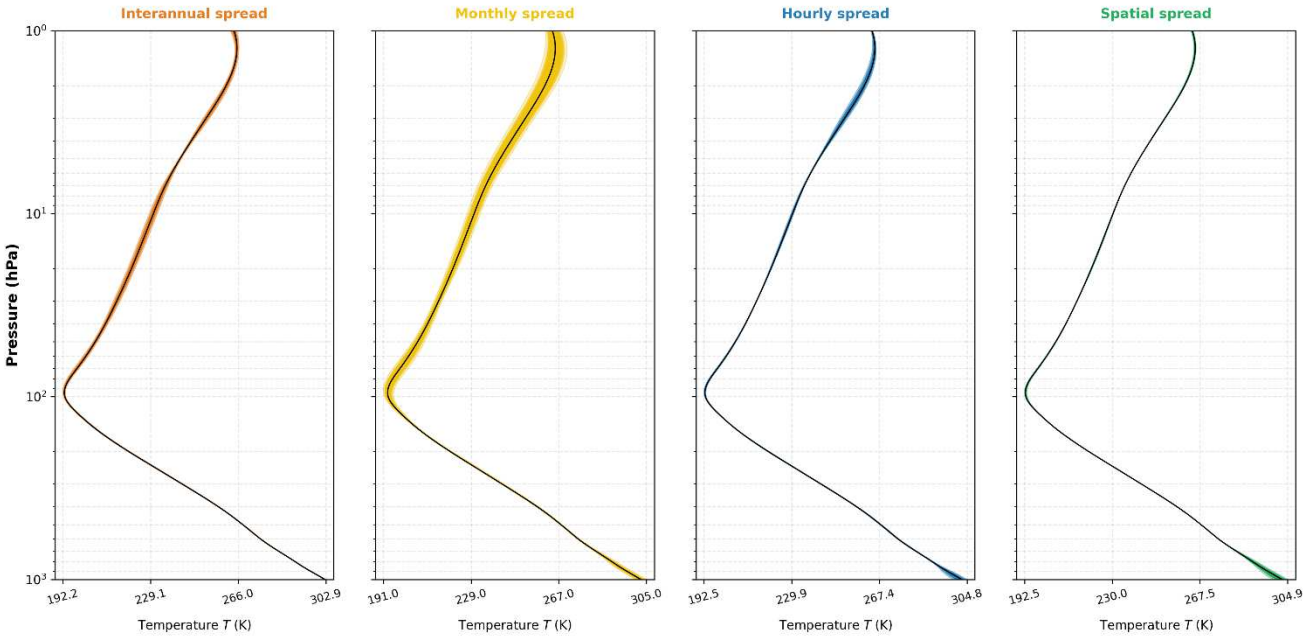
360 consistent with the transition from the troposphere to the stratospheric extension and with ozone-related
 361 stratospheric radiative absorption (Hersbach et al. 2020; WMO 2022).

362 Humid-air density decreases from 1026.56 g m^{-3} at 875 hPa to 649.36 g m^{-3} at 500 hPa, 180.49 g m^{-3} at 100 hPa,
 363 84.62 g m^{-3} at 50 hPa and 1.32 g m^{-3} at 1 hPa. Water vapour exhibits a steep vertical gradient: it decreases from
 364 12.57 g m^{-3} at 875 hPa to 11.62 g m^{-3} at 850 hPa, 5.88 g m^{-3} at 700 hPa, 1.68 g m^{-3} at 500 hPa, $4.70 \times 10^{-4} \text{ g m}^{-3}$
 365 at 100 hPa and $5.06 \times 10^{-6} \text{ g m}^{-3}$ at 1 hPa. Most of the absolute H_2O signal within the analysed column is
 366 concentrated in the troposphere.

367 Ozone has a distinct vertical geometry. Its mean mass concentration is $52.9 \text{ } \mu\text{g m}^{-3}$ at 875 hPa and $57.7 \text{ } \mu\text{g m}^{-3}$
 368 at 500 hPa; it increases in the stratospheric extension to $2.06 \times 10^{-4} \text{ g m}^{-3}$ at 50 hPa and $2.38 \times 10^{-4} \text{ g m}^{-3}$ at 10
 369 hPa, then decreases to $6.40 \text{ } \mu\text{g m}^{-3}$ at 1 hPa. This behaviour is consistent with the concentration of ozone in the
 370 stratospheric ozone layer (WMO 2022; Clough et al. 2005; Iacono et al. 2008).

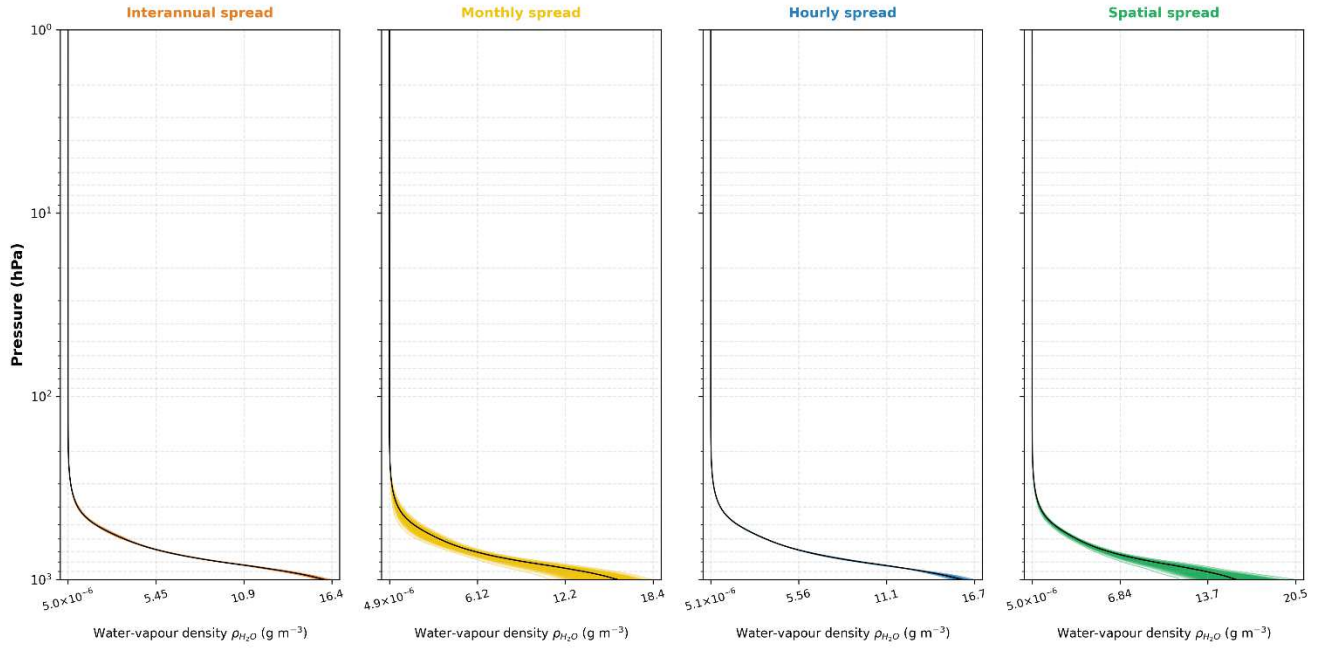
371 For temperature and water vapour, inter-site contrasts are greatest at 875 hPa and become much smaller by 500
 372 hPa. At 875 hPa, temperature ranges from 292.54 K at Douala to 297.01 K at Maroua, a 4.47 K contrast, while
 373 H_2O ranges from 8.93 g m^{-3} at Maroua to 14.66 g m^{-3} at Ambam, a 5.72 g m^{-3} contrast. At 500 hPa, the
 374 corresponding contrasts fall to 0.22 K for T and 0.49 g m^{-3} for H_2O .

