

Supplementary Material

Supplementary Table S1. Measured precipitation-isotope datasets and analytical coverage. Coverage columns report finite physical-anomaly and hydroclimate observations by archive.

Source	Sampling support	Records, n	Stations, n	Physical anomaly coverage	Hydroclimate coverage
Australian GNIP monthly	Monthly collections	2,849	22	2,779/2,849 (97.5%)	0/2,849 (0.0%)
IAEA tropical daily	Daily collections	4,729	15	4,729/4,729 (100.0%)	0/4,729 (0.0%)
Mendeley event/interval collection	Event/interval collections	689	30	689/689 (100.0%)	689/689 (100.0%)
All sources	Source-balanced analysis	8,267	67	8,197/8,267 (99.2%)	689/8,267 (8.3%)

Supplementary Table S2. Variance partitioning and isotope-line slopes across measured observation scales. Between-station shares include intervals; slopes relate $\delta^2\text{H}$ to $\delta^{18}\text{O}$.

Source	Record s, n	Station s, n	$\delta^{18}\text{O}$ between [95% CI] (%)	$\delta^2\text{H}$ between [95% CI] (%)	d-excess between [95% CI] (%)	Within- station slope [95% CI]	Between- station slope [95% CI]
Australian GNIP monthly	2,849	22	+5.7 [+2.5, +9.0]	+4.9 [+2.7, +7.4]	+17.6 [+9.1, +22.9]	7.016 [+6.650, +7.302]	5.857 [+4.494, +7.978]
IAEA tropical daily	4,729	15	+25.5 [+14.6, +31.8]	+25.5 [+14.3, +32.5]	+13.6 [+6.7, +19.4]	7.796 [+7.547, +8.025]	7.890 [+7.211, +8.608]
Mendeley event/interval collection	689	30	+75.7 [+41.0, +86.7]	+76.1 [+42.8, +86.7]	+40.8 [+22.8, +59.7]	7.562 [+7.205, +7.844]	7.775 [+7.543, +8.167]

Supplementary Table S3. Seasonal, latitudinal, and physical organization of measured precipitation isotopes. Rows report annual amplitude, peak day, latitude slope, and standardized physical association.

Source	Coordinate	Annual amplitude [95% CI] (‰)	Peak DOY	Latitude slope [95% CI] (‰ degree ⁻¹)	Physical-anomaly β [95% CI]
Australian GNIP monthly	$\delta^{18}\text{O}$	1.45 [+1.12, +1.89]	307	-0.018 [-0.092, +0.015]	+0.477 [+0.387, +0.563]
Australian GNIP monthly	$\delta^2\text{H}$	10.84 [+8.11, +14.49]	298	-0.077 [-0.627, +0.161]	+0.497 [+0.411, +0.591]
Australian GNIP monthly	d-excess	1.97 [+1.32, +2.65]	188	+0.070 [-0.018, +0.209]	—
IAEA tropical daily	$\delta^{18}\text{O}$	0.73 [+0.20, +1.44]	65	-0.054 [-0.137, +0.132]	+0.276 [+0.185, +0.362]

Source	Coordinate	Annual amplitude [95% CI] (‰)	Peak DOY	Latitude slope [95% CI] (% degree ⁻¹)	Physical-anomaly β [95% CI]
IAEA tropical daily	$\delta^2\text{H}$	6.46 [+1.66, +12.26]	62	-0.345 [-1.004, +1.120]	+0.281 [+0.178, +0.384]
IAEA tropical daily	d-excess	0.67 [+0.14, +2.45]	34	+0.086 [-0.065, +0.170]	—
Mendeley event/interval collection	$\delta^{18}\text{O}$	3.03 [+2.07, +4.33]	122	-0.554 [-1.200, -0.071]	-0.038 [-0.177, +0.092]
Mendeley event/interval collection	$\delta^2\text{H}$	23.14 [+16.02, +33.08]	111	-4.761 [-9.974, -1.150]	-0.055 [-0.189, +0.066]
Mendeley event/interval collection	d-excess	4.37 [+2.41, +6.32]	11	-0.332 [-1.148, +0.441]	—
Source-adjusted pooled	$\delta^{18}\text{O}$	—	—	-0.084 [-0.167, -0.017]	—
Source-adjusted pooled	$\delta^2\text{H}$	—	—	-0.631 [-1.287, -0.128]	—
Source-adjusted pooled	d-excess	—	—	+0.043 [-0.073, +0.131]	—

Supplementary Table S4. Adjusted precipitation-memory associations in the Mendeley event/interval collection. Coefficients compare collection-interval, 7-day, and 30-day precipitation after adjustment.

