



A 204-year tree-ring reconstruction of dry-season precipitation for the Lugu Lake basin, southeastern Tibetan Plateau

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Abstract

Southeastern Tibetan Plateau instrumental records are too short to characterise multidecadal dry-season variability. We reconstruct previous-October to current-May (pOct–cMay) precipitation for the Lugu Lake basin from two *Picea likiangensis* residual chronologies (204-year mainline 1817–2020, plus a descriptive extension to 1647); a nested principal-component transfer function explains 44.4% of Ninglang variance (1960–2020), with positive RE and CE in both split-period verifications. Over 1817–2020 (29 $|z| \geq 1.5$ extremes; 13 wet, 16 dry), extremes show no monotonic trend (logistic $P = 0.63$), the recent 30-yr window is not exceptional ($P > 0.73$), and only the most extreme tail tends upward ($P = 0.042$ for $|z| \geq 2$). The dominant signal is decadal variability: the wettest (2000s, 197.7 mm) and driest (2010s, 128.2 mm) decades occur consecutively, and a 46-yr drought (1764–1809) in the single-tree segment exceeds red-noise expectations but lacks corroboration. Without local gauges, hydrological consistency rests on CNRD v1.0 natural runoff ($r = 0.46$) and soil-moisture and scPDSI fields ($r = 0.33$ – 0.41). Wet extremes coincide with La Niña-like cooling and stronger 700-hPa moisture convergence; dry extremes with the opposite configuration, an El Niño–dry teleconnection opposite in sign to Northeast Asia. Four CMIP6 models project wetter dry seasons with amplified wet tails.

Keywords: Tree rings; Dry-season precipitation reconstruction; Hydroclimatic extremes; Non-stationarity; Moisture transport; ENSO teleconnection; southeastern Tibetan Plateau

1. Introduction

The Lugu Lake region of NW Yunnan is a water-limited margin where lake levels, streamflow, forest productivity and livelihoods depend on seasonal precipitation (Piao et al., 2010; Liang et al., 2025), and where the Indian and East Asian summer monsoons meet the mid-latitude westerlies (He et al., 2025;



33 Wu et al., 2026). The dry season supplies only ~17% of annual rainfall at Ninglang station, yet it
 34 governs pre-monsoon recharge, lake storage and early xylem formation, and recent droughts and
 35 pluvials have exposed the vulnerability of regional water and forest systems (Keyimu et al., 2021).
 36 Instrumental records are too short to establish whether recent anomalies are unusual.

37 Tree rings extend hydroclimatic information beyond the instrumental period, moisture-sensitive
 38 chronologies preserving precipitation, drought and runoff signals over centuries (Fritts, 1976; Cook et
 39 al., 2010; Yang et al., 2014; Ljungqvist et al., 2020; Morales et al., 2020; Chen et al., 2023). In SW
 40 China and on the southeastern Plateau, however, most reconstructions emphasise the summer monsoon
 41 or local site signals (Liang et al., 2025; Wu et al., 2026). Three gaps remain: long dry-season
 42 reconstructions are scarce; they are rarely tested against independent regional hydroclimate, which is
 43 needed to show that ring records capture hydrologically meaningful variability rather than local growth
 44 responses (Chen et al., 2026); and the persistence and circulation context of their extremes are poorly
 45 known.

46 We therefore establish a tree-ring pOct–cMay precipitation reconstruction for the Lugu Lake basin,
 47 following the integrated tree-growth–precipitation–hydroclimate–circulation framework applied in
 48 Northeast Asia (Hou et al., 2026), using two co-located *Picea likiangensis* sites 4.4 km apart and
 49 Ninglang station (2367 m), with ENSO and PDO/AMO variability supplying large-scale context. We
 50 ask how dry-season precipitation has varied, whether it is coherent with independent hydroclimate
 51 fields, how persistent wet and dry regimes are, what controls them, and how the record compares with
 52 CMIP6 projections.

53 2. Materials and methods

54 2.1 Tree-ring sampling and chronology development

55 Sampling targeted two *Picea likiangensis* sites south of Lugu Lake, NW Yunnan (SFSC; DYF; ~4.4 km
 56 apart; Table 1, Fig. 1), where at least 20 mature, undisturbed trees per site were cored, yielding 48
 57 (SFSC) and 42 (DYF) series (Fritts, 1976; Cook and Kairiukstis, 1990; Speer, 2010).

58 **Table 1. Information of the two tree-ring sampling sites and the Ninglang meteorological station.**

Code	Site / station	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Species	Series	Period
SFSC	Shifoshancun, Hongqiao, Ninglang	27.5503	100.7213	3192	<i>Picea likiangensis</i>	48	1647–2020
DYF	Dayanfang, Hongqiao, Ninglang	27.5461	100.6770	3218	<i>Picea likiangensis</i>	42	1817–2020
56567	Ninglang	27.2500	100.8500	2367	—	—	1960–2020



	meteorological station						(calibration)
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Note: SFSC = Shifoshancun; DYF = Dayanfeng. The two sites are ~4.4 km apart. Series are measured ring-width series after cross-dating. The Ninglang station provides the pOct–cMay precipitation target; the continuous gap-free segment 1960–2020 (n = 61) is used for calibration.

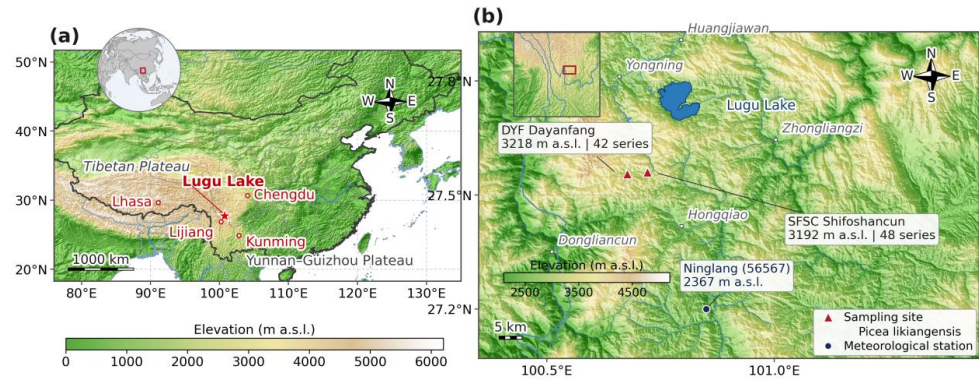


Figure 1. Study area and tree-ring sampling network. (a) Topographic overview of China (hypsometric tints with shaded relief) with the study area marked by a red rectangle and the Lugu Lake site by a red star; the globe inset locates the region within Asia, and the colour bar gives elevation in metres above sea level. (b) Detailed map of the Lugu Lake sampling area, showing the two *Picea likiangensis* (Lijiang spruce) sampling sites (red triangles; SFSC = Shifoshancun, 3192 m a.s.l., 27.550°N, 100.721°E; DYF = Dayanfeng, 3218 m a.s.l., 27.546°N, 100.677°E; 48 and 42 measured series, respectively, 4.4 km apart), the Ninglang meteorological station (56567; navy circle; 2367 m a.s.l., 27.250°N, 100.850°E), Lugu Lake, and the surrounding rivers and settlements; the inset shows the regional setting, including the Jinsha (upper Yangtze), Yalong, Lancang (Mekong) and Nu (Salween) rivers. Base map: shaded-relief terrain derived from the AWS Terrain Tiles (Terrarium) digital elevation model; province boundaries from the DataV.GeoAtlas national platform; national boundaries, rivers and lakes from Natural Earth; Lugu Lake shoreline, settlements and streams from OpenStreetMap (data © OpenStreetMap contributors). Maps are drawn in geographic coordinates (WGS 84).

Ring widths were measured at 0.01-mm resolution and cross-dating verified with COFECHA (Holmes, 1983) and standardised in ARSTAN (Cook, 1985) to residual (RES) chronologies. Running 50-yr EPS and rbar (Wigley et al., 1984) gave truncation boundaries of 1647 (SFSC) and 1817 (DYF) at the EPS > 0.85 criterion (Fig. 2); the pre-1817 segment (one tree to 1659) is descriptive only. PC1 captures 76.9% of the variance of the two chronologies.

