

Convergent warming signals without detectable rainfall reorganization in the Mandena basin of southern Madagascar

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Article

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Abstract

Small coastal basins may express climate change through thermal forcing even when rainfall change is unresolved. We analysed 1993–2022 hydroclimate over the 85.84 km² Mandena basin in southeastern Madagascar using institutional DGM-RFE rainfall, a NASA POWER/MERRA-2 temperature series, and basin-weighted CHIRPS3 and ERA5-Land comparisons. Theil–Sen slopes were paired with circular-block bootstrap intervals, multiplicity control, shared-block family tests and detection-power calculations. NASA POWER mean temperature increased by 0.140°C decade⁻¹ (95% interval 0.027 to 0.246; unadjusted $p = 0.0177$; Holm $p = 0.0885$), while ERA5-Land increased by 0.133°C decade⁻¹ (0.067 to 0.196; $q = 0.0030$). The annual-temperature family was detected globally ($p = 0.0354$), and the products had $r = 0.801$ with no trend in their difference. DGM-RFE and CHIRPS3 precipitation trends had opposite signs (-38.3 and $+33.8$ mm decade⁻¹), with a 40% difference in annual means. No joint rainfall signal emerged across totals, extremes, seasons, July–June panels or 54 fixed onset definitions. ERA5-Land wind speed decreased by 0.137 m s⁻¹ decade⁻¹, whereas reference evapotranspiration showed no trend. Mandena therefore exhibited more consistent thermal and wind change than rainfall reorganization.

Introduction

Climate change does not appear identically at every spatial scale. In a small coastal basin, annual rainfall is shaped by a limited number of storms, local topography and product-specific spatial averaging, whereas air temperature generally varies more coherently over space. Thermal change can therefore be resolved while precipitation totals, extremes or season boundaries remain dominated by interannual variability. Distinguishing these responses matters because water-balance interpretation and environmental attribution require climatic exposure to be defined before local land-use effects are assessed.

Madagascar already shows this contrast. Quality-controlled station records for 1950–2018 indicate widespread warming but mostly non-detected station-level precipitation trends, with greater spatial coherence for temperature than rainfall [1]. High-resolution datasets likewise show widespread warming across East Africa while rainfall trends vary by season and location [2]. In southern Madagascar, the 2019–2021 rainfall deficit prompted different attribution conclusions depending on the event definition and data source [3, 4]. More recent regional analyses report later rainy-season onset, reduced early-season water availability and severe drought impacts on vegetation [5, 6]. These studies establish a regional hazard, but they do not determine whether the same signal is resolved over every individual basin, period and product.

The Mandena basin lies on the southeastern coast near Taolagnaro. Its low relief, sandy substrates, littoral wetlands and short drainage pathways make its hydrology sensitive to both atmospheric forcing and land disturbance [7, 8]. The 85.84 km² boundary used here was inherited without modification from a companion before–after–control–impact record [9]. Preserving that geometry and the same 1993–2022

calendar years is required for a later mine-by-climate analysis: redefining the exposure window or boundary would create artificial misalignment with the annual mining assessment.

A basin assessment also faces a measurement problem. The institutional DGM-RFE daily rainfall product provides complete coverage over the required period but is not a dense-gauge reference. CHIRPS3 has a different satellite–station processing chain and can expose product dependence, yet product agreement is not equivalent to field validation [10, 11]. Temperature comparisons have the same limitation: NASA POWER is derived from MERRA-2, whereas ERA5-Land is a separate land reanalysis with different support and processing [12, 13]. Conclusions therefore need to combine effect sizes, dependence-aware uncertainty, multiplicity control, product comparisons and the trend magnitudes that a 30-year record could detect.

This study asked whether observed change in Mandena from 1993 to 2022 was expressed primarily through warming, rainfall amount and extremes, seasonal timing or atmospheric evaporative demand. A basin-wide thermal signal was expected to have similar decadal slopes in NASA POWER and ERA5-Land, whereas rainfall reorganization would need support across annual totals, extremes, seasons, hydrological-year boundaries and a pre-defined onset set. Five endpoints were designated before inference because they represented distinct annual dimensions of the water-balance problem: mean moisture supply (annual DGM-RFE precipitation), thermal forcing (NASA POWER mean temperature), short-duration rainfall intensity (DGM-RFE Rx1day), persistence of rain-free conditions (maximum consecutive dry days) and integrated atmospheric demand (FAO-56 reference evapotranspiration). Each endpoint had complete annual support over the exact 30-year contract. Secondary analyses examined product agreement, temperature extremes, wind, climatic water balance and onset sensitivity.

Methods

Study area and geometry

The study unit was the Mandena basin near Taolagnaro in southeastern Madagascar, bounded by 46.98384–47.08250° E and 24.98396–24.84899° S. The area includes low-relief coastal sands, littoral wetlands and open water [7, 8]. The projected polygon was inherited without editing from the companion archive in WGS 84 / UTM zone 38S (EPSG:32738) [9]. The workflow compared the ordered coordinate sequence in the source GeoJSON with the DGM-RFE extraction GeoPackage, confirming one feature, 3,351 coordinates and exact numerical identity. Planar and ellipsoidal areas were retained separately.

Time domain

Formal inference used calendar years 1993–2022 ($n = 30$) to match the companion record. The year, not the day or grid cell, was the inferential unit. DGM-RFE rainfall was retained from 1992 through 2023 only to complete boundary calculations. Start-year labels 1993–2022 represented July 1993–June 2023; end-

year labels represented July 1992–June 2022. December–February seasons were labelled by January. Only the calendar-year table is eligible for direct joining to the mining assessment.

Precipitation data

Daily DGM-RFE-MON rainfall from the Madagascar Directorate General of Meteorology was the primary input [10]. Basin-cell intersections were calculated in EPSG:32738, and rainfall was area-weighted across 13 intersecting cells. Values had to be finite and non-negative; no missing-day substitution was permitted. Daily volume was checked against rainfall depth multiplied by the ellipsoidal basin area. The institutional product was selected for continuous daily coverage, not as field truth. CHIRPS3 monthly and pentad rainfall provided a comparison based on a different satellite–station chain [11]. Ten 0.05° cells intersected the basin. CHIRPS3 was not used to replace DGM-RFE or assert field validation.

Temperature and atmospheric data

NASA POWER daily 2 m maximum and minimum temperatures were the primary thermal variables [12, 14]. The deposited SWAT+-formatted derivative was associated with the POWER request location at 25.03° S, 46.99° E and a recorded elevation of 30 m and covered 1987–2022; the complete 1993–2022 subset was analysed. The request location lies approximately 5.4 km outside the basin boundary, but POWER meteorological variables are supplied on the native MERRA-2 0.5° latitude × 0.625° longitude grid and represent grid-cell averages rather than point observations; this offset is therefore small relative to the spatial support of the source data [12, 14].