Coordinate	Collection-interval precipitation β [95% CI]	Prior 7-day precipitation β [95% CI]	Prior 30-day precipitation β [95% CI]	30-day model R^2
$\delta^{18}\text{O}$	-0.058 [-0.159, +0.031]	-0.107 [-0.256, +0.030]	-0.306 [-0.434, -0.166]	0.235
$\delta^2\text{H}$	-0.063 [-0.166, +0.026]	-0.080 [-0.220, +0.056]	-0.276 [-0.404, -0.136]	0.211
d-excess	-0.013 [-0.181, +0.123]	+0.135 [-0.004, +0.334]	+0.182 [+0.053, +0.350]	0.131

Supplementary Table S5. Residual and geometry structural grid. Rows compare parameterization and fusion mass under identical complete-station folds.

Component	Fusion mass	$\delta^{18}\text{O}$ MAE (‰)	$\delta^2\text{H}$ MAE (‰)	Joint loss	Skill vs meteorology (%)	Selected
Direct physical	0.50	2.971	22.010	1.611	+8.47	No
Direct physical	0.75	2.873	21.568	1.568	+10.92	No
Direct physical	1.00	2.819	21.432	1.548	+12.05	No
Direct geometry	0.50	2.971	29.812	1.890	-7.36	No
Direct geometry	0.75	2.873	38.097	2.159	-22.61	No
Direct geometry	1.00	2.819	47.369	2.475	-40.57	No

Component	Fusion mass	$\delta^{18}\text{O}$ MAE (‰)	$\delta^2\text{H}$ MAE (‰)	Joint loss	Skill vs meteorology (%)	Selected
Residual physical	0.50	2.919	21.952	1.595	+9.41	No
Residual physical	0.75	2.805	21.596	1.550	+11.94	No
Residual physical	1.00	2.750	21.659	1.538	+12.67	No
Residual geometry	0.50	2.919	21.703	1.586	+9.92	No
Residual geometry	0.75	2.805	21.304	1.540	+12.53	No
Residual geometry	1.00	2.750	21.431	1.529	+13.13	Yes

Supplementary Table S6. Residual-geometry objective and learner sensitivity. Rows retain the same folds, information set, and aggregation rule.

Analysis	Learner / objective	$\delta^{18}\text{O}$ MAE (‰)	$\delta^2\text{H}$ MAE (‰)	Joint loss	Rank	Status
Objective comparison	XGBoost / Pseudo-Huber	2.750	21.431	1.529	1	Primary specification
Objective comparison	XGBoost / L1	2.793	21.854	1.556	2	Alternative
Objective comparison	XGBoost / L2	2.816	22.163	1.574	3	Alternative
Learner sensitivity	Catboost / MAE	2.715	21.259	1.513	1	Sensitivity comparator
Learner sensitivity	Xgboost / Pseudo-Huber	2.750	21.431	1.529	2	Primary specification
Learner sensitivity	Catboost / RMSE	2.773	21.562	1.540	3	Sensitivity
Learner sensitivity	Lightgbm / Huber	2.816	22.056	1.570	4	Sensitivity
Learner sensitivity	Lightgbm / L1	3.974	31.604	2.232	5	Sensitivity

Supplementary Table S7. Source-specific complete-station reconstruction performance. Rows report archive errors, skill, and station-win fraction.

Source	Records , n	Stations , n	$\delta^{18}\text{O}$ MAE (‰)	$\delta^2\text{H}$ MAE (‰)	Joint loss	Vs meteorology (% skill; % wins)	Vs physical (% skill; % wins)
Australian GNIP monthly	2,849	22	1.604	11.780	0.866	+23.54; 95.5	+6.69; 86.4
IAEA tropical daily	4,729	15	2.402	19.079	1.349	+18.28; 93.3	+2.14; 46.7
Mendeley event/interval collection	689	30	4.244	33.434	2.373	+5.02; 70.0	+9.66; 63.3

Supplementary Table S8. Station-specific performance in the Nepal independent-confirmation set. Kathmandu and Lete contain 64 and 111 response-blind queries, respectively.