Vertical Profiles of Temperature (T) over Cameroon — Aggregation-related spread



375 **Fig. 3a** Vertical structure and aggregation-related spread for temperature over Cameroon. The coloured
 376 envelopes represent min–max dispersion for interannual, monthly, hourly and spatial aggregation dimensions,
 377 while the black curve represents the mean profile
 378

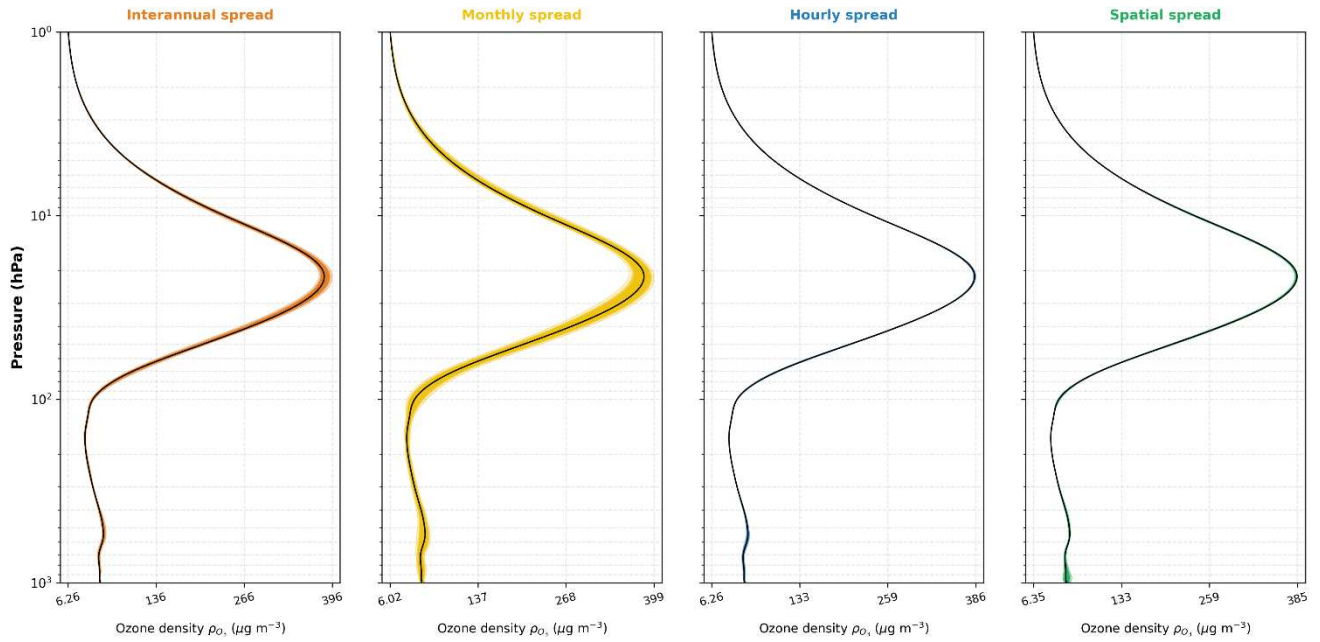
Vertical Profiles of Water Vapour (ρ_{H_2O}) over Cameroon — Aggregation-related spread



379

380 **Fig. 3b** Vertical structure and aggregation-related spread for water-vapour mass concentration over Cameroon.
 381 The figure highlights the strong lower-tropospheric concentration of water-vapour variability

Vertical Profiles of Ozone (ρ_{O_3}) over Cameroon — Aggregation-related spread



382

383 **Fig. 3c** Vertical structure and aggregation-related spread for ozone over Cameroon. The figure shows the
 384 differentiated behaviour of ozone between the lower troposphere and the stratospheric extension

385 4.2. Hourly and monthly variability

386 Variability over the five sampled UTC hours is strongest in the common-valid lower troposphere. At 875 hPa,
 387 the ten-site mean temperature increases from 293.23 K at 06 UTC to 296.18 K at 15 UTC; humid-air density
 388 decreases from 1032.01 to 1021.69 g m⁻³ over the same interval. The network mean H₂O concentration varies

389 from 12.48 g m^{-3} at 06 UTC to 12.77 g m^{-3} at 09 UTC, while the mean of site-specific sampled-hour amplitudes
390 at this level is 0.72 g m^{-3} .

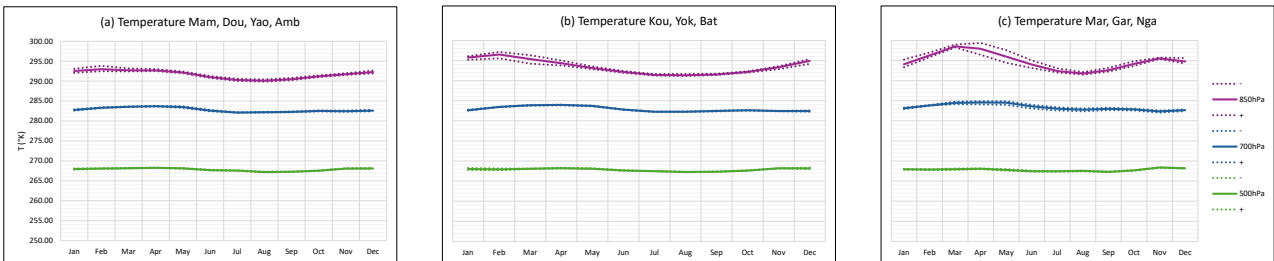
391 Inter-date variability among the sampled days remains non-negligible after averaging the five available daily
392 hours. Across the common-valid 875–850 hPa layer, the daily-to-monthly mean absolute deviation is 0.84 g m^{-3}
393 for H_2O (RMSD = 1.29 g m^{-3}), 0.70 K for T (RMSD = 0.96 K) and 2.30 g m^{-3} for humid-air density. A monthly
394 profile based on these sampled dates therefore smooths appreciable day-to-day variability.