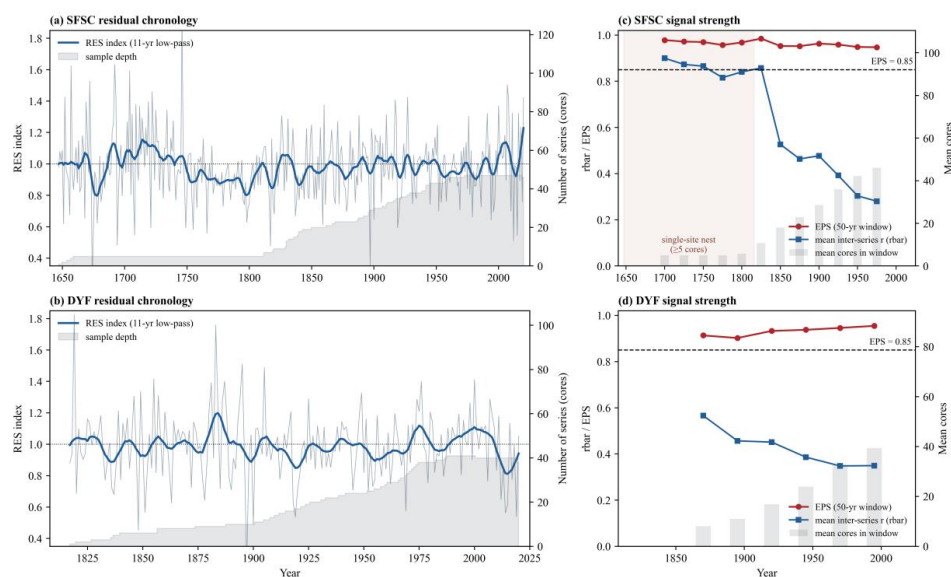


Figure 2. Chronology quality. (a,b) SFSC and DYF residual chronologies with 11-yr Gaussian low-pass (red) and sample depth (bars, right axis). (c,d) Running 50-yr EPS and $\bar{r}$ (25-yr step); dashed line is $EPS = 0.85$. All windows exceed the threshold (SFSC 0.947–0.985; DYF 0.902–0.955), but pre-1800 SFSC values rest on five cores from a single tree (see text).

2.2 Climate data and precipitation reconstruction

Monthly precipitation and temperature from Ninglang station (56567; 2367 m) were the instrumental target, and a start- and end-month correlation search over 171 candidate windows (Zang and Biondi, 2015) identified previous-October to current-May (pOct–cMay) totals as the optimal target.

Because the two chronologies differ in length, a nested regression design was used; for the primary two-site nest (1817–2020),

$$\hat{P}_t = 46.70 \times PC1_t + 157.35 \text{ (mm)}$$

where $\hat{P}_t$ is reconstructed pOct–cMay precipitation in year t and $PC1_t$ the residual index. The SFSC-only nest (1647–1816) was spliced to the $PC1$ series, but all trend statements are restricted to 1817–2020.

Calibration used 1960–2020 ($n = 61$), with correlation, explained variance, Durbin–Watson, reduction of error (RE) and coefficient of efficiency (CE) assessed in split-period tests (1960–1990 vs. 1991–2020 and the reverse; Fritts, 1976); grid-point correlations tested spatial coherence.

2.3 Regional hydroclimatic comparison

The University of Delaware dataset v5.01 (UDel; 0.5°, 1901–2017; Willmott and Matsuura, 2001) supported spatial-correlation and wet-minus-dry composites over 1901–2017 ($n = 117$), with a Walker field-significance test (Wilks, 2006). The Monsoon Asia Drought Atlas (MADA; Cook et al., 2010), a



101 summer scPDSI network, served as a consistency reference over 1647–2005 ($n = 359$) and each nest.
 102 All P values use effective degrees of freedom (Bretherton et al., 1999).

103 **2.4 Extreme-event identification and duration–severity analysis**

104 Extremes and trends are reported for 1817–2020, z-scores being standardised against the two-site mean.
 105 Pluvial and drought years were anomalies $\geq +1.5$ SD and ≤ -1.5 SD (Touchan et al., 2005; Wilks,
 106 2011). Persistent regimes (≥ 10 consecutive years above or below the mean of an 11-yr LOWESS;
 107 Cleveland, 1979; Liang et al., 2025) were retained only if mean $|z| \geq 0.3$ and tested against 2,000
 108 random-phase spectral surrogates; duration and severity were combined in a copula analysis (Shiau,
 109 2006).

110 Trends in rare, serially dependent extremes were tested with an annual logistic regression of $I(|z| \geq 1.5)$
 111 on year (likelihood-ratio and Wald tests; moving-block bootstrap), and 20- and 30-yr blocks anchored at
 112 1817 provided independent count units, the overlapping 1991–2020 window being assessed across all
 113 partition offsets.

114 **2.5 Ocean–atmosphere composites and moisture-flux diagnostics**

115 Composites used NOAA ERSSTv5 SST (2° ; Huang et al., 2017) and Z500, humidity and winds from
 116 20CRv3 (1837–2015; Slivinski et al., 2021). Because the region lies at ~ 3200 m, moisture transport was
 117 diagnosed at 700 hPa, and moisture flux convergence was computed from linearised flux anomalies
 118 (Trenberth and Guillemot, 1995; Banacos and Schultz, 2005).

119 The ten wettest and ten driest dry seasons within 1837–2015 (Table S6) were composited after linear
 120 detrending, with t-tests and a post-1900 sensitivity test; Niño3.4, PDO, AMO and IOD indices were
 121 correlated as supplementary diagnostics.

122 **2.6 Spectral analysis and wavelet coherence**

123 Periodicity was assessed with a Welch periodogram and a Morlet wavelet spectrum (Torrence and
 124 Compo, 1998). Squared wavelet coherence with Niño3.4 (1855–2020) followed Grinsted et al. (2004).

125 **2.7 CMIP6 historical and SSP5-8.5 projections**

126 Four CMIP6 models (BCC-CSM2-MR, CanESM5, MIROC6, IPSL-CM6A-LR; r1i1p1f1) were
 127 analysed for the historical and SSP5-8.5 experiments (Eyring et al., 2016; O'Neill et al., 2016). Monthly
 128 precipitation from ESGF gave pOct–cMay totals over the Lugu Lake box ($25\text{--}30^\circ\text{N}$, $99\text{--}104^\circ\text{E}$);
 129 because the coarse grid overestimates the rain-shadow site total, only relative changes are interpreted.
 130 Changes are reported for 2041–2060 and 2081–2100 relative to 1995–2014, with the frequency of years
 131 beyond the baseline 10th and 90th percentiles (10% under stationarity).