Method	Station	Queries	$\delta^{18}\text{O}$ MAE (‰)	$\delta^2\text{H}$ MAE (‰)	d-excess MAE (‰)	Joint loss
IsoRole	Kathmandu	64	2.484	20.147	7.196	1.410
IsoRole	Lete	111	2.325	18.616	4.373	1.311
Direct CatBoost-MAE	Kathmandu	64	2.472	20.840	7.196	1.431
Direct CatBoost-MAE	Lete	111	3.907	28.941	4.373	2.119
Raw ICM + fallback	Kathmandu	64	4.010	32.777	3.324	2.285
Raw ICM + fallback	Lete	111	5.961	43.211	5.227	3.199

Supplementary Table S9. Same-information comparator boundary in complete-station development. Rows distinguish direct controls, residual parents, and fixed refinements.

Model	$\delta^{18}\text{O}$ MAE (‰)	$\delta^2\text{H}$ MAE (‰)	Joint loss	Rank	Analysis status
Fixed one-third/two-thirds parent blend	2.684	21.021	1.496	1	Fixed-blend sensitivity
Residual-geometry CatBoost-MAE parent	2.715	21.259	1.513	2	Learner sensitivity
Direct full-feature CatBoost-MAE	2.738	21.460	1.527	3	Strongest direct control
Residual-geometry XGBoost parent	2.750	21.431	1.529	4	Primary specification
Direct full-feature XGBoost	2.819	21.432	1.548	5	Matched-grid direct control
Nested cross-fit residual refinement	2.853	22.331	1.590	6	Nested refinement

Supplementary Table S10. Sequential evidence stages used to form and confirm IsoRole. Rows distinguish development, adaptive design, and final independent confirmation.

Evidence stage	Data	Queries / records	Stations	Role in IsoRole formation	Isotope-label use
Complete-station development	Three measured archives	8,267	67	RGF selection; blend fixed after learner comparison and before blend evaluation	Grouped cross-validation within development
Adaptive design I	PAPIN and Indianapolis	208	13	Geographic support-gate design	Opened after fixed predictions; design evidence only
Adaptive design II	Yadong and Pali	224	2	Coordinate-role composition	Opened after fixed predictions; design evidence only
Independent confirmation	Kathmandu and Lete	175	2	Final fixed-rule evaluation	Opened only by the independent evaluator

Supplementary Table S11. Geographic-gate and record-block sensitivity in the Nepal independent-confirmation set. Gate rows report active queries; block rows report joint skill intervals.

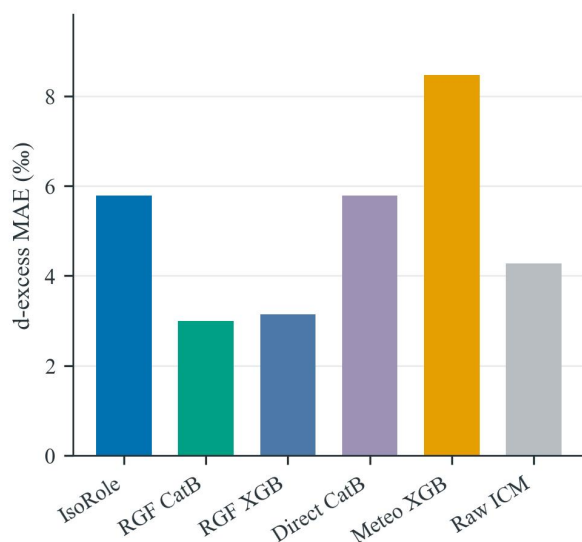
Sensitivity component	Setting	Active Nepal queries	Joint skill vs direct CatBoost [95% CI] (%)	Joint skill vs raw ICM [95% CI] (%)
Geographic gate	0.75 τ	175 / 175	Unchanged	Unchanged
Geographic gate	1.00 τ	175 / 175	23.37 [9.11, 33.81]	50.39 [38.74, 60.02]
Geographic gate	1.25 τ	175 / 175	Unchanged	Unchanged
Circular record blocks	7 records	—	23.37 [12.32, 32.45]	50.39 [38.89, 59.87]
Circular record blocks	14 records	—	23.37 [9.11, 33.81]	50.39 [38.74, 60.02]
Circular record blocks	21 records	—	23.37 [8.26, 34.16]	50.39 [39.63, 59.36]
Circular record blocks	28 records	—	23.37 [6.86, 34.75]	50.39 [40.95, 58.84]

Supplementary Table S12. Held-station phase, variance, slope, and error fidelity across three reconstruction candidates. Contrasts are candidate–observation; phase is wrapped, variance is percent bias, and signed errors are observation–prediction.