Daily mean temperature was $(T_{\max} + T_{\min})/2$ because the file lacked the separate T2M daily-mean parameter. ERA5-Land hourly data supplied the comparison temperature and variables needed for atmospheric demand [13, 15]. CHIRPS3 and ERA5-Land were used as separate comparison products to assess product dependence; neither was treated as a statistically independent observation or as independent field validation. Three 0.1° cells were area-weighted, and every local day required 24 source hours. Wind was converted from 10 m to 2 m with the FAO-56 logarithmic profile.

Indicators and rainfall onset

Rainfall and temperature indicators were based on the Expert Team on Climate Change Detection and Indices framework where applicable [16]. Percentile-based temperature indices were implemented as study-relative adaptations rather than strict ETCCDI implementations. A wet day had rainfall ≥ 1 mm. Rainfall metrics included annual total, wet-day precipitation and count, simple daily intensity, Rx1day, Rx5day, consecutive dry and wet days, threshold counts, upper-percentile amounts and cumulative-rain timing. Temperature metrics included annual Tmin, Tmax, mean temperature, diurnal range, TXx, TXn, TNx, TNn, TX90p, TN10p, spell duration and hot-and-dry days. Calendar-day percentile thresholds used a circular 11-day window centered on each calendar day across 1993–2022. The wider window was a

deliberate smoothing choice to increase the number of observations contributing to each calendar-day percentile while retaining the annual seasonal cycle. Consequently, TX90p, TN10p and related spell indices are interpreted as study-relative sensitivity indicators rather than strict ETCCDI indices.

Onset was treated as definition-sensitive. Fifty-four rules were fixed as the product of two search starts (1 October, 1 November), three accumulation windows (3, 5, 7 days), three thresholds (20, 30, 40 mm) and three largest permitted dry runs during the following 30 days (7, 10, 15 days). The ranges bracket published African agronomic definitions, including criteria applied in Madagascar [17–19], that combine accumulated rainfall with a post-trigger dry-spell screen to avoid false onset [17, 18]. The grid quantified sensitivity to the definition rather than identifying a universally correct rule. Onset was the first date meeting the accumulation and post-trigger criteria. Trends for all rules were corrected together. No definition was chosen after results were viewed.

Reference evapotranspiration

Daily ET_0 was calculated with the FAO-56 Penman–Monteith equation using ERA5-Land net radiation, surface pressure, actual and saturation vapour pressure, 2 m wind and mean temperature [20]. Soil heat flux was zero, vapour-pressure deficit was bounded at zero and negative ET_0 estimates were set to zero. Climatic water balance was DGM-RFE precipitation minus ET_0 . ET_0 represented atmospheric demand under a reference surface, not actual evapotranspiration or a hydrological-model output.

Trend inference and multiplicity

The point estimate was the median of all pairwise slopes, reported per decade [21]. Circular moving blocks preserved local year-to-year dependence [22]. With $n = 30$, block length was fixed at $\text{round}(n^{1/3}) = 3$ years. Trend-preserving residual resamples produced percentile intervals; detrended-null residual resamples produced two-sided p values. Primary endpoints used 10,000 replicates and other annual families 2,000. All tests used $\alpha = 0.05$.

Holm adjustment controlled familywise error across the five pre-specified endpoints [23]. Other annual families used Benjamini–Hochberg q values [24]. For each family and joint replicate, one circular-block index sequence was drawn and applied to the detrended residuals of every metric. The maximum absolute standardized null slope then supplied a family-level p value and metric-level adjusted p values from 10,000 joint replicates. These joint-resamples were generated directly and were not constructed by aligning metric-specific bootstrap streams. Ordinary Mann–Kendall [25] and Hamed–Rao [26] results were diagnostics rather than primary p values. Lag caps 1–7 and block lengths 2–5 were sensitivity analyses. Pettitt change points [27] used 5,000 rank permutations and within-family q values and were interpreted as candidate shifts, not causal breaks.

Agreement and detection power

Product comparisons used Pearson and Spearman correlation, Lin concordance [28], mean difference, root-mean-square error, percent bias and Kling–Gupta efficiency. Monthly and annual rainfall were reported separately, together with trends in product differences and ratios. Correlation was never interpreted as removal of bias. Detection limits used 3,000 joint circular-block resamples across the five primary endpoints. Within each replicate, the same block indices were applied to every endpoint. The 95th percentile of the maximum standardized null statistic set the familywise threshold; slopes were injected one endpoint at a time to identify 80% and 90% detection magnitudes.

Analytical reproducibility

The archived analysis runs offline from deposited basin-level source subsets with CPython 3.10 or later and only the standard library for analysis; figure export additionally requires a local SVG renderer (Inkscape or librsvg); the reference execution used CPython 3.12.13. One command regenerates result tables, figures, tests, a run receipt and a SHA-256 manifest. The DGM-RFE QGIS extraction source is included. Acquisition and basin-extraction scripts are not included for NASA POWER, CHIRPS3, ERA5-Land or Landsat; for those products, reproducibility begins from deposited source subsets rather than provider services. No network request is made during analysis.

Results

Spatial and temporal contract

The inherited polygon contained 3,351 coordinates in EPSG:32738 and matched the companion basin geometry coordinate by coordinate. Its planar area was 85.8594 km² and its ellipsoidal area was 85.8388 km²; the 0.024% difference reflected the area calculation rather than a boundary change. DGM-RFE rainfall was averaged across 13 intersecting 0.0375° cells, CHIRPS3 across 10 intersecting 0.05° cells and ERA5-Land across three supported 0.1° cells. NASA POWER temperature was associated with the request location at 25.03° S, 46.99° E and the native MERRA-2 grid-cell support described in Methods (Fig. 1; Table 1).

All primary endpoints contained 30 annual observations from 1993 through 2022. DGM-RFE additionally covered 1 January 1992 through 31 December 2023, providing complete July–June seasons at both boundaries. The extended rainfall series contained 11,688 consecutive dates, finite non-negative values and no substituted missing days. The inferential unit remained the year; days and grid cells were not treated as replicates.

Table 1. Data sources, spatial support and analytical roles. DGM-RFE denotes the Madagascar Directorate General of Meteorology rainfall estimate; ET₀ denotes FAO-56 reference evapotranspiration.