132 **2.8 Hydrological consistency with independent land-water-balance records**

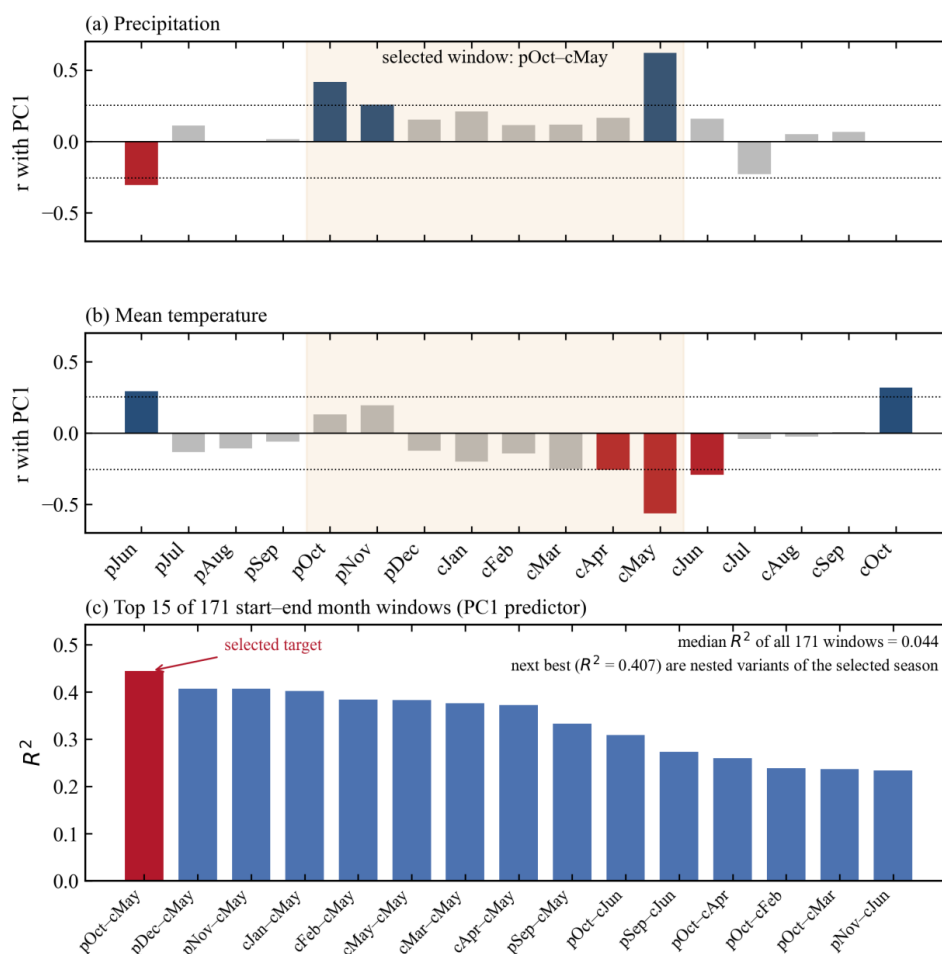
133 With no local gauges, coherence with independent land-surface moisture states and runoff was tested as
 134 a consistency check rather than discharge validation. The runoff comparison parallels Hou et al. (2026):
 135 the China Natural Runoff Dataset v1.0 (CNRD; 0.25°; Gou et al., 2021; Miao et al., 2022) begins in
 136 January 1961, so 57 complete pOct–cMay water years (1962–2018) were analysed. Three further
 137 products were used: CPC global monthly soil moisture (0.5°, from 1948; Fan and van den Dool, 2004),
 138 NCEP/NCAR Reanalysis 1 soil moisture (0–10 and 10–200 cm; Kalnay et al., 1996) and NOAA/PSL
 139 scPDSI (2.5°, 1892–2014; Wells et al., 2004). Correlation and field-significance statistics follow
 140 Section 2.6.

141 Two published reconstructions provide independent multi-century context: the 1600–2005 non-
 142 growing-season southeastern Plateau series (Keyimu et al., 2021) and the 1814–2022 central-Yunnan
 143 winter–spring series (Liang et al., 2025). Pre-calibration and instrumental sub-periods were compared,
 144 and the 1764–1809 drought was quantified against the pre-1900 distribution of the former. Because
 145 these are model-derived analyses rather than gauged discharge, agreement establishes consistency, not
 146 validation.

147 **3. Results**

148 **3.1 Climate–growth relationships and the precipitation reconstruction**

149 Growth is most strongly associated with accumulated precipitation from previous October to current
 150 May ($r = 0.667$, $P < 0.01$), while temperature correlations are weak (Fig. 3); the dry season contributes
 151 17.5% of annual precipitation at Ninglang (910 mm). Across the 171 candidate windows the median R^2
 152 is only 0.044 and pOct–cMay ranks first ($R^2 = 0.444$).



153
 154 *Figure 3. Climate-growth relationships. (a,b) Monthly Pearson correlations between the regional chronology and*
 155 *Ninglang precipitation and temperature from previous June through current October; dotted lines mark the two-sided 5%*
 156 *significance threshold and the shaded window (pOct–cMay) identifies the selected dry-season target. (c) Ranking of the*
 157 *15 strongest start–end month combinations for the PC1 predictor among all 171 candidate windows, with the selected*
 158 *target (pOct–cMay, red) and the median R^2 over all windows (0.044); the next-best windows are nested variants of the*
 159 *same dry season.*

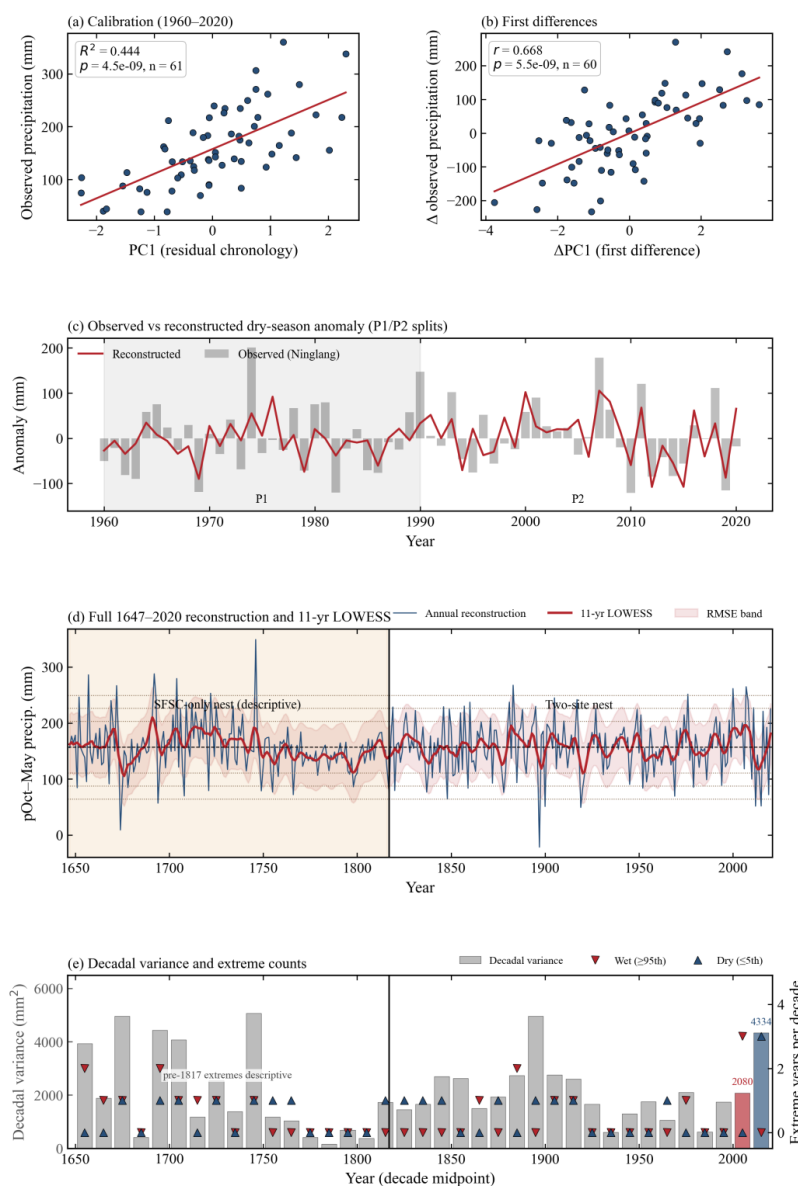
160 The calibrated reconstruction is robust (Fig. 4; Table 2), explaining 44.4% of instrumental variance over
 161 1960–2020 ($r = 0.667$; RMSE = 53.8 mm) with no significant residual autocorrelation (DW = 2.21).
 162 Split-period verification is positive in both directions (RE = 0.337–0.375, CE = 0.339–0.377), and first-
 163 differenced correlations, which cannot be inflated by shared trends, are 0.668–0.707. The two-site mean
 164 (1817–2020) is 157.3 ± 46.7 mm; the wettest reconstructed year is 1746 (349.0 mm) and the driest 1674
 165 (9.0 mm).