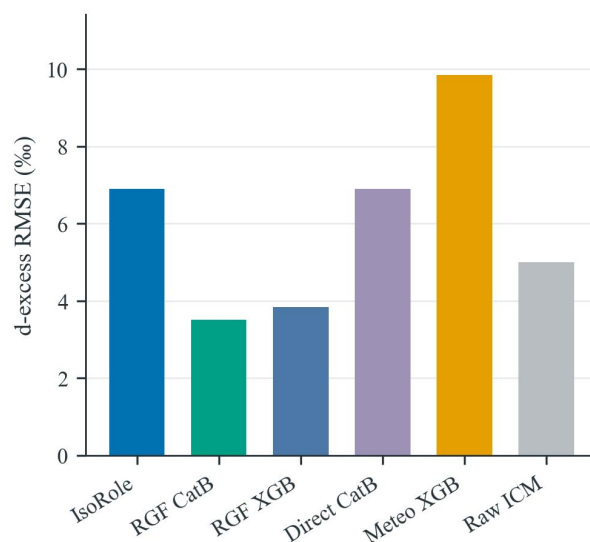
Structure	Archive / scale	Isotope	Observed	IsoRole OOF (Δ [95% CI])	Direct CatBoost (Δ [95% CI])	Raw ICM (Δ [95% CI])
Annual peak day	Mendeley	$\delta^{18}\text{O}$	121.73 d	126.20 d (+4.47 [−19.17, 27.95])	126.68 d (+4.94 [−22.02, 28.04])	28.19 d (−93.54 [−128.93, −60.49])
Annual peak day	Mendeley	$\delta^2\text{H}$	111.32 d	108.77 d (−2.55 [−26.14, 18.54])	104.55 d (−6.77 [−36.10, 13.88])	27.51 d (−83.80 [−122.77, −51.47])
Isotope-line slope	Tropical, between	$\delta^2\text{H}$ on $\delta^{18}\text{O}$	7.890	7.617 (−0.273 [−1.254, 1.257])	7.350 (−0.540 [−1.542, 1.311])	6.879 (−1.011 [−1.880, −0.087])
Isotope-line slope	Mendeley, within	$\delta^2\text{H}$ on $\delta^{18}\text{O}$	7.562	7.826 (+0.264 [−0.164, 0.777])	7.339 (−0.223 [−0.646, 0.270])	8.040 (+0.477 [0.182, 0.849])
30-day adjusted β	Mendeley, within	$\delta^{18}\text{O}$	−0.306	−0.380 (−0.074 [−0.263, 0.090])	−0.420 (−0.113 [−0.347, 0.075])	−0.116 (+0.191 [−0.035, 0.409])
30-day error β	Mendeley, within	$\delta^{18}\text{O}$	0.000	−0.129 [−0.262, 0.023]	−0.162 [−0.300, 0.010]	−0.201 [−0.353, −0.042]
30-day adjusted β	Mendeley, within	$\delta^2\text{H}$	−0.276	−0.360 (−0.084 [−0.247, 0.062])	−0.409 (−0.133 [−0.340, 0.026])	−0.099 (+0.177 [−0.046, 0.378])
30-day error β	Mendeley, within	$\delta^2\text{H}$	0.000	−0.092 [−0.217, 0.051]	−0.125 [−0.261, 0.042]	−0.183 [−0.326, −0.020]
Within-station variance bias	Australia	$\delta^{18}\text{O}$	0% bias	−63.30% [−70.36, −54.13]	−78.10% [−82.32, −71.76]	−46.48% [−56.78, −33.17]
Within-station variance bias	Australia	$\delta^2\text{H}$	0% bias	−57.33% [−63.83, −48.12]	−75.81% [−80.05, −69.43]	−41.16% [−50.66, −27.62]

Structure	Archive / scale	Isotope	Observed	IsoRole OOF (Δ [95% CI])	Direct CatBoost (Δ [95% CI])	Raw ICM (Δ [95% CI])
Within- station variance bias	Tropical	$\delta^{18}\text{O}$	0% bias	-64.00% [-74.74, -48.96]	-80.89% [-86.85, -72.27]	-46.50% [-59.53, -29.53]
Within- station variance bias	Tropical	$\delta^2\text{H}$	0% bias	-62.48% [-74.66, -44.78]	-80.07% [-87.17, -69.38]	-45.79% [-59.88, -26.70]
Within- station variance bias	Mendeley	$\delta^{18}\text{O}$	0% bias	-75.06% [-82.55, -66.60]	-84.73% [-89.01, -79.74]	-53.37% [-66.92, -34.04]
Within- station variance bias	Mendeley	$\delta^2\text{H}$	0% bias	-72.15% [-79.88, -63.69]	-84.02% [-87.95, -79.55]	-49.35% [-63.28, -28.97]

Supplementary Figures