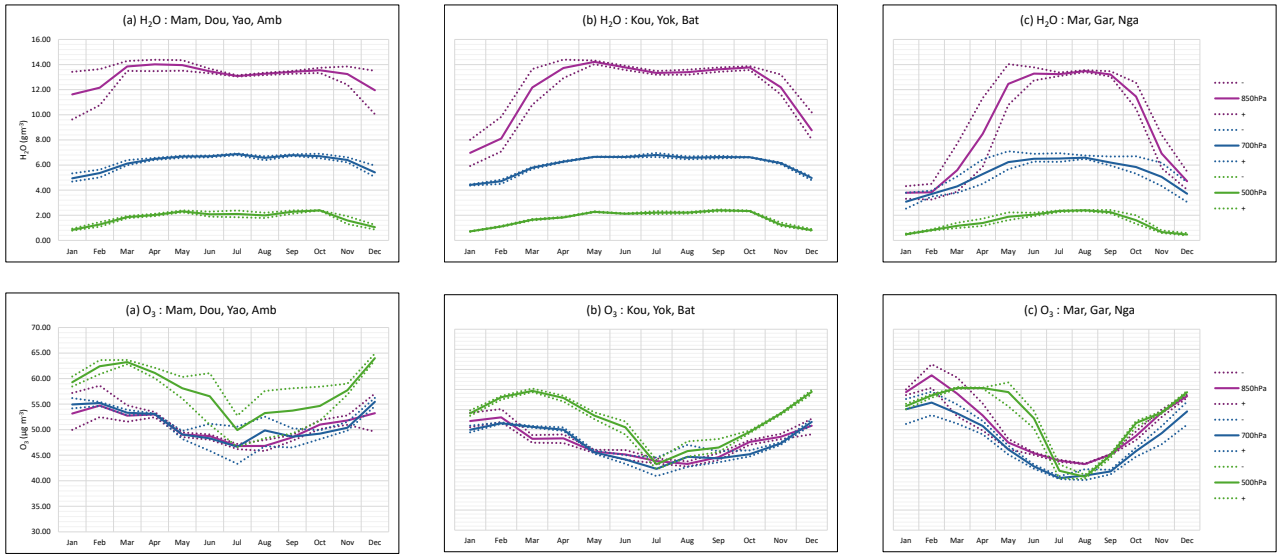
395 Within the sampled 2015–2020 profiles, temperature and water vapour show pronounced monthly cycles in the
396 lower and middle troposphere. The mean of site-specific monthly amplitudes for H_2O is 6.61 g m^{-3} at 875 hPa,
397 6.15 g m^{-3} at 850 hPa, 2.59 g m^{-3} at 700 hPa and 1.71 g m^{-3} at 500 hPa. The corresponding temperature amplitudes
398 are 5.13 K at 875 hPa, 4.78 K at 850 hPa and 1.82 K at 700 hPa. These amplitudes exceed the respective mean
399 interannual amplitudes at the same terrain-valid levels.

400 The ten-site monthly mean cycle is physically interpretable at 875 hPa: T reaches 296.98 K in March and 292.46
401 K in August, while H_2O increases from 8.58 g m^{-3} in January to 14.64 g m^{-3} in May. At 850 hPa, H_2O increases
402 from approximately 7.88 g m^{-3} in January to 13.58 g m^{-3} in May. At 500 hPa, seasonal moisture variation persists,
403 but the absolute concentrations are much smaller. Fig. 4 shows monthly cycles at 850, 700 and 500 hPa, all valid
404 across the complete site network.

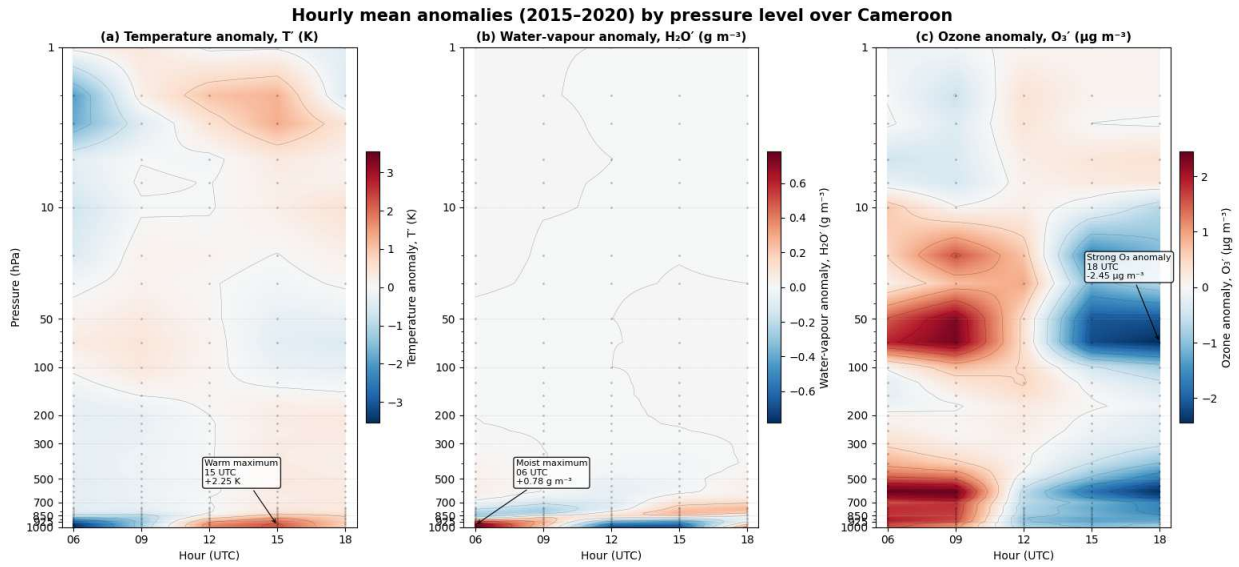
405 The seasonal composites summarize the same within-year pattern. At 875 hPa, mean H_2O concentration across
406 the ten sites is 9.14 g m^{-3} in DJF, 13.19 g m^{-3} in MAM, 14.38 g m^{-3} in JJA and 13.57 g m^{-3} in SON. Mean
407 temperature is highest in MAM (296.19 K) and lowest in JJA (293.03 K). At 850 hPa, the H_2O seasonal signal
408 also persists. Ozone shows an altitude-dependent seasonal structure, so surface-adjacent behaviour should not be
409 generalized to the stratospheric extension.