166 **Table 2. Calibration and verification statistics of the PC1-based pOct–cMay precipitation transfer function.**

Test	Calibration	Verification	r_cal	R ² _cal	r_ver	R ² _ver	RE	CE
P1	1960–1990	1991–2020	0.657	0.432	0.709	0.503	0.337	0.339
P2	1991–2020	1960–1990	0.709	0.503	0.657	0.432	0.375	0.377

167 *Note: Full calibration (1960–2020, n = 61): r = 0.667, R² = 0.444, adjusted P < 10^{−4}, Durbin–Watson DW = 2.21, RMSE = 53.8 mm; transfer*
 168 *function $\hat{P} = 46.70 \cdot PC1_RES + 157.35$. RE = reduction of error; CE = coefficient of efficiency. The first-differenced reconstruction–*
 169 *observation correlation over the full instrumental overlap (1961–2020) is r = 0.707 (R² = 0.50), a single full-period high-frequency skill*
 170 *statistic. Positive RE and CE in both split directions indicate stable reconstruction skill.*



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Figure 4. Calibration and reconstruction. (a) Calibration scatter of PC1 against observed pOct–cMay precipitation (1960–2020, $R^2 = 0.444$). (b) First-difference scatter ($\Delta PC1$ versus Δ observed precipitation), which removes any trend shared by the two series and therefore isolates year-to-year agreement ($r = 0.668$, $n = 60$). (c) Observed (bars) versus reconstructed (line) anomalies over the instrumental period, with split periods P1/P2. (d) Full 1647–2020 reconstruction with 11-yr LOWESS, RMSE band, $\pm 1/\pm 1.5/\pm 2$ SD thresholds (1817–2020 basis), and shading for the SFSC-only nest. (e) Decadal variance (bars; red 2000s, blue 2010s) with counts of wet (∇) and dry (Δ) extremes per decade (right axis); the 2010s are the highest-variance decade of the two-site period (4330 mm^2).



179 3.2 Regional hydroclimatic coherence

180 UDel gridded dry-season precipitation correlates positively with the reconstruction over a broad region
 181 centred on the site (1901–2017, $n = 117$; Fig. S3), with a maximum grid-point correlation of $r = 0.499$
 182 and a box median of 0.228, and the field passes a Walker field-significance test with effective-degrees-
 183 of-freedom P values essentially unchanged.

184 MADA supports regional coherence (Fig. S7): $r = 0.346$ over the full overlap (1647–2005, $n = 359$; $P =$
 185 1.5×10^{-11}), strengthening to 0.390 for 1817–2005, with 91% sign agreement among 34 co-extreme
 186 years and seven common ≥ 31 -yr regimes; MADA is itself tree-ring based, so this is a consistency
 187 reference rather than independent validation.

188 3.3 Persistent regimes and extreme-event statistics

189 The full series contains 54 extreme years, of which 29 fall within 1817–2020 (13 wet, 16 dry).
 190 Anomalies are organised into persistent regimes (Fig. 5; Table 3): the 11-yr LOWESS yields 14 runs of
 191 ≥ 10 years, 10 of them amplitude-qualified. The count is unremarkable against a persistence-matched
 192 null ($P = 0.08$), but the amplitude-qualified count is elevated ($P = 0.01$) and the 46-yr drought of 1764–
 193 1809 exceeds the surrogate maximum duration ($P < 0.001$).

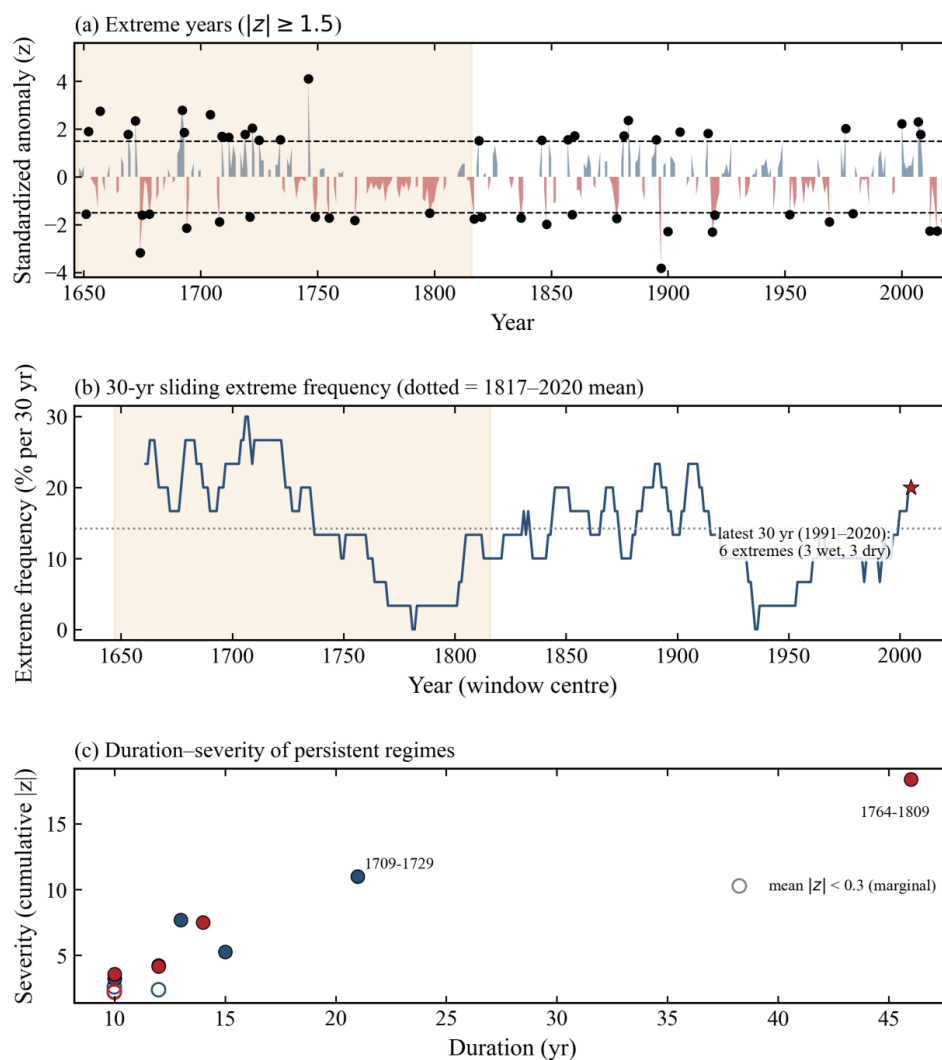
194 **Table 3. Persistent wet and dry regimes identified from the 11-yr LOWESS reconstruction (≥ 10 consecutive**
 195 **years above/below the 1817–2020 mean).**

No.	Type	Start	End	Duration (yr)	Severity ($\Sigma z $)	Mean z	Mean pOct–cMay precip. (mm)
1	Dry	1673	1686	14	7.50	-0.54	132.3
2	Wet	1698	1707	10	3.29	+0.33	172.7
3	Wet	1709	1729	21	10.99	+0.52	181.8
4†	Wet	1731	1740	10	2.60	+0.26	169.5
5	Dry	1749	1760	12	4.23	-0.35	140.9
6	Dry	1764	1809	46	18.35	-0.40	138.7
7†	Dry	1814	1823	10	2.19	-0.22	147.1
8	Wet	1824	1833	10	3.22	+0.32	172.4
9	Dry	1834	1843	10	3.57	-0.36	140.7
10	Wet	1880	1894	15	5.27	+0.35	173.8
11†	Wet	1901	1912	12	2.38	+0.20	166.6
12	Dry	1952	1963	12	4.17	-0.35	141.1
13†	Dry	1978	1987	10	2.26	-0.23	146.8
14	Wet	1998	2010	13	7.68	+0.59	184.9