Variable	Source and support	Deposited period	Role	Mandena processing
Rainfall	DGM-RFE-MON; 13 × 0.0375° cells	1992–2023 daily	Primary	Area-weighted intersections in EPSG:32738
Rainfall	CHIRPS3; 10 × 0.05° cells	1981–2025 monthly/pentad	Comparison	Deposited weights; 1993–2022 monthly and annual values
Tmin, Tmax	NASA POWER / MERRA-2 request location; 25.03° S, 46.99° E; native meteorological grid 0.5° × 0.625°	1987–2022 daily	Primary temperature	Tmean = (Tmin + Tmax)/2; 1993–2022 subset
Temperature and atmospheric variables	ERA5-Land; 3 × 0.1° cells	1993–2022 hourly	Temperature comparison; ET ₀ inputs	Local-day aggregation from 24 hours; basin weights
Basin boundary	Companion record; EPSG:32738	Fixed geometry	Spatial contract	Coordinate identity and SHA-256 authentication

Concordant warming across temperature products

NASA POWER-derived annual mean temperature averaged 23.017 °C and increased by 0.140 °C decade⁻¹ (95% circular-block bootstrap interval 0.027 to 0.246; two-sided p = 0.0177). This corresponds to 0.406 °C across the 29-year endpoint separation. Because temperature was one of five pre-specified endpoints, its Holm-adjusted p value was 0.0885 and did not cross the familywise 0.05 threshold (Table 2). Its interval excluded zero for every tested block length from two to five years, with p values from 0.0110 to 0.0225.

ERA5-Land annual mean temperature averaged 22.320 °C and increased by 0.133 °C decade⁻¹ (0.067 to 0.196; p = 0.0005; Benjamini–Hochberg q = 0.0030; max-statistic adjusted p = 0.0032). The annual series were strongly associated (Pearson r = 0.801; Spearman ρ = 0.748), although ERA5-Land was cooler by 0.696 °C and Lin concordance was 0.181 because of this offset. The ERA5-Land minus NASA POWER difference had a slope of −0.016 °C decade⁻¹ (Hamed–Rao p = 0.748), providing no evidence that the products drifted apart (Fig. 2).

Secondary indices indicated a non-uniform temperature-family response. The 13-variable annual-temperature family had a global shared-block max-statistic p value of 0.0354. Annual Tmax increased by 0.184 °C decade⁻¹ (0.011 to 0.355; q = 0.127), while Tmin increased by 0.090 °C decade⁻¹ (−0.006 to 0.178; q = 0.153). TXn increased by 0.318 °C decade⁻¹ (0.078 to 0.520; q = 0.084; family-adjusted p =

0.0354). Hot-and-dry days increased by 6.32 days decade⁻¹ (1.51 to 11.69; unadjusted p = 0.0195), but q = 0.084 and max-statistic adjusted p = 0.157. These secondary directions did not replace the five-endpoint Holm result.

No resolved rainfall reorganization

Mean annual DGM-RFE precipitation was 1,589.2 mm. Its slope was -38.3 mm decade⁻¹ (-180.1 to 103.5; p = 0.4386; Holm p = 0.8771), equivalent to -2.4% decade⁻¹. CHIRPS3 was wetter, averaging 2,218.8 mm yr⁻¹, and its trend had the opposite sign (+33.8 mm decade⁻¹; Hamed-Rao p = 0.721). Annual product correlation was 0.789, but CHIRPS3 exceeded DGM-RFE by 629.5 mm yr⁻¹ (39.6%), producing concordance of 0.304. The CHIRPS3-minus-DGM trend was -11.8 mm decade⁻¹ (p = 0.669), and the ratio showed no trend (p = 0.915). The products tracked much of the interannual variation while disagreeing on absolute rainfall and trend direction (Fig. 3).

None of the 18 annual DGM-RFE precipitation indicators produced a family-level signal (global shared-block max-statistic p = 0.546). Rx1day decreased by 9.05 mm decade⁻¹ (-24.12 to 5.17; Holm p = 0.756), Rx5day decreased by 20.95 mm decade⁻¹ (-47.72 to 2.95; q = 0.725), and maximum consecutive dry days increased by 1.33 days decade⁻¹ (-1.08 to 3.57; Holm p = 0.756). Wet-day count, wet-day intensity, heavy-rain thresholds and cumulative-rainfall timing likewise had intervals spanning zero. No precipitation change point survived within-family correction.

Seasonal totals also lacked a joint signal (global shared-block max-statistic p = 0.764): slopes were -36.9, +32.5, -16.5 and -0.7 mm decade⁻¹ for December-February, March-May, June-August and September-November. Two complete July-June panels retained negative slopes but intervals spanning zero. The start-labelled panel, July 1993-June 2023, had -79.4 mm decade⁻¹ (-222.4 to 70.0); the end-labelled panel, July 1992-June 2022, had -46.3 mm decade⁻¹ (-170.0 to 83.2). Their joint family p value was 0.335.

Wind declines without an ET_o trend

ERA5-Land 10 m wind speed averaged 3.431 m s⁻¹ and decreased by 0.137 m s⁻¹ decade⁻¹ (-0.204 to -0.071; p = 0.0030; q = 0.0090; max-statistic adjusted p = 0.0049), or 3.99% decade⁻¹. A permutation Pettitt test located a candidate shift after 2004, with the first post-shift year in 2005 (q = 0.032). This was a secondary reanalysis-based result and does not establish a physical cause. The six-variable atmospheric-demand family had global shared-block max-statistic p = 0.0032, driven by ERA5-Land temperature and wind.

Annual FAO-56 reference evapotranspiration (ET_o) averaged 1,440.9 mm and had a slope of -1.63 mm decade⁻¹ (-17.20 to 13.58; p = 0.7173; Holm p = 0.8771). Climatic water balance, defined as DGM-RFE precipitation minus ET_o, averaged +148.3 mm and changed by -55.4 mm decade⁻¹ (-204.4 to 95.2; q =

0.530). The absence of an ET_0 trend despite warming is consistent with compensation among Penman–Monteith terms, especially wind, but causal contributions were not partitioned (Fig. 4).

Primary inference, power and onset sensitivity

None of the five pre-specified endpoints crossed the Holm-adjusted 0.05 threshold (Fig. 5; Table 2). This outcome does not make the effects equivalent to zero. The 80% familywise minimum detectable slopes were 237.9 mm decade⁻¹ for annual precipitation, 0.188 °C decade⁻¹ for mean temperature, 25.77 mm decade⁻¹ for Rx1day, 4.03 days decade⁻¹ for consecutive dry days and 28.38 mm decade⁻¹ for ET_0 . The NASA temperature estimate was 75% of its 80% threshold, explaining why its interval excluded zero while the five-endpoint Holm test did not.