410 Interannual variability in annual mean profiles is comparatively weak over 2015–2020. At 875 hPa, the mean
411 site-specific interannual amplitude is 0.58 K for T , 1.84 g m^{-3} for humid-air density, 0.81 g m^{-3} for H_2O and 2.78
412 $\mu\text{g m}^{-3}$ for O_3 . Thermal interannual variability increases at 50–10 hPa, with amplitudes of 1.90 K at 50 hPa and
413 3.41 K at 10 hPa. In the lower troposphere, intra-annual variability therefore clearly exceeds interannual
414 variability. The partial intradiurnal signal is shown by pressure level in Fig. 5.





415 Fig. 4 Six-year monthly-mean cycles of temperature, water vapour and ozone at selected pressure levels. For
 416 each group, the solid line represents the mean across the sites included in the panel, and dotted lines of the same
 417 colour indicate the corresponding site-wise minimum and maximum. Pressure levels are 850, 700 and 500 hPa;
 418 groups are (a) Mamfe-Douala-Yaounde-Ambam, (b) Koutaba-Yoko-Batouri and (c) Maroua-Garoua-
 419 Ngaoundere



420
 421 **Fig. 5** Mean hourly anomalies for temperature, water vapour and ozone by pressure level over 2015–2020.
 422 Anomalies are computed relative to the mean of the five available hours (06, 09, 12, 15 and 18 UTC) at each
 423 pressure level. A logarithmic pressure axis is used because pressure decreases approximately exponentially
 424 with altitude, thereby providing a more physically meaningful vertical spacing and avoiding compression of the
 425 upper troposphere and stratospheric extension. The figure represents partial intradiurnal variability rather than a
 426 complete 24-hour cycle

427 4.3. Spatial variability across the climatic gradient

428 Horizontal differences are substantial throughout the common-valid lower troposphere. At 875 hPa, the Ambam–
 429 Maroua H₂O contrast of 5.72 g m⁻³ is 7.1 times the mean site-specific interannual amplitude (0.81 g m⁻³). The

430 Douala–Maroua temperature contrast of 4.47 K is 7.7 times the corresponding interannual amplitude (0.58 K).
 431 At 850 hPa, spatial amplitudes are 5.37 g m⁻³ for H₂O and 3.89 K for T, against interannual amplitudes of 0.73 g
 432 m⁻³ and 0.52 K, respectively.

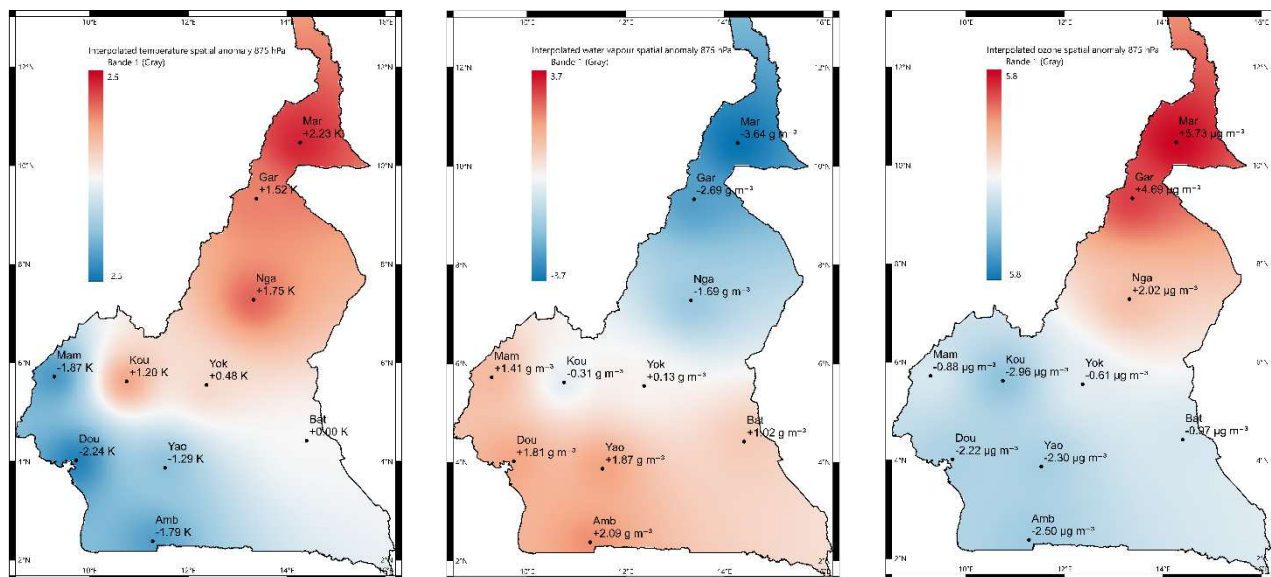
433 Site-specific monthly amplitudes also vary across the climatic gradient at the common-valid 875-hPa level. The
 434 H₂O amplitude is 1.47 g m⁻³ at Ambam, 1.54 g m⁻³ at Douala and 2.36 g m⁻³ at Yaounde, compared with 10.52
 435 g m⁻³ at Ngaoundere, 11.18 g m⁻³ at Garoua and 11.59 g m⁻³ at Maroua. For T, the monthly amplitude is 2.72 K
 436 at Douala, 7.60 K at Garoua and 7.87 K at Maroua. The northern sites thus exhibit a markedly stronger annual
 437 cycle than the humid southern and coastal sites.

438 The spatial signal in O₃ is more nuanced. At 50 hPa, spatial amplitude is 6.31 µg m⁻³, whereas the mean site-
 439 specific monthly amplitude reaches 45.96 µg m⁻³. These amplitudes are constructed from different index sets and
 440 do not by themselves establish which resolution matters more for a particular application.

441 Temperature exhibits a clear spatial contrast at 875 hPa (Fig. 6a), with anomalies ranging from -2.24 K at Douala
 442 to +2.23 K at Maroua, corresponding to a total inter-site amplitude of 4.47 K. Negative anomalies also
 443 characterize Mamfe (-1.87 K), Ambam (-1.79 K) and Yaounde (-1.29 K), whereas positive departures occur at
 444 Koutaba (+1.20 K), Garoua (+1.52 K), Ngaoundere (+1.75 K) and Maroua (+2.23 K). Batouri remains close to
 445 the network mean. The site values therefore reveal a broad transition from cooler southern and coastal profiles
 446 towards warmer northern and interior profiles at this level, although local altitude and regional circulation also
 447 contribute to the observed departures.

448 Water vapour displays an opposite broad geographical organisation (Fig. 6b). The largest positive anomaly occurs
 449 at Ambam (+2.09 g m⁻³), with similarly positive departures at Yaounde (+1.87 g m⁻³), Douala (+1.81 g m⁻³),
 450 Mamfe (+1.41 g m⁻³) and Batouri (+1.02 g m⁻³). Negative anomalies become progressively stronger towards the
 451 northern sites, reaching -2.69 g m⁻³ at Garoua and -3.64 g m⁻³ at Maroua. The resulting inter-site amplitude is
 452 5.73 g m⁻³, confirming substantial lower-tropospheric moisture heterogeneity across the network.