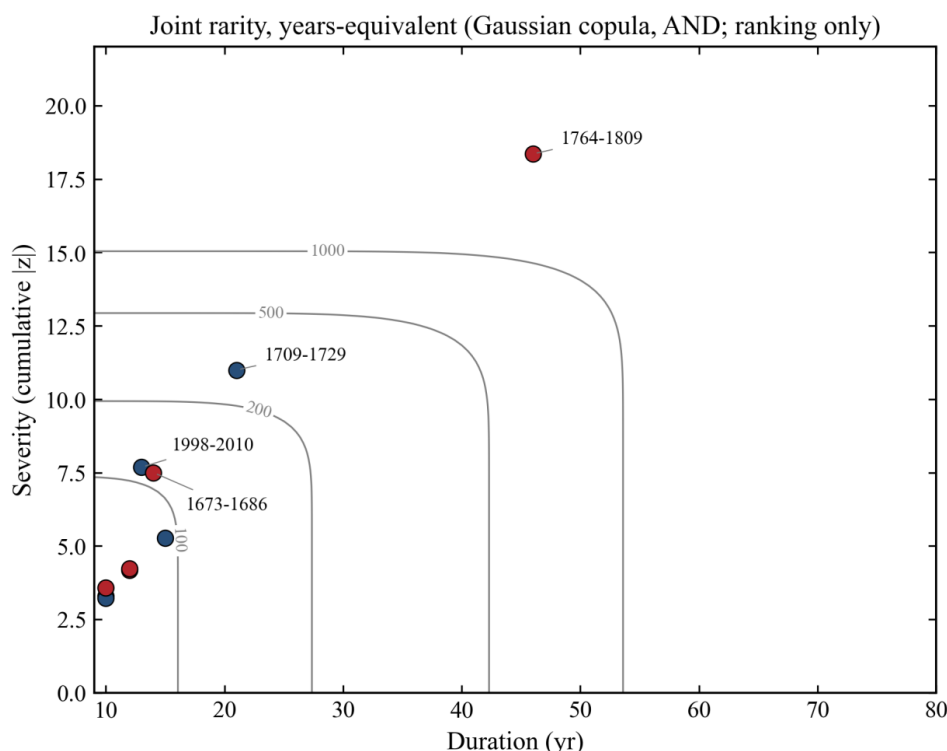
196 *Note: Regimes are defined on the 11-yr LOWESS-smoothed series standardised against 1817–2020; severity is the cumulative absolute*
 197 *standardised anomaly over the regime. † Marginal runs with mean $|z| < 0.3$ (1647–1662, 1852–1862, 1900–1918, 1952–1963, 1978–1987)*
 198 *are physically close to normal conditions and are excluded from interpretation and from the copula rarity analysis (Fig. 6); they are listed for*
 199 *completeness. Regimes before 1817 rest on the SFSC-only nest (single tree before ~1800) and are descriptive only. The 46-yr duration of*



200 1764–1809 exceeds the 95th percentile (25 yr) of a persistence-matched spectral-surrogate null ($P < 0.001$), whereas the regime count itself
201 does not ($P = 0.08$).



202
203 *Figure 5. Extreme years and their occurrence. (a) Standardised reconstruction (1817–2020 basis) with $|z| \geq 1.5$*
204 *extremes marked (black circles; shading = SFSC-only nest 1647–1816, shown descriptively). (b) 30-yr sliding extreme*
205 *frequency (descriptive only, not used for significance testing; dotted line = 1817–2020 mean, 14.2%); the red star*
206 *marks the latest 30-yr window 1991–2020 (6 extremes; three wet, three dry). (c) Duration–severity scatter of persistent*
207 *regimes (≥ 10 yr on the 11-yr LOWESS); filled points pass the minimum-amplitude criterion (mean $|z| \geq 0.3$), open*
208 *points are marginal runs.*



209

210 *Figure 6. Duration–severity joint rarity of the ten amplitude-qualified persistent regimes (exponential duration, gamma*
 211 *severity, Gaussian copula; contours = AND-type joint exceedance probability scaled by the mean regime recurrence*
 212 *interval, in years-equivalent). Values provide a relative rarity ranking only, not return periods in the statistical sense.*

213 Extremes show no significant trend or recent amplification (Fig. 7): the logistic slope over 1817–2020
 214 is -0.016 per decade ($P = 0.63$), neither tail is significant (wet $P = 0.67$; dry $P = 0.81$), and only the
 215 highest thresholds show a positive slope ($P = 0.042$ for $|z| \geq 2.0$, nine events), which is threshold-
 216 marginal. The non-stationary GEV model finds no change in tail magnitude ($P \geq 0.54$).

217 The overlapping 1991–2020 window contains six extremes (three wet, three dry), and the latest
 218 complete block is maximal in only 13% of partition offsets. The latest-minus-earliest contrast is not
 219 significant under bootstrap or spectral-surrogate nulls ($P = 0.63$ – 0.91), and a 1960–1990-only
 220 calibration reproduces the same six recent extremes. The dominant signal is decadal: the wettest decade
 221 of the record (2000s, 197.7 mm) is immediately followed by the driest and highest-variance decade
 222 (2010s, 128.2 mm), while the mean state shows no trend (Mann–Kendall $P = 0.73$).

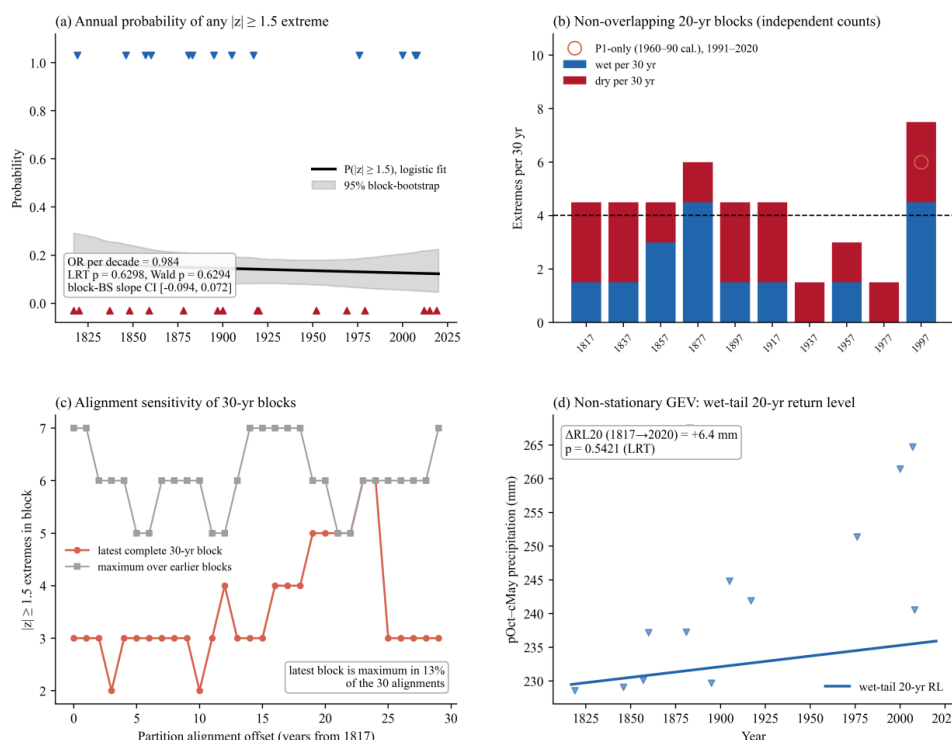


Figure 7. Non-stationarity diagnostics for reconstructed extremes (two-site period 1817–2020). (a) Annual probability of any $|z| \geq 1.5$ extreme from logistic regression (odds ratio 0.984 per decade; likelihood-ratio $P = 0.63$, Wald $P = 0.63$) with 95% moving-block-bootstrap band; triangles mark observed extreme years. (b) Extreme counts in non-overlapping 20-yr blocks (blue = wet, red = dry; rates scaled per 30 yr); dashed line = stationary Gaussian expectation; the partial 2017–2020 block is excluded, and the open circle (right) shows the recent 1991–2020 count recomputed from a transfer function calibrated on 1960–1990 only (P1-only), confirming the recent concentration is not a fitting artefact (Table S3d). (c) Alignment sensitivity: count in the latest complete 30-yr block (red) versus the maximum over earlier blocks (grey) for all 30 partition offsets; the latest block is maximal in only 13% of alignments and uniquely maximal for a single offset (1990–2019). (d) Wet-tail non-stationary GEV 20-yr return level ($\Delta\text{RL}_{20} = +6.4$ mm, likelihood-ratio $P = 0.54$).