Rainy-season onset was examined under all 54 combinations of two search dates, three accumulation windows, three accumulation thresholds and three post-trigger dry-spell limits. Complete records were available for 29 or 30 seasons depending on the rule. Slopes ranged from earlier to later onset, but every Benjamini–Hochberg q value was at least 0.693 (Fig. 6). No rule was selected after its result was known, and the data did not support a basin-wide onset shift that persisted across the definition set.

Table 2. Central trend estimates for 1993–2022. Slopes are Theil–Sen estimates per decade. Intervals and p values are from circular moving-block resampling unless marked HR. Multiplicity values are Holm-adjusted for primary endpoints and Benjamini–Hochberg q values within secondary families. Family-adjusted p values use 10,000 joint shared-block max-statistic resamples. All tests were two-sided.

Metric (source)	Slope per decade (95% interval)	Unadjusted p	Multiplicity	Interpretation
Annual precipitation (DGM-RFE)	−38.3 mm (−180.1, 103.5)	0.4386	Holm 0.8771	Primary; not detected
Mean temperature (NASA POWER)	+0.140 °C (0.027, 0.246)	0.0177	Holm 0.0885	Primary; family threshold not crossed
Rx1day (DGM-RFE)	−9.05 mm (−24.12, 5.17)	0.1889	Holm 0.7555	Primary; not detected
Consecutive dry days (DGM-RFE)	+1.33 d (−1.08, 3.57)	0.2015	Holm 0.7555	Primary; not detected
Reference ET _o (ERA5-Land)	−1.63 mm (−17.20, 13.58)	0.7173	Holm 0.8771	Primary; not detected
Mean temperature (ERA5-Land)	+0.133 °C (0.067, 0.196)	0.0005	q 0.0030	Family adjusted p = 0.0032
10 m wind speed (ERA5-Land)	−0.137 m s ^{−1} (−0.204, −0.071)	0.0030	q 0.0090	Family adjusted p = 0.0049
Annual precipitation (CHIRPS3)	+33.8 mm (HR trend test)	HR 0.7212	Diagnostic	Opposite sign; not detected
Hot-and-dry days	+6.32 d (1.51, 11.69)	0.0195	q 0.0845	Secondary direction
Climatic water balance	−55.4 mm (−204.4, 95.2)	0.3533	q 0.5300	Not detected

Discussion

Consistent warming contrasts with uncertain rainfall change

The central result is a separation between thermal and pluviometric evidence at the Mandena-basin scale. Two temperature products yielded nearly identical warming slopes, substantial interannual association and no drift in their difference. In contrast, two precipitation products agreed on much of the year-to-year variation but differed by 40% in mean annual amount and produced opposite trend directions. Within DGM-RFE, no joint signal emerged across totals, extremes, seasons, hydrological boundaries or 54 onset definitions. Observed change was therefore expressed more consistently through temperature and ERA5-Land wind than through rainfall reorganization.

Separate reanalysis-based temperature products converge on warming

The temperature result fits broader evidence from Madagascar and East Africa. National station records show that warming indices are more spatially coherent than precipitation indices, although those records often show stronger change in minimum temperature than observed here [1]. East African gridded analyses likewise report widespread warming with less uniform rainfall trends [2]. For the Mandena assessment, the NASA POWER/MERRA-2 and basin-weighted ERA5-Land series yielded nearly identical rates of approximately $0.14^{\circ}\text{C decade}^{-1}$, or about 0.4°C across the study endpoints. The NASA endpoint did not pass Holm correction across the five primary endpoints, whereas the 13-metric annual-temperature family passed its global shared-block max-statistic test ($p = 0.0354$); these are distinct inference levels. Agreement in slope, the non-trending product difference and block-length sensitivity form a consistent evidence chain without treating either reanalysis-based product as independent field validation.

Local rainfall non-detection remains compatible with regional drought evidence

The rainfall result does not contradict reports of drought or delayed onset across southern Madagascar [3–6, 30]. The studies answer different questions. Regional work averages large parts of Anosy, Androy and Atsimo-Andrefana, often begins in the early 1980s, and examines September–November moisture or vegetation alongside rainfall [5]. This assessment used one 85.84 km^2 coastal basin, a 1993–2022 inferential window and definitions constrained by exact alignment with a companion environmental study. A regional shift can coexist with non-detection in one basin when local variability is high, periods differ and products have different station integration and spatial support.

Rainfall correlation masks substantial disagreement in magnitude and trend

Product disagreement is itself informative. DGM-RFE and CHIRPS3 annual rainfall had $r = 0.789$, yet CHIRPS3 exceeded DGM-RFE by 630 mm yr^{-1} and concordance was 0.304. A correlation alone would have hidden this discrepancy. Evaluation over Madagascar has shown that gridded precipitation performance varies by region, season, elevation and metric [29]. Neither product can be treated as field truth for Mandena because no dense independent basin network was available. The conclusion concerns what the archived products resolve, not the absence of any physical rainfall change.

Declining wind may offset warming-driven evaporative demand

The secondary wind result merits attention because its magnitude was large and detected within the atmospheric-demand family (global $p = 0.0032$). The ERA5-Land decline of $0.137\text{ m s}^{-1}\text{ decade}^{-1}$ was close to the mean decline synthesized across many terrestrial studies, although global evidence shows regional heterogeneity and later reversals [31]. Wind is a direct aerodynamic term in FAO-56 ET_0 , so declining wind can offset part of the temperature effect. Similar compensation underlies the observation that evaporative demand need not rise in step with temperature [32]. At Mandena, ET_0 showed no trend

while temperature rose and wind fell. This interpretation remains reanalysis-based because no local anemometer series verifies the shift after 2004.

Detection limits constrain the interpretation of non-significant trends

The power analysis bounds the non-detections. With 30 annual values and familywise control, annual rainfall needed a slope near $238 \text{ mm decade}^{-1}$ for 80% detection probability, Rx1day about $25.8 \text{ mm decade}^{-1}$, dry spells about $4.0 \text{ days decade}^{-1}$ and ET_0 about $28.4 \text{ mm decade}^{-1}$. The intervals exclude changes beyond their reported bounds but do not exclude smaller shifts. Reporting these limits prevents a non-detected test from being translated into a claim of climatic constancy.

Data and inference limitations

Several limitations define the scope. DGM-RFE lacks a peer-reviewed product-method paper permitting a full audit of station blending and corrections. CHIRPS3 is a comparison, not an independent field validation. NASA POWER and ERA5-Land are reanalysis-based and differ in spatial support. The NASA source is a deposited SWAT+-formatted derivative containing Tmin and Tmax rather than a native API response, so analytical reproducibility begins from that derived file. Temperature percentile indices are study-relative adaptations: they use 1993–2022 as the reference period and a circular 11-day calendar window rather than the standard ETCCDI 5-day window. They should therefore not be interpreted as strict ETCCDI implementations or compared directly with indices based on standard climatological normals [16]. SPI tails are estimated from 30 values per calendar month and remain descriptive [33]. Pettitt shifts are exploratory and do not identify causes.