453 Ozone exhibits a different spatial structure (Fig. 6c). At 875 hPa, the largest positive anomalies occur at Maroua
 454 (+5.73 µg m⁻³) and Garoua (+4.69 µg m⁻³), followed by Ngaoundere (+2.02 µg m⁻³), whereas most southern and
 455 central sites show negative departures from the network mean. The most negative anomaly occurs at Koutaba
 456 (-2.96 µg m⁻³), giving a total inter-site amplitude of 8.69 µg m⁻³. Among the ten sites, lower-tropospheric ozone
 457 contrasts are marked and have a different spatial pattern from those of temperature and water vapour.



458 **Fig. 6** Spatial anomalies of (a) temperature, (b) water-vapour mass concentration and (c) ozone mass
 459 concentration at 875 hPa across the ten study sites in Cameroon

460 Anomalies are departures of each site-specific 2015–2020 mean from the unweighted ten-site mean at 875 hPa,
 461 the lowest level valid at all sites; site labels give values in K (T), g m^{-3} (H_2O) and $\mu\text{g m}^{-3}$ (O_3). The coloured
 462 background is an inverse-distance-weighted interpolation (power 2) shown for visualization only; quantitative
 463 interpretation rests on the labelled site values.

464 4.4. Aggregation-deviation diagnostics and balanced variance partition

465 Aggregation-related amplitudes depend on the variable and altitude (Tables 3–6). Temperature, humidity and air
 466 density show their largest absolute lower-tropospheric spreads, while ozone exhibits strong variation higher in
 467 the profile. Maximum-to-minimum amplitudes across different index sets are sensitive to the number of samples
 468 and should not be used alone to rank contributions from site, season and year. The balanced site $\times$ calendar-month
 469 $\times$ year partition described in Section 3.4 provides a direct comparison of these contributions for monthly means
 470 at 875 and 850 hPa.

471 Table 3. Temperature T statistics by pressure level (K); ten-site common-valid domain (875–1 hPa).

p (hPa)	Mean z (km)	Mean	Interannual amp.	Monthly amp.	Hourly amp.	Spatial amp.
875	1.26	294.78	0.58	5.13	3.03	4.47
850	1.51	293.18	0.52	4.78	2.11	3.89
700	3.16	283.02	0.46	1.82	0.70	0.98
500	5.88	267.82	0.47	1.04	0.75	0.22
100	16.59	193.05	0.89	3.98	0.72	0.86
50	20.62	205.90	1.90	5.15	0.67	0.46

p (hPa)	Mean z (km)	Mean	Interannual amp.	Monthly amp.	Hourly amp.	Spatial amp.
10	30.93	230.30	3.41	5.72	1.21	0.36
1	47.81	264.18	2.71	7.42	1.08	0.93

472

473 Table 4. Humid-air density statistics by pressure level (g m^{-3}); ten-site common-valid domain (875–1 hPa).

p (hPa)	Mean z (km)	Mean	Interannual amp.	Monthly amp.	Hourly amp.	Spatial amp.
875	1.26	1026.56	1.84	15.66	10.49	12.26
850	1.51	1003.04	1.69	14.12	7.32	10.48
700	3.16	858.08	1.38	5.71	2.19	1.97
500	5.88	649.36	1.08	2.12	1.79	0.78
100	16.59	180.49	0.81	3.69	0.66	0.82
50	20.62	84.62	0.76	2.10	0.27	0.20
10	30.93	15.13	0.22	0.38	0.08	0.03
1	47.81	1.32	0.01	0.04	0.01	0.00

474

475 Table 5. Water-vapour statistics by pressure level (g m^{-3}); ten-site common-valid domain (875–1 hPa).

p (hPa)	Mean z (km)	Mean	Interannual amp.	Monthly amp.	Hourly amp.	Spatial amp.
875	1.26	12.57	0.81	6.61	0.72	5.73
850	1.51	11.62	0.73	6.15	0.69	5.37
700	3.16	5.88	0.35	2.59	0.37	1.63
500	5.88	1.68	0.29	1.71	0.11	0.49
100	16.59	4.70×10^{-4}	4.33×10^{-5}	2.23×10^{-4}	1.48×10^{-5}	1.73×10^{-5}
50	20.62	2.20×10^{-4}	1.49×10^{-5}	4.38×10^{-5}	5.29×10^{-7}	5.25×10^{-6}
10	30.93	4.25×10^{-5}	1.28×10^{-6}	1.82×10^{-6}	2.12×10^{-7}	1.03×10^{-6}
1	47.81	5.06×10^{-6}	1.63×10^{-7}	3.15×10^{-7}	3.48×10^{-8}	3.40×10^{-8}

476

477 Table 6. Ozone statistics by pressure level ($\mu\text{g m}^{-3}$); ten-site common-valid domain (875–1 hPa).

p (hPa)	Mean z (km)	Mean	Interannual amp.	Monthly amp.	Hourly amp.	Spatial amp.
875	1.26	52.88	2.78	12.54	3.37	8.69
850	1.51	52.75	2.99	13.37	3.27	7.38
700	3.16	51.60	4.62	12.95	3.56	2.99
500	5.88	57.70	6.05	18.02	3.37	3.28
100	16.59	42.84	4.76	28.66	1.57	3.69
50	20.62	206.34	19.63	45.96	4.80	6.31
10	30.93	237.57	13.65	27.37	1.34	5.43
1	47.81	6.40	0.32	0.60	0.22	0.11

478

479 Table 7. Mean absolute aggregation deviations over the lowest common-valid layer (875–850 hPa).

Variable	Aggregation scale	Mean absolute deviation (875–850 hPa)	Interpretation
H ₂ O	Monthly vs annual	2.14 g m ⁻³	Mean monthly departure from annual profile
H ₂ O	Site vs spatial mean	1.56 g m ⁻³	Mean site departure from network mean
T	Seasonal vs annual	1.32 K	Mean seasonal departure from annual profile
T	Monthly vs annual	1.46 K	Mean monthly departure from annual profile
T	Site vs spatial mean	1.33 K	Mean site departure from network mean

480

481 Replacing monthly by annual profiles produces a larger mean absolute departure in H₂O (2.14 g m⁻³) than
 482 replacing site profiles by the network mean (1.56 g m⁻³), whereas the corresponding T departures are similar
 483 (1.46 and 1.33 K; Table 7).

484 Table 8. Orthogonal partition of the sampled monthly-mean variation by site, month and year; each row uses
 485 720 balanced site–month–year cells.