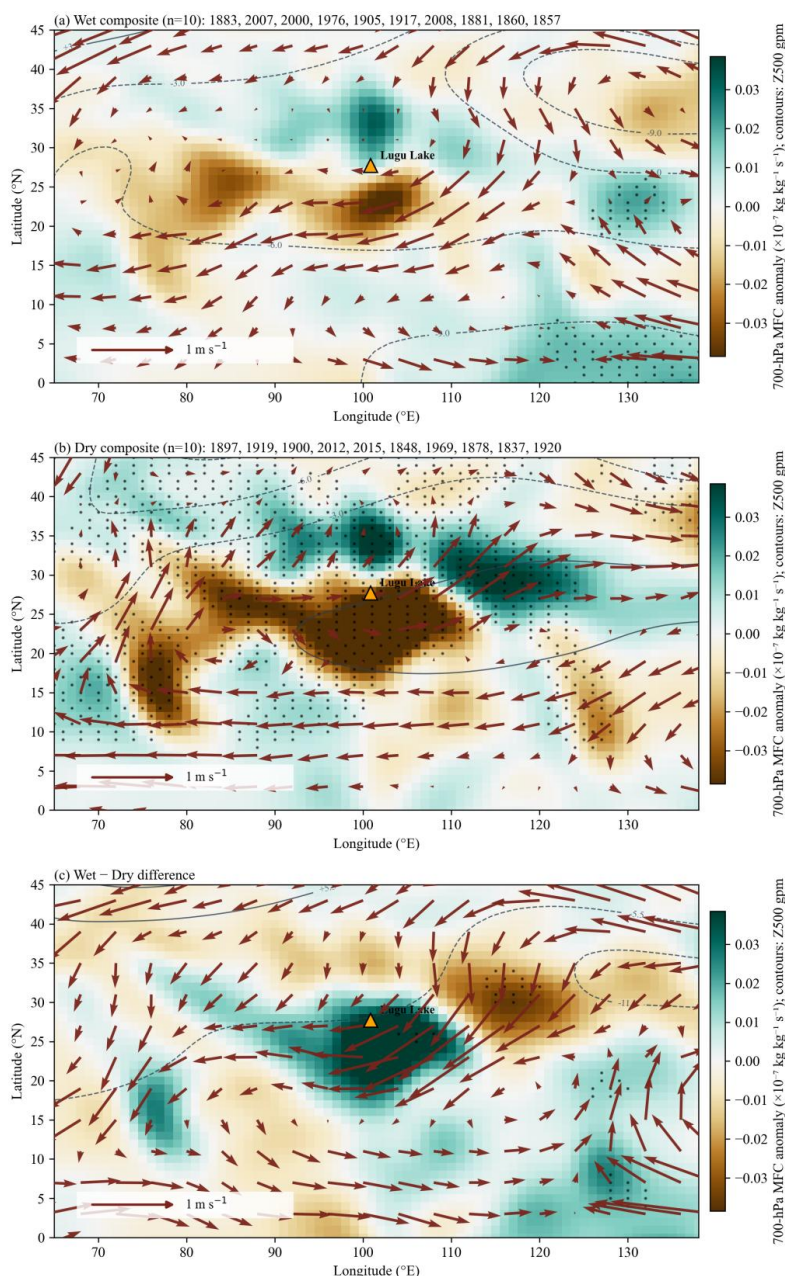
3.4 Ocean–atmosphere and moisture-transport controls

Wet extremes coincide with La Niña-like cooling, negative Z500 anomalies (~ -2.9 gpm) and organised 700-hPa southwesterly transport; dry extremes show El Niño-like warming, positive Z500 anomalies ($\sim +2.8$ gpm) and strongly reduced moisture flux convergence (Fig. 8). The contrast is asymmetric—near zero in the wet composite but a marked deficit in the dry composite (-0.95 mm day^{-1} ; Welch $P = 0.0009$)—and strengthens for post-1900 years (Table S6).

The Welch spectrum shows significant red-noise-corrected peaks at 2.4–10.9 yr, and wavelet coherence with Niño3.4 (1855–2020) is strongest at 2–8 yr, with phase arrows toward $-\pi$ (El Niño $\rightarrow$ dry, La Niña



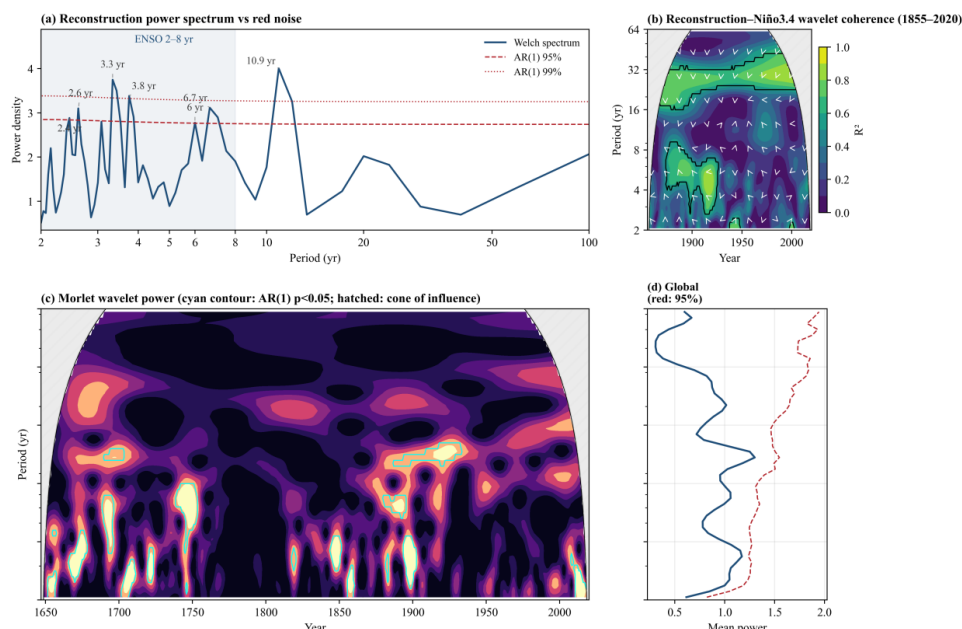
242 → wet; Fig. 9). The single-series Niño3.4 correlation is modest but significant ($r = -0.223$, $P = 0.004$),
 243 whereas PDO, AMO and IOD correlations are weak.



244
 245 *Figure 8. Moisture-flux and circulation composites for the ten wettest and ten driest reconstructed dry seasons (1837–*
 246 *2015; Table S6), based on per-grid detrended 20CRv3 pOct–cMay fields. (a) Wet composite: 700-hPa moisture-flux*
 247 *vectors, column-equivalent moisture flux convergence (shading, mm day⁻¹; single-level flux divergence scaled by $\Delta p =$*



248 200 hPa and expressed as mm day^{-1} , see Section 2.5), and 500-hPa height. (b) Dry composite. (c) Wet – Dry difference
249 (basin-mean MFC $+0.09$ vs. $-0.95 \text{ mm day}^{-1}$; Welch $P = 0.0009$). 700-hPa wind vectors are drawn at an identical scale
250 in all three panels, with the reference vector shown in each panel.



251
252 *Figure 9. Spectral behaviour and ENSO coupling. (a) Welch periodogram with AR(1) red-noise 95/99% levels*
253 *(significant peaks 2.4, 2.6, 3.3, 3.8, 6.0, 6.7, 10.9 yr); the x axis is labelled with actual periods. (b) Squared wavelet*
254 *coherence with Niño3.4 (1855–2020), 95% significance contours and anti-phase phase arrows; 16.2% of cells are*
255 *significant in the 2–8-yr band ($3.2 \times$ chance), with consistent anti-phase behaviour (mean all-cell coherence 0.56). (c)*
256 *Morlet wavelet power with COI and 95% contours. (d) Global wavelet spectrum.*

257 3.5 Twenty-first-century projections (CMIP6 SSP5-8.5)

258 All four models project wetter dry seasons, with large spread (Fig. 10): the multi-model median change
259 relative to 1995–2014 is $+8.2\%$ (range -1.7 to $+14.6\%$) by mid-century and $+21.0\%$ (range $+13.1$ to
260 $+67.4\%$) by end-century, with four-of-four sign agreement and a 15.6 – 65.7% rise in interannual
261 variability.