A spatiotemporally matched climate record for mine–climate attribution

The exact spatial and temporal contract enables subsequent attribution. The climate archive contains one calendar-year row for each year of the companion BACI study, including separate rank-normalized heat and dryness scores and a joint exposure score. No mine indicator, hydrological-model output or Landsat surface response enters that exposure. A later mine-by-climate model can join the records one-to-one by year without redefining the basin or mixing July–June seasons with calendar-year mining effects. The present study characterizes atmospheric exposure only; it does not attribute change to mining, project future climate or test a mine–climate interaction.

Conclusion

From 1993 to 2022, Mandena showed a convergent warming rate of about $0.13\text{--}0.14 \text{ }^{\circ}\text{C decade}^{-1}$ across NASA POWER and ERA5-Land and a secondary ERA5-Land wind decline, but no resolved reorganization of annual rainfall, extremes, seasons, hydrological-year totals or rainy-season onset. The

rainfall conclusion is bounded by product bias and the detectable effect sizes of a 30-year record; it is not evidence that smaller hydrologically relevant changes were absent. This scale-specific result indicates that thermal and circulation-related exposure changed more consistently than precipitation. Its unmodified geometry and calendar alignment provide the climate input for a later mine-by-climate interaction assessment.

Declarations

Data availability

The exact basin geometry and companion annual mining assessment are openly available at <https://doi.org/10.5281/zenodo.21633869> [9]. The complete hydroclimate compendium accompanying this article, including all source subsets used for analysis, spatial weights, derived daily and annual tables, the 30-row interaction bridge, statistical outputs, figures in SVG, 600-dpi PNG and vector PDF, tests, provenance records and SHA-256 authentication, is archived on Zenodo at <https://doi.org/10.5281/zenodo.22113639>. Public provider records are listed in Table 1 and the references [10–15,29].

Code availability

All analysis code required to regenerate the reported tables and figures from deposited source subsets is included in the hydroclimate compendium. Root commands support common operating systems. The QGIS processing source used for DGM-RFE extraction is archived under provenance. The upstream-acquisition boundary is stated in Analytical reproducibility.

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Author contributions

Z.R.R. conceived the study, curated the data, developed the methodology and software, performed the analysis, prepared the figures, interpreted the results and wrote the manuscript.

Competing interests

The author declares no competing interests.

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Figures

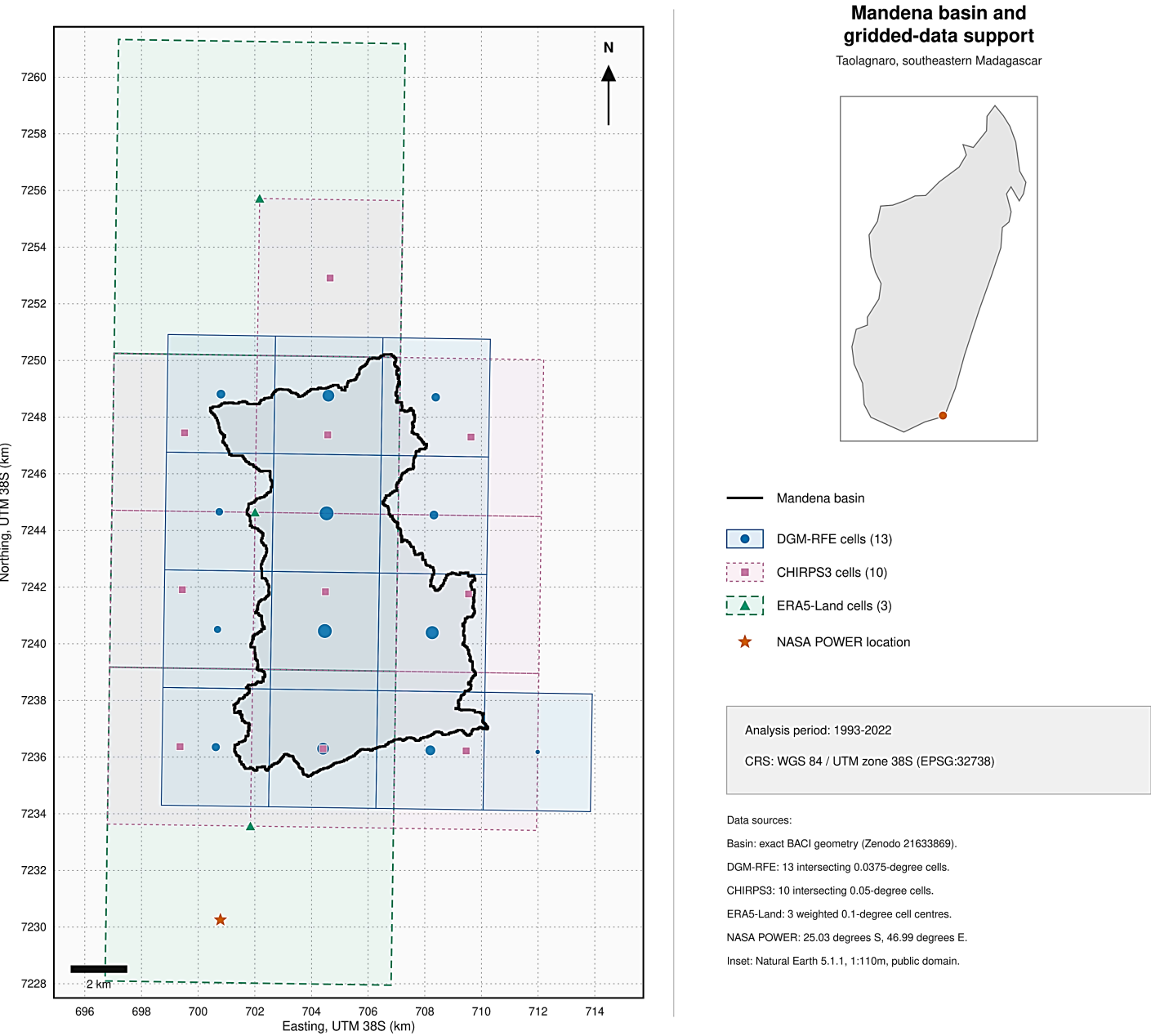


Figure 1

Spatial support of the hydroclimate assessment. The outline is the unmodified basin boundary. Intersecting CHIRPS3 and ERA5-Land support cells and the NASA POWER request location are shown; DGM-RFE used 13 intersecting 0.0375° cells. The geometry source is the companion archive [9]. Product

sources are listed in Table 1 [10–15,29]. Generated by the author from archived inputs using CPython 3.12.13.