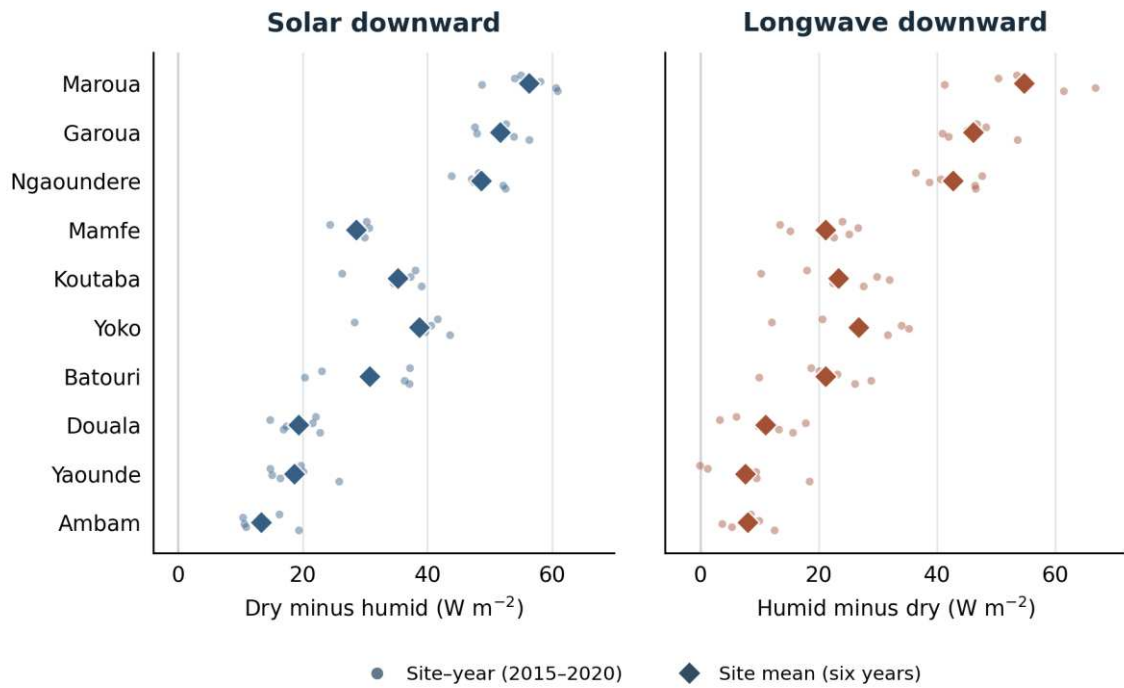
Level, variable	Site (%)	Month (%)	Site × month (%)	Year (%)	Other interactions (%)
875 hPa T	41.86	37.98	14.11	0.51	5.54
875 hPa H ₂ O	29.69	38.05	26.73	0.52	5.01
850 hPa T	38.35	42.32	13.14	0.56	5.64
850 hPa H ₂ O	28.89	40.83	24.35	0.47	5.46

486 At 875 hPa (Table 8), the water-vapour site × month term accounts for 26.73% of the balanced monthly-mean
 487 variation, reflecting different seasonal cycles across the sites. Temperature is more strongly differentiated by site
 488 (41.86%) and month (37.98%). The common year effect is small (0.52% for H₂O; 0.51% for T), while the
 489 remaining interactions involving year amount to approximately five percent. The corresponding 850-hPa pattern
 490 is similar.

491 4.5. Radiative response of coherent annual and extreme-month profiles

492 All 360 model runs completed; in the solar calculations, downward global flux equals the sum of the direct-
 493 horizontal and diffuse components to numerical precision. Across the 60 site–year pairs, the dry profile yields
 494 23.70 W m^{−2} more global solar irradiance than the annual profile on average, whereas the humid profile yields
 495 10.41 W m^{−2} less. The paired dry-minus-humid contrast averages 34.11 W m^{−2} and is positive in all 60 cases. For
 496 downward longwave irradiance, the mean dry-minus-annual contrast is −20.29 W m^{−2} and the mean humid-
 497 minus-annual contrast is +5.99 W m^{−2}. The humid-minus-dry contrast averages +26.28 W m^{−2} and is positive in
 498 59 of 60 cases. These values refer to the model’s virtual 875-hPa boundary.

499 The six-year mean dry-minus-humid solar contrast ranges from 13.38 W m^{−2} at Ambam to 56.28 W m^{−2} at
 500 Maroua; the corresponding humid-minus-dry longwave contrast ranges from 7.54 W m^{−2} at Yaounde to 54.77 W
 501 m^{−2} at Maroua (Fig. 7). For Maroua in 2016, the driest month is January (8.85 mm integrated water vapour) and
 502 the wettest is July (34.55 mm), compared with 22.74 mm for the annual profile. Their respective global solar
 503 fluxes are 990.26, 929.58 and 950.40 W m^{−2}; downward longwave fluxes are 285.63, 352.49 and 334.78 W m^{−2}.
 504 The longwave ordering is not universal: in eight site–years the humid profile has lower downward longwave flux
 505 than the annual profile despite higher integrated water vapour. The only humid-minus-dry reversal occurs at
 506 Yaounde in 2020 and is nearly zero (−0.05 W m^{−2}).



507

508 **Fig. 7** Clear-sky downward-flux contrasts at the virtual 875-hPa boundary for the ten Cameroon sites. Solar
 509 differences are dry minus humid; longwave differences are humid minus dry. Circles show each of six site-year
 510 pairs (2015–2020), and diamonds their site-specific mean; grey vertical lines indicate zero difference. The
 511 monthly profiles are selected by the minimum and maximum 875–1 hPa water-vapour column in each year. All
 512 profiles use the same fixed solar geometry within each pair; clouds and aerosols are excluded.

513 5. Discussion

514 5.1. Spatial, seasonal and year contributions to sampled variability

515 Within the sampled 2015–2020 monthly means, both calendar month and site contribute strongly to lower-
 516 tropospheric variation, and their interaction is especially pronounced for water vapour. At 875 hPa, month, site
 517 and site $\times$ month account for 38.05%, 29.69% and 26.73% of the water-vapour sum of squares, respectively; for
 518 temperature, site accounts for 41.86%, month 37.98% and site $\times$ month 14.11% (Table 8). The common year
 519 effect is below 1% for either variable, but interactions involving year also contribute. These are descriptive shares
 520 of the complete array of sampled monthly means, not estimates of the relative importance of processes outside
 521 2015–2020, a trend test or evidence that an annual profile is radiatively adequate. A small shared-year
 522 contribution to the ERA5 profile variance cannot establish a small interannual change in radiative sensitivity:
 523 ERA5-based radiative kernels have been shown to vary with the background atmospheric state across years
 524 (Huang and Huang 2023).

525 The observed site and month structure is consistent with Cameroon’s contrasting climate regimes and the seasonal
 526 displacement of moist and dry air masses, along with altitude, coastal influence and continentality. The sizeable
 527 site $\times$ month component for water vapour indicates that one monthly cycle averaged across these ten sites would
 528 conceal within-network differences. Year-related terms are smaller in the observed six-year monthly-mean array,
 529 but the sparse daily sampling and limited period preclude a claim that additional years or hours would not change

530 this partition. Profile libraries intended for applications should retain the distinct sampled site and seasonal
531 structures and document their coverage.