262 For 2081–2100 the models place 35 – 75% of years above the baseline 90th percentile (stationary
263 expectation 10%), while below-10th-percentile years nearly disappear in three models. The change is
264 therefore strongly asymmetric: wet extremes become far more frequent, whereas severe dry years do
265 not increase at the regional-box scale.

266 The ENSO teleconnection is partly reproduced historically but shows no robust future change:
267 correlations with NDJF Niño3.4 range from -0.19 to $+0.31$ over 1950–2014, with three of four models



reproducing the reconstructed negative sign, and span -0.35 to $+0.26$ at end-century, where 20-yr windows have limited power.

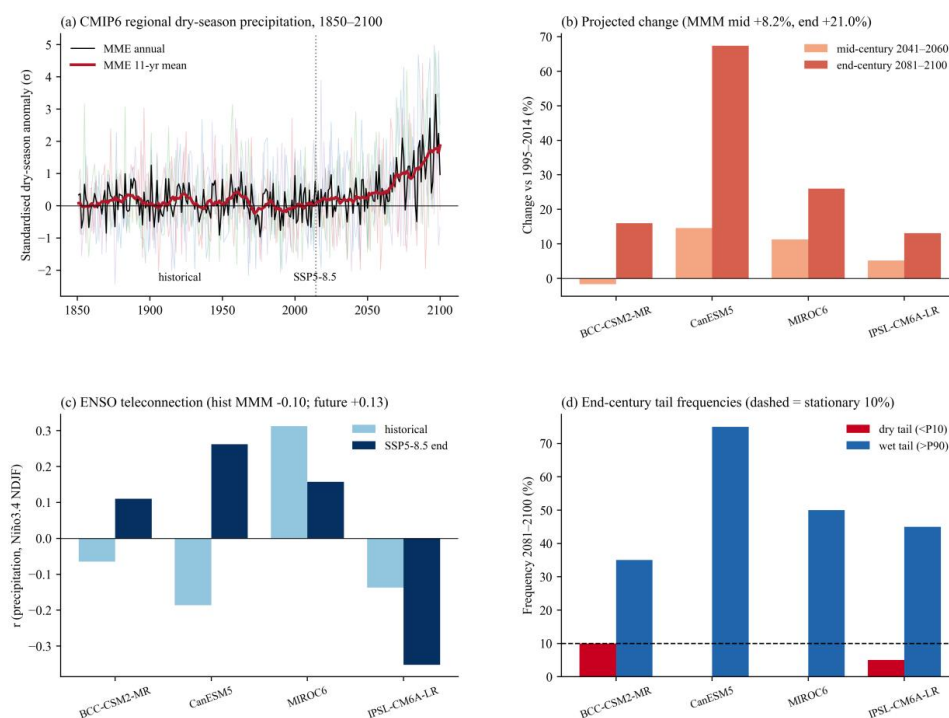


Figure 10. CMIP6 historical and SSP5-8.5 regional dry-season projections for the Lugu Lake box (25–30°N, 99–104°E; four models, *r1i1p1f1*). (a) Standardised regional dry-season precipitation anomalies for each model (thin coloured lines), the four-model ensemble (black) and its 11-yr mean (dark red), 1850–2100 (dotted line separates historical and scenario periods). (b) Percentage change vs. 1995–2014 at mid-century (2041–2060) and end-century (2081–2100); four-of-four models positive at end-century (multi-model median +21.0%). (c) Correlation of regional dry-season precipitation with the NDJF Niño3.4 index for 1950–2014 and 2081–2100 (20-yr future windows lack power for per-model inference; range shown only). (d) End-century occurrence of years beyond the baseline 10th/90th percentiles (dashed line = stationary 10% expectation): the wet tail rises to 35–75% while the dry tail falls to 0–10%.

3.6 Hydrological consistency with independent land-moisture records

Reconstructed precipitation against CNRD v1.0 natural runoff over the 57 complete water years 1962–2018 (Fig. S9; Tables S7, S9) shows significant but bounded coherence: $r = 0.464$ in the Lugu box ($P = 3 \times 10^{-4}$), 0.505 in first differences and 0.307 on the 11-yr LOWESS component, with 63% sign agreement. The finer 0.25° field is spatially coherent (24.3% of 1,674 land cells nominally significant) but narrowly misses the strict Walker threshold, and wavelet coherence is strongest at 2–8 yr (mean $r = 0.626$). Three independent land-moisture products covary with the reconstruction at $r = 0.383$ (CPC soil moisture), 0.396 and 0.327 (NCEP 0–10 and 10–200 cm) and 0.410 (scPDSI; all $P \leq 0.01$), extending coherence beyond runoff to land-surface moisture states.



288 The multi-century comparisons are mixed (Table S8): the Keyimu et al. (2021) non-growing-season
 289 reconstruction correlates with ours over 1647–1959 ($r = 0.227$, $P = 10^{-4}$) and more strongly over 1960–
 290 2005 ($r = 0.443$), whereas the central-Yunnan winter–spring series (Liang et al., 2025) agrees only
 291 modestly before calibration. Most importantly, the Keyimu record does not corroborate the 1764–1809
 292 drought ($z = -0.04$), so the 46-yr event remains a feature of the single-tree nest rather than a region-
 293 wide megadrought.

294 4. Discussion

295 4.1 A dry-season precipitation signal and its regional hydroclimatic patterns

296 The strong pOct–cMay signal in both *Picea likiangensis* chronologies shows that subalpine trees at the
 297 southeastern Plateau margin preserve hydroclimatic information outside the summer monsoon window,
 298 consistent with seasonal replenishment of the soil water that controls earlywood formation (Rossi et al.,
 299 2016). PC1 explains 76.9% of the variance of two independent sites 4.4 km apart, and calibration and
 300 verification skill match recent seasonal reconstructions in SW China and Northeast Asia (Liang et al.,
 301 2025; Hou et al., 2026). The stable split-period RE/CE indicates no weakening of climate–growth
 302 coupling (Chen et al., 2026).

303 The 1764–1809 drought corresponds in timing to multidecadal monsoon-Asia anomalies in MADA, and
 304 the common regimes and 91% co-extreme sign agreement show that the framework is not purely local;
 305 these comparisons therefore indicate coherence rather than exact validation.

306 4.2 Moisture-transport control and the ENSO teleconnection

307 The composites explain these relationships physically: wet dry seasons require an organised
 308 configuration—La Niña-like tropical Pacific SSTs, a deeper trough over the southeastern Plateau and
 309 enhanced 700-hPa transport of Bay of Bengal moisture—whereas dry conditions arise under El Niño-
 310 like warming, higher Z500 and weakened transport. The convergence contrast is dominated by the dry
 311 composite's deficit, so coherent dryness reflects a failure of moisture delivery, as in Northeast Asia
 312 where droughts were more spatially extensive than pluvials (Hou et al., 2026), and is consistent with
 313 cross-watershed coherence requirements (Morales et al., 2020) and with the circulation linked to
 314 Eurasian steppe biomass anomalies (Chen et al., 2026).

315 The sign of the ENSO teleconnection here is opposite to that in Northeast Asia and is regionally
 316 diagnostic: El Niño accompanies dry dry seasons and La Niña wet ones, whereas Northeast Asian wet
 317 extremes have been linked to El Niño-like warming (Hou et al., 2026). El Niño suppresses convection
 318 over the western Pacific warm pool and weakens the Bay of Bengal moisture branch in the post-
 319 monsoon dry season, and the intermittency of this coupling explains the weak contemporaneous
 320 Niño3.4 correlation; the weak PDO/AMO/IOD relationships suggest that interannual ENSO forcing, not
 321 a decadal ocean mode, is the leading large-scale control.



322 **4.3 Decadal variability, the absence of a monotonic trend, and implications**

323 The principal finding concerning extremes is strong decadal variability without a significant monotonic
 324 trend, rather than recent amplification: the latest 30 years are not exceptional under nulls that preserve
 325 serial dependence and multidecadal variance. The decadal expression is the striking feature, with the
 326 wettest decade followed immediately by the driest and highest-variance decade while the mean state
 327 shows no trend.