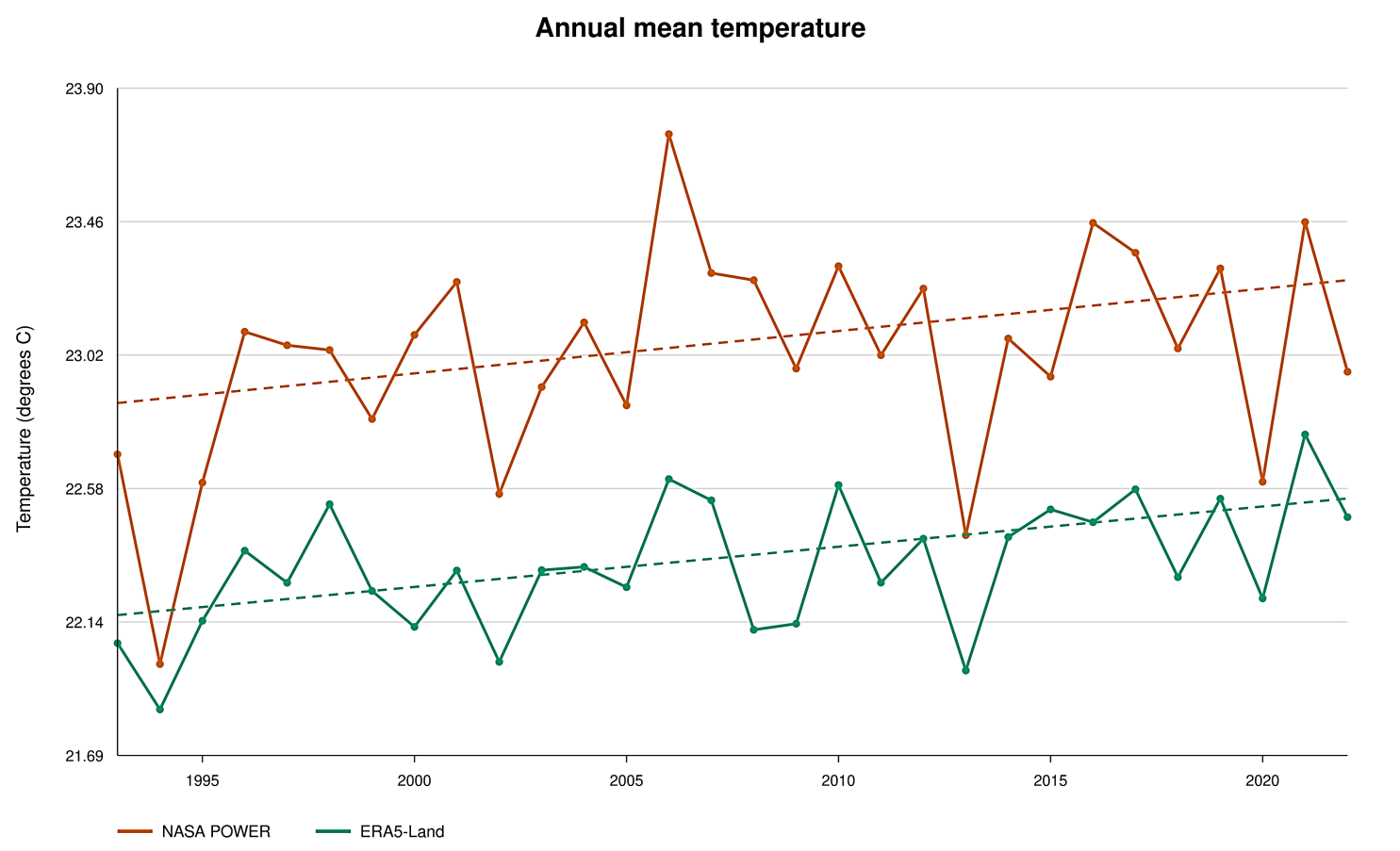


Figure 2

Annual mean temperature from NASA POWER and ERA5-Land, 1993–2022. Lines show annual values and separate Theil–Sen trends. NASA POWER increased by 0.140 °C decade⁻¹ and ERA5-Land by 0.133 °C decade⁻¹; the product difference had no detected trend [13–15]. Generated by the author with CPython 3.12.13.