532 **5.2. Variable-specific implications: H₂O, T, air density and O₃**

533 The variables must be interpreted separately. Water vapour warrants particular attention in the lower troposphere
534 (875–700 hPa), where the sampled profiles show steep vertical gradients and large spatial and seasonal contrasts.
535 The radiative experiments select monthly end members by integrated water vapour, but their flux differences
536 reflect complete profiles in which temperature and constituents also vary. Temperature matters for thermal
537 emission and contributes to humid-air density and the resulting mass concentrations of atmospheric constituents.
538 In this study, humid-air density is a derived thermodynamic quantity rather than an independent constituent; its
539 lower-tropospheric contrasts are interpreted alongside temperature and specific humidity.

540 Ozone requires an application-specific assessment. In the stratospheric extension, sampled monthly O₃ profiles
541 differ substantially; for example, the reported maximum-to-minimum monthly amplitude at 50 hPa is 45.96 µg
542 m⁻³. This statistic is descriptive and cannot by itself be ranked against spatial or interannual amplitudes computed
543 from differently sized index sets. Ozone and temperature profiles influence UV calculations, ozone-column
544 retrievals and radiative heating (WMO 2022; Iacono et al. 2008; Lapeta et al. 2000; Bais et al. 2019). Monthly
545 and seasonal ozone choices should therefore be tested for those applications; the broadband, end-member flux
546 experiments here do not establish the required ozone resolution.

547 **5.3. Consequences for atmospheric and radiative modelling**

548 For atmospheric and radiative modelling, profiles should be selected according to the target variable, atmospheric
549 layer and temporal scale. Six-year mean profiles provide a descriptive reference for this sampled period. For
550 clear-sky radiative applications, the paired simulations reported in Section 4.5 demonstrate that annual site
551 profiles can conceal substantial differences between the driest and wettest coherent monthly profiles. They do
552 not directly test spatially averaged profiles or establish the flux error for every month. Reference radiative
553 schemes identify T, H₂O and O₃ as controls on fluxes, making profile choice pertinent to radiative sensitivity
554 (Mlawer et al. 1997; Clough et al. 2005; Iacono et al. 2008).

555 The aggregation deviations in Table 7 describe atmospheric-state representativeness within ERA5 rather than
556 errors in radiative output. Differences in lower-tropospheric H₂O mass concentration cannot be converted into
557 millimetres of precipitable water or W m⁻² from the layer-mean deviation alone. The present experiment instead
558 integrates the complete 875–1 hPa water-vapour profiles and computes the radiative response of each coherent
559 atmospheric state under a specified geometry. The resulting paired flux contrasts must not be divided by the 875–
560 850 hPa mass-concentration deviation to infer a universal response per unit H₂O. Established work supports the
561 sensitivity of solar extinction to water vapour (Gueymard 2014; Bennartz and Lohmann 2001; Tarasova and
562 Fomin 2000; Pei et al. 2019), but the effects of temperature and co-varying constituents remain part of the
563 simulated contrasts.

564 The practical relevance of preserving site-specific atmospheric profiles is supported by previous work over
565 northern Cameroon. In Maroua, Fotsing Talla et al. (2018) used ECMWF atmospheric profiles as inputs to

MODTRAN simulations of downward global solar radiation and showed that these profiles were more suitable for clear-sky simulations than standard MODTRAN atmospheric profiles. Their study addressed the same broad problem (replacing generic atmospheric representations with dynamically informed vertical profiles) in a Cameroonian radiative-transfer context. The present study extends this perspective to ten sites across Cameroon's climatic gradient and directly compares clear-sky fluxes for coherent annual and contrasting monthly profiles.

For thermal radiation, humidity and temperature must be interpreted jointly. Clear-sky radiative-kernel and outgoing-longwave studies show sensitivity to both variables and nonlinear responses in warm, humid atmospheres (Huang et al. 2007; Dessler et al. 2008; Feng et al. 2023). In the present paired simulations, the humid profile produces greater downward longwave irradiance than the dry profile in 59 of 60 site-years. Yet eight humid profiles have lower downward longwave irradiance than their corresponding annual profile despite greater integrated water vapour; all eight also have a colder 875-hPa temperature. Changes elsewhere in the vertical temperature and constituent profiles also contribute, so this association does not isolate a temperature effect. The near-zero humid–dry reversal at Yaounde in 2020 (-0.05 W m^{-2}) reinforces the need to evaluate complete profiles rather than assume a monotonic longwave response to column water vapour.

The atmospheric analysis motivates retaining site and calendar-month detail in exploratory lower-tropospheric profiles, particularly for H_2O and T . For event or subdaily studies the corresponding sampled instantaneous states are more appropriate than a six-year mean, although the five selected hours do not characterize night-time conditions. For UV or stratospheric heating, O_3 and upper-level T require separate application-specific sensitivity tests. The present radiative experiment compares the annual profile with only the two monthly water-vapour end members; it cannot determine a universal minimum time resolution for radiation calculations.

5.4. Implications for profile selection in applications

These results suggest design considerations for atmospheric-profile inputs to radiative-transfer and solar-resource applications in Cameroon. The usefulness of climate information for the energy sector depends on matching its spatial and temporal resolution to the downstream application (Bartók et al. 2019), and insufficient resolution has been reported as a barrier to the use of climate information in West Africa (Sultan et al. 2020). Table 9 lists candidate profile resolutions by application; they are hypotheses for further radiative and observational testing rather than validated minimum resolutions.

Table 9. Candidate profile resolutions by application, requiring further radiative and observational evaluation.

Application	Temporal representation to test	Spatial scale	Priority variables	Justification
Description of sampled means	Six-year or annual sampled-period mean	By site	T , air, H_2O	Mean structure only; seasonal detail is lost

Clear-sky radiative transfer	Site-specific monthly profiles; test against finer sampled profiles	By site	H ₂ O, T, air	Site and seasonal structure; radiative tests cover two end members
Exploratory solar-resource profiles	Monthly profiles; assess clouds and aerosols	By site	H ₂ O, T; O ₃ secondary; aerosols and clouds to be added	Clear-sky end-member flux contrasts are sizeable; clouds and aerosols were omitted
Instantaneous calculations / event studies	Available sampled hours or instantaneous profiles	By site	H ₂ O, T, air and O ₃ depending on objective	Individual sampled states differ from their aggregates
UV / stratospheric heating	Monthly or seasonal profiles; test by spectral application	Site or region	Stratospheric O ₃ and T above 100 hPa	Upper-level ozone has sampled monthly structure; UV effects remain untested
Cross-site composite profile	Network mean only	Spatial mean only	By application	A network average hides sampled site contrasts

595

596 The site-specific monthly profiles are a useful starting point for sensitivity studies of seasonal clear-sky radiative
597 transfer under specified conditions. The end-member experiment shows sizeable potential contrasts, but
598 determining whether monthly profiles are sufficiently resolved for a particular flux product requires simulations
599 for all twelve sampled monthly states and comparison with fluxes computed from the finer input states. Hourly
600 or instantaneous profiles remain appropriate when subdaily variation is the target. The effect of replacing a site
601 profile by the cross-site mean was quantified for atmospheric variables but not tested in the radiative model.
602 Solar-resource products additionally require clouds, aerosols, real terrain, sampling coverage and independent
603 evaluation. A subsequent stage should consult atmospheric modellers, solar-resource analysts, renewable-energy
604 planners and Cameroonian meteorological and energy organizations, then test the resulting profile products in
605 the applications they identify.