328 Thermodynamically, a warmer atmosphere holds more moisture (roughly 7% K⁻¹; Trenberth et al.,
 329 2003), and dynamically the wet 2000s and dry 2010s coincide with intervals of strong ENSO coherence,
 330 suggesting that teleconnected events modulate dry-season amplitude without imposing a trend (He et al.,
 331 2025). For the Lugu Lake basin the implications are direct, because the dry 2010s coincide with
 332 reported lake-level declines and water stress while the preceding wet decade delivered pluvials that
 333 challenge storage management. The 1764–1809 dry state, although local to the single-tree nest, shows
 334 that the record contains sustained dry anomalies far longer than anything instrumental, although part of
 335 that persistence may be tree- or site-specific (Chen et al., 2026).

336 **4.4 The twenty-first-century trajectory: a wetter, more variable dry season**

337 Under SSP5-8.5, four structurally independent models agree on the sign of end-century regional dry-
 338 season wetting and, more robustly, on a large increase in wet-tail frequency with rising interannual
 339 variability—the expected thermodynamic signature for a monsoon-transition season whose moisture is
 340 partly oceanic, since Clausius–Clapeyron scaling increases the available moisture while the circulation
 341 term that determines whether it is delivered shows little consensus. The very large CanESM5 response
 342 reflects its high climate sensitivity (≈ 5.6 K; Swart et al., 2019), so we emphasise sign agreement and tail
 343 behaviour rather than median magnitude. Residual drought risk nonetheless persists, because a single
 344 circulation failure in a wetter, higher-variance climate can still produce severe dry years.

345 Several caveats bound the projection: the coarse box overestimates absolute dry-season precipitation at
 346 the rain-shadow site, a single ensemble member per model does not separate forced change from
 347 internal variability, the ENSO teleconnection change has no model consensus, and 20-yr windows have
 348 limited power. SSP5-8.5 is a high-emissions reference scenario rather than a forecast.

349 **4.5 What the land-water-balance comparison can and cannot establish**

350 With no local gauge or lake-level data, the hydrological question can only be addressed indirectly: a
 351 reconstruction of the land-water balance should covary with naturalised runoff and model-derived soil
 352 moisture. Because the model was calibrated against precipitation rather than discharge, exact year-to-
 353 year agreement with runoff is neither expected nor required (OLS slope 0.46). A box correlation of $r =$
 354 0.46 over 57 water years therefore constitutes meaningful qualitative consistency, although
 355 reconstructed regimes should not be read as one-to-one runoff anomalies.



356 Cross-proxy support is likewise bounded: significant pre-calibration covariance with the nearest long
 357 reconstruction (Keyimu et al., 2021; $r = 0.23$ across 313 years) indicates shared regional non-growing-
 358 season moisture variability, but the absence of the 1764–1809 drought from that record and the lack of
 359 low-frequency agreement with the central-Yunnan series show that the event is spatially or seasonally
 360 restricted.

361 **4.6 Limitations**

362 Several limitations bound the interpretation. The reconstruction underestimates amplitude, because
 363 RMSE (53.8 mm) exceeds its own standard deviation and the regression retains ~44% of observed
 364 variance, so the $|z|$ thresholds refer to the reconstruction rather than the true climate amplitude, although
 365 extreme timing is verified by the P1-only check. The calibration target is a valley station ~35 km from
 366 the lake and ~300 m below the lake surface, and the dry season supplies only ~17.5% of annual rainfall,
 367 so the series represents the wider Lugu Lake region. Station homogeneity was not formally tested; the
 368 pre-1800 segment rests on five cores from one tree, restricting inference to 1817–2020; MADA,
 369 20CRv3 and ERSSTv5 are sparsely constrained over or not fully independent of the region; no local
 370 gauged runoff or lake-level record exists; the 1764–1809 drought lacks corroboration; and CO₂-
 371 fertilisation or nitrogen-deposition effects on ring width cannot be fully separated from the climate
 372 signal.

373 **5. Conclusions**

374 To our knowledge, this is the first tree-ring reconstruction of dry-season (pOct–cMay) precipitation for
 375 the Lugu Lake basin, extending the instrumental record to a 204-year mainline (1817–2020) from two
 376 *Picea likiangensis* residual chronologies.

- 377 1. Reliable reconstruction. A nested PC1 transfer function explains 44.4% of Ninglang dry-season
 378 precipitation variance (1960–2020), with positive, stable RE and CE in both split directions (0.34–
 379 0.38) and first-differenced correlations of 0.668–0.707.
- 380 2. Decadal variability without a monotonic trend. Over 1817–2020, extreme occurrence shows no trend
 381 (logistic $P = 0.63$) and no change in tail magnitude ($P \geq 0.54$), and the wettest (2000s) and driest
 382 (2010s) decades occur consecutively.
- 383 3. Persistent regimes. Fourteen ≥ 10 -yr regimes are identified, ten amplitude-qualified; the count is
 384 consistent with red noise ($P = 0.08$) whereas the amplitude-qualified count is elevated ($P = 0.01$).
 385 The 46-yr drought of 1764–1809 exceeds the null ($P < 0.001$) but is treated as a local feature of the
 386 single-tree nest, not a region-wide megadrought.
- 387 4. Regional coherence and hydrological consistency. The reconstruction correlates with UDel gridded
 388 precipitation and passes a Walker field test, while MADA agreement ($r = 0.390$; 91% sign



389 agreement) is a consistency reference rather than validation. Consistency rests on CNRD v1.0
 390 natural runoff ($r = 0.46$), CPC and NCEP soil moisture and scPDSI ($r = 0.33-0.41$).

391 5. Moisture-transport and ENSO controls. Wet extremes couple to La Niña-like cooling, lower Z500
 392 and organised 700-hPa southwesterly transport; dry extremes to El Niño-like warming and a
 393 marked moisture-convergence deficit ($P = 0.0009$). Anti-phase coherence with Niño3.4 is
 394 intermittent but phase-consistent, and its sign is opposite to that reported for Northeast Asia.

395 6. Future trajectory (SSP5-8.5). All four models project end-century regional wetting (median +21.0%;
 396 range +13.1 to +67.4%) and a strong wet-tail asymmetry (35–75% of late-century years above the
 397 baseline 90th percentile versus 10% expected).

398 These findings support an integrated tree-growth–precipitation–hydroclimate–circulation framework for
 399 the southeastern Tibetan Plateau and a multi-century baseline dominated by decadal variability with no
 400 significant trend in extremes, while CMIP6 projects a future risk envelope shifted toward wet extremes.

401 **Data availability**

402 The reconstruction, chronologies, and all derived tables will be deposited in a public repository upon
 403 acceptance. The numbered Python analysis scripts that generate every statistic reported in the text,
 404 tables, and figures from the raw inputs are available from the corresponding author and will be
 405 deposited together with the data, including the derived seasonal box series used for the hydrological-
 406 consistency analysis. Ninglang station precipitation was obtained from the China Meteorological
 407 Administration; UDel v5.01, ERSSTv5, 20CRv3, MADA, the CPC global soil-moisture analysis,
 408 NCEP/NCAR Reanalysis 1, the NOAA/PSL self-calibrated PDSI, and the Niño3.4/PDO/AMO/IOD
 409 indices are publicly available from their respective providers. The Keyimu et al. (2021) non-growing-
 410 season reconstruction is published in the *Climate of the Past* supplement and the Liang et al. (2025)
 411 winter–spring series is published with that article in *Humanities and Social Sciences Communications*.
 412 CMIP6 data (BCC-CSM2-MR, CanESM5, MIROC6, IPSL-CM6A-LR; historical and SSP5-8.5; *pr*
 413 *Amon* and *tos* *Omon*; *r1i1p1f1*) are publicly available via the ESGF federation; per-model regional dry-
 414 season series and projection statistics from this study are provided in the supplementary tables.

415 **Author contributions**

416 Z.C. designed the study, performed the analyses and wrote the manuscript. F.C. supervised the study
 417 and acquired funding. H.Z., S.W., M.H., H.C., Y.C., Y.D. and T.H. contributed to fieldwork, sample
 418 preparation and data curation. All authors discussed the results and approved the final manuscript.

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423 **Competing interests**

424 The authors declare that they have no competing interests.

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