Annual precipitation products

Comparison product is not treated as station truth

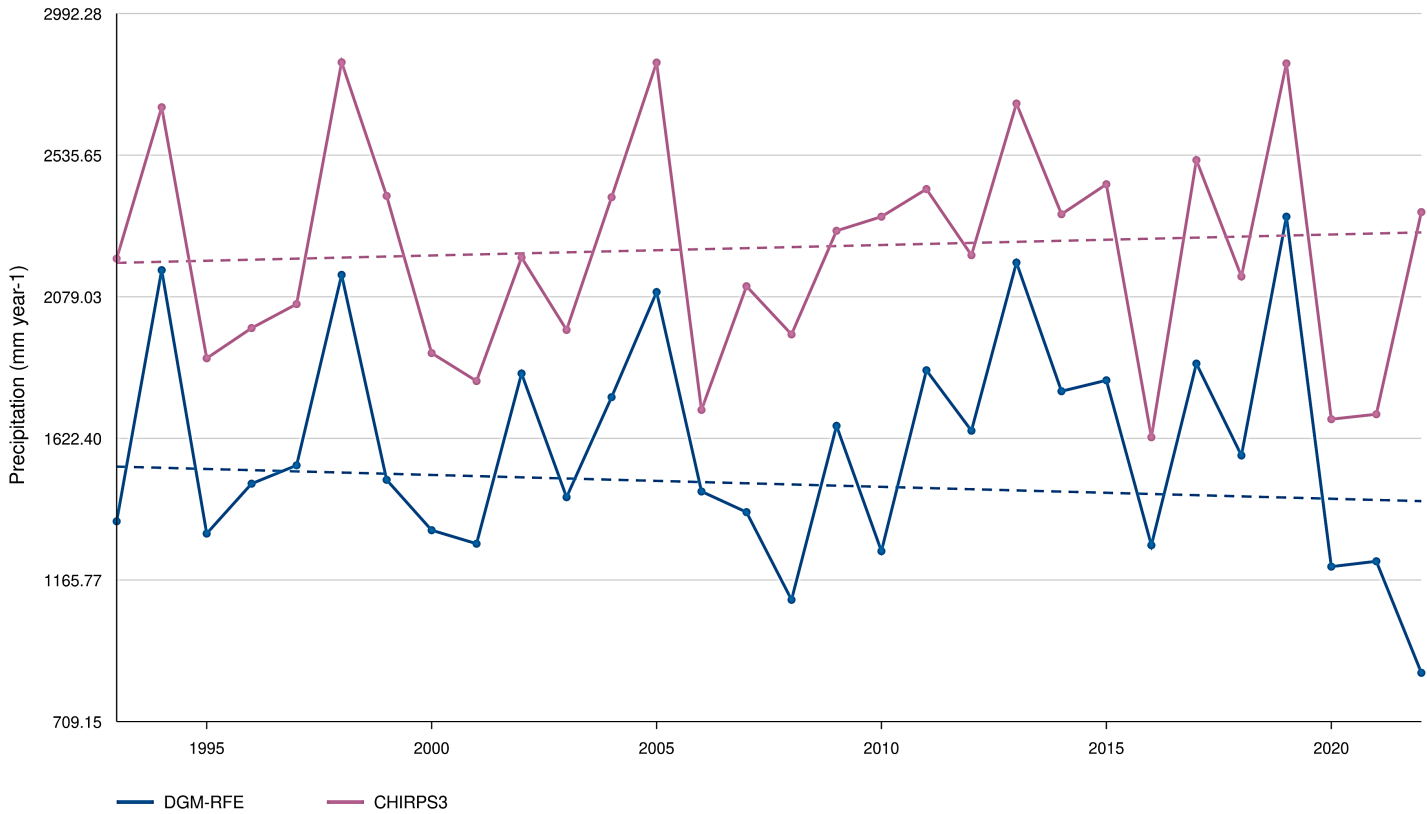


Figure 3

Annual precipitation from DGM-RFE and CHIRPS3, 1993–2022. Product-specific Theil–Sen lines are shown. DGM-RFE decreased by $38.3 \text{ mm decade}^{-1}$ and CHIRPS3 increased by $33.8 \text{ mm decade}^{-1}$; neither trend was detected. CHIRPS3 is a comparison product rather than field truth [10,11,29]. Generated by the author with CPython 3.12.13.

Evaporative demand and climatic water balance

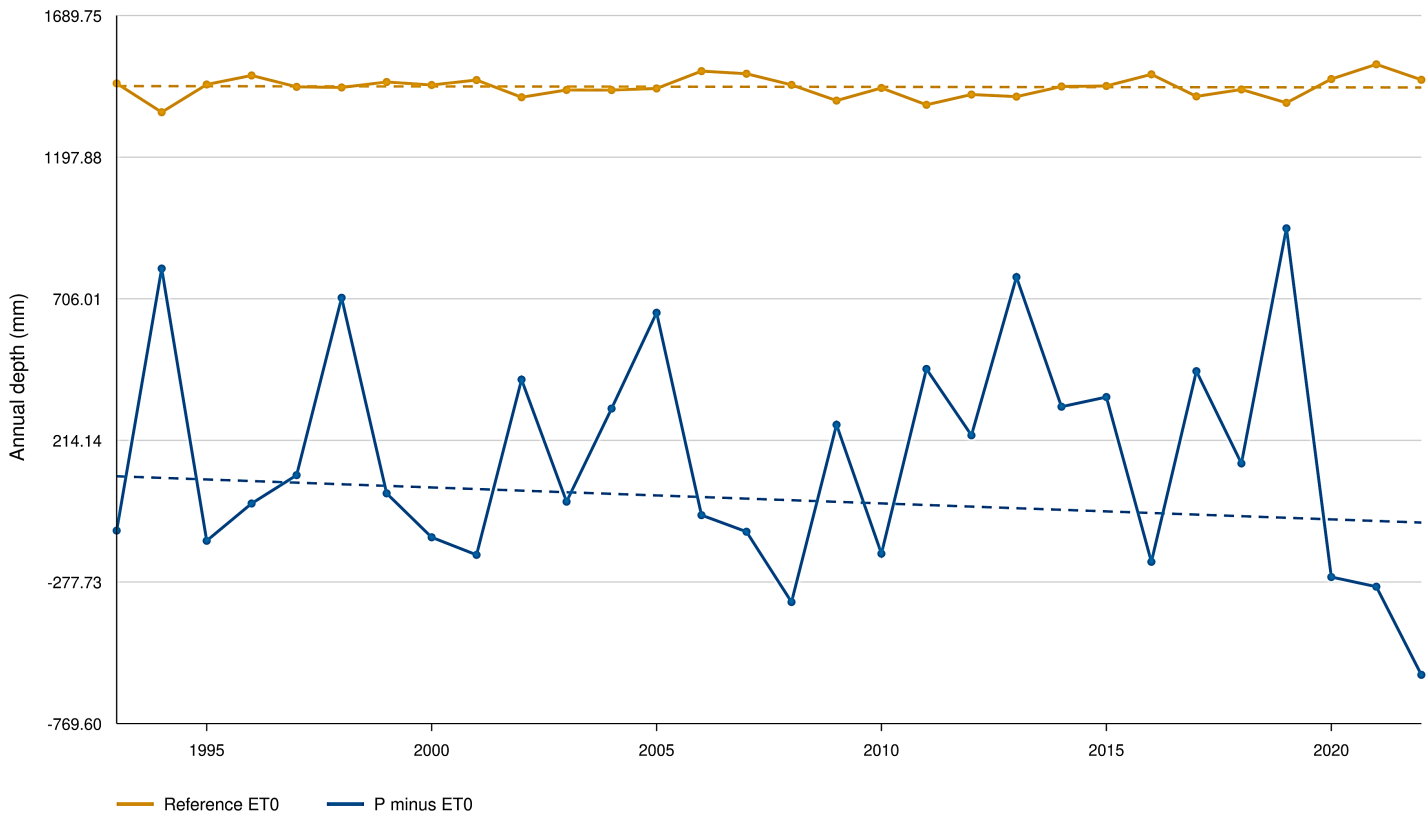


Figure 4

Annual FAO-56 reference evapotranspiration and climatic water balance, 1993–2022. Climatic water balance is DGM-RFE precipitation minus ERA5-Land-based ET_0 . Neither slope was detected. ET_0 represents atmospheric demand, not actual evapotranspiration [13,15,20]. Generated by the author with CPython 3.12.13.