606 5.5. Limitations and future work

607 The six-year period (2015–2020) is too short to establish a climatological normal or long-term stability. The
608 balanced variance partition finds a small common year component for the available monthly means, but
609 interactions between year, site and month remain and later years may differ. No trend or uncertainty across longer
610 periods was evaluated. The profiles are sampled-period summaries useful for testing profile resolution, not
611 validated national climate normals.

612 The original data comprise 360 sampled dates per site over six years: the same five calendar dates (days 1, 8, 15,
613 22 and 28) were selected each month, each with five UTC hours. This systematic, roughly weekly coverage
614 cannot establish full-month daily representativeness, capture every brief event, or characterize nocturnal
615 behaviour or a complete diurnal cycle. Masking excludes below-ground pressure levels in the common 875–1
616 hPa network column but cannot remove model-orography or reanalysis uncertainty. Some site-specific 900–1000
617 hPa values remain valid at individual times but are unsuitable for a simultaneous ten-site level comparison. The
618 ERA5 differences presented here were not validated against independent radiosondes.

619 The radiative-transfer experiment propagates coherent annual and extreme-month profiles through libRadtran,
620 but its scope is restricted. All fluxes refer to a virtual 875-hPa boundary in cloud-free, aerosol-free columns with
621 fixed solar zenith angle and simplified boundary properties; neither observed surface irradiance nor actual
622 monthly or annual irradiance is reproduced. The profile mean is not the mean of the corresponding radiative
623 fluxes. In addition, the upper boundary at 1 hPa omits atmospheric layers above that level, and the extreme-month
624 design does not measure typical monthly error or the radiative effect of substituting the network mean. Future
625 work should run all twelve available monthly mean profiles for each site–year, compare the resulting monthly
626 fluxes with annual-profile fluxes under identical forcing, and then extend the simulations to the five sampled
627 UTC hours, represent site-specific terrain, aerosols, clouds and realistic surface properties, quantify radiative
628 responses to spatial averaging, and compare with independent radiative schemes and observations.

629 Finally, the profile-resolution recommendations were derived from physical diagnostics and published radiative
630 sensitivities; they were not co-designed or evaluated with prospective users. Such engagement is required before
631 the profiles are used as operational climate-information products (Sultan et al. 2020).

632 **6. Conclusions**

633 Across the sampled site–year–month profiles, the ten Cameroonian locations exhibit substantial site and calendar-
634 month variation in lower-tropospheric temperature and humidity. A balanced partition shows that their interaction
635 is also substantial, particularly for water vapour. The common year component is small within 2015–2020, a
636 finding limited to these sampled monthly means and their six-year window.

637 For the selected sites and period, retaining site and calendar-month detail is informative when comparing lower-
638 tropospheric H₂O and temperature profiles or designing radiative sensitivity tests. Ozone and upper-level
639 temperature warrant separate time-resolution tests for UV and heating-rate applications. The present evidence
640 does not define a universal temporal resolution for radiative products.

641 Site-specific six-year mean profiles provide a descriptive baseline for the available sample; site-specific monthly
642 profiles retain much of its systematic seasonal structure. A cross-site mean obscures the sampled site signal and
643 must be evaluated against the intended location and use. Finer sampled profiles are needed to examine individual
644 atmospheric states. Before any profile resolution is adopted as an operational standard, its radiative consequences
645 should be tested for all available months, the sampling schedule assessed, and the outcome compared with
646 independent observations.

647 The clear-sky end-member experiment illustrates within-year radiative sensitivity: at the virtual 875-hPa
 648 boundary, the dry–humid solar contrast averaged 34.11 W m^{-2} across 60 site–years and the humid–dry
 649 downward longwave contrast averaged 26.28 W m^{-2} . Temperature and humidity covary in these complete
 650 profiles. These contrasts are neither observed ground-level irradiances nor estimates of the typical monthly
 651 difference caused by replacing a profile with its annual mean.

652 The resulting product is a documented collection of site-specific sampled-period profiles at several time scales,
 653 with coverage and terrain-validity constraints stated explicitly. Its suitability for solar-resource or energy
 654 applications requires broader radiative experiments, observational validation and testing with intended users.

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 784

785 **Statements and Declarations**

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798 **Competing Interests**

799 The authors have no relevant financial or non-financial interests to disclose.

800 **Author Contributions**

801 Emmanuel Guemene Dountio: Conceptualization, Resources, Methodology, Data curation, Software, Formal
802 analysis, Visualization, Investigation, Writing – original draft, Writing – review & editing. Donatien Njomo:
803 Supervision, Methodology, Validation, Resources, Writing – original draft, Writing – review & editing. Samuel
804 Domngang: Supervision, Validation, Resources. Elie Bertrand Kengne Signe: Resources, Investigation, Writing
805 – review & editing.

806 **Data Availability**

807 This study analysed publicly available ERA5 reanalysis data produced by the Copernicus Climate Change Service
808 (C3S) at ECMWF. Temperature, specific humidity, ozone mass mixing ratio and geopotential were obtained
809 from "ERA5 hourly data on pressure levels from 1940 to present" (<https://doi.org/10.24381/cds.bd0915c6>).
810 Surface pressure, used for terrain masking, was obtained from "ERA5 hourly data on single levels from 1940 to
811 present" (<https://doi.org/10.24381/cds.adbb2d47>). Both datasets are freely accessible from the Copernicus
812 Climate Data Store after registration. The datasets generated during the current study, namely the processed site-
813 specific profiles, aggregation diagnostics, figure-supporting data, and libRadtran input files and numerical
814 outputs, are available from the corresponding author on reasonable request..

815 **Code Availability**

816 The analysis scripts used for ERA5 extraction, profile derivation, aggregation diagnostics and libRadtran
817 simulations are available from the corresponding author upon reasonable request.

818 **Ethics Approval, Consent to Participate and Consent for Publication**

819 Not applicable.