Primary trend estimates and block-bootstrap intervals

Slopes per decade divided by each series' interannual standard deviation

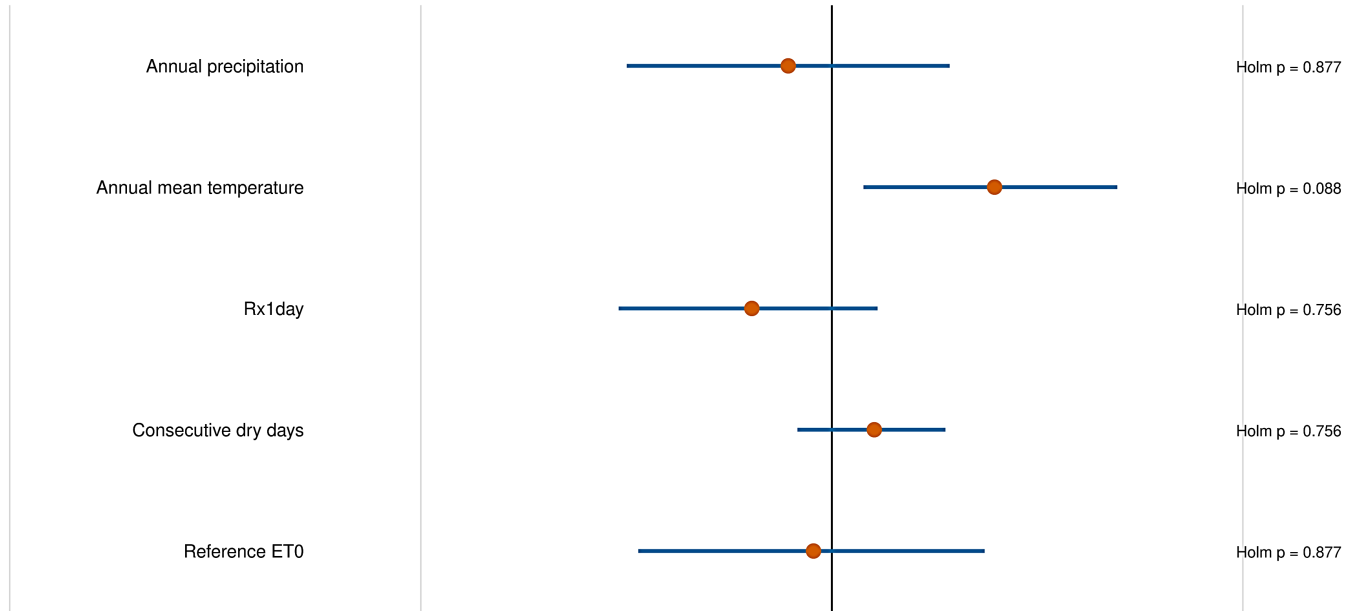


Figure 5

Standardized Theil–Sen slopes for the five pre-specified endpoints. Points are slopes per decade in annual-series standard-deviation units; bars are 95% trend-preserving circular-block bootstrap intervals. None crossed the five-endpoint Holm threshold. Raw units and exact p values appear in Table 2. Generated by the author with CPython 3.12.13.

Rainy-season onset across 54 fixed definitions

Median and interquartile range; hydrological years start on 1 July

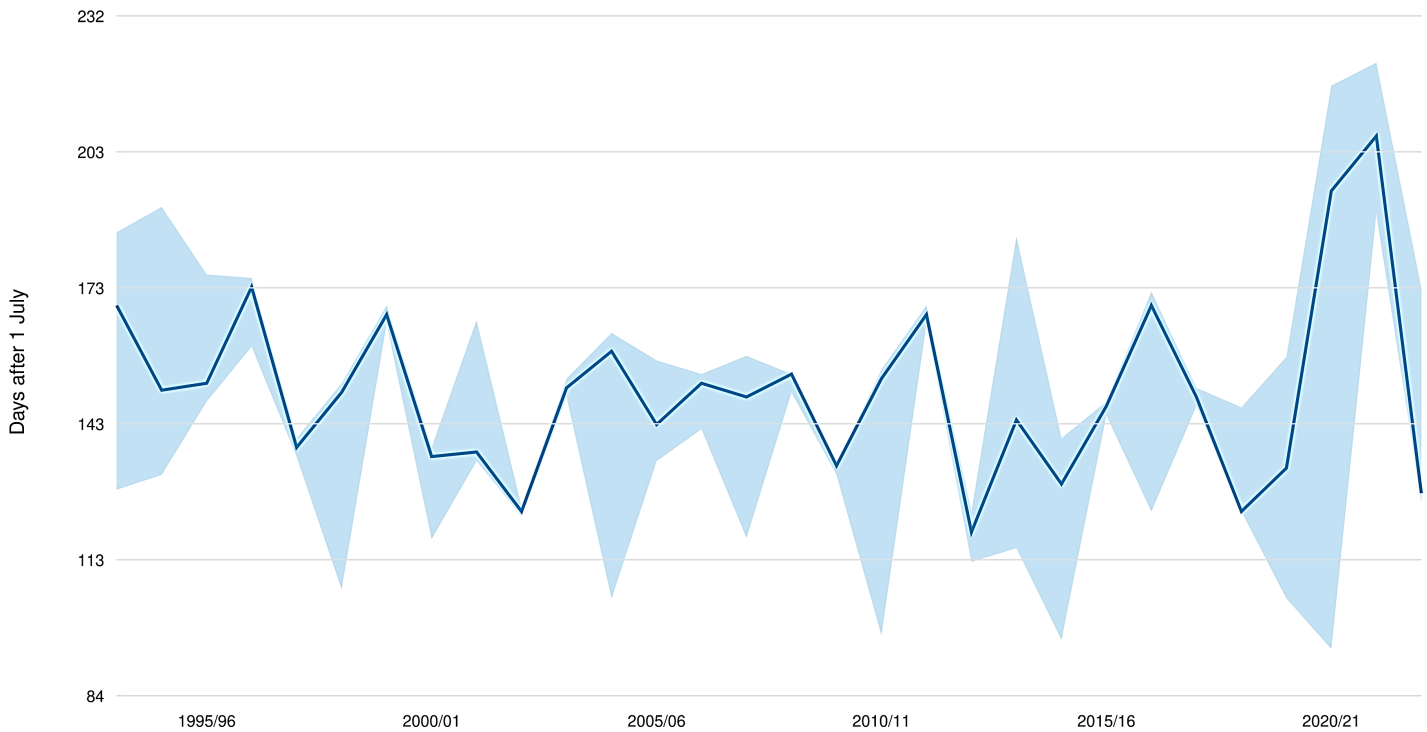


Figure 6

Rainy-season onset under 54 definitions fixed before execution. The line is the annual median and shading the interquartile range. Rules combined search starts of 1 October or 1 November; 3-, 5- or 7-day windows; 20, 30 or 40 mm thresholds; and maximum 7-, 10- or 15-day dry spells during the following 30 days. Every definition-specific q value was at least 0.693. Generated by the author with CPython 3.12.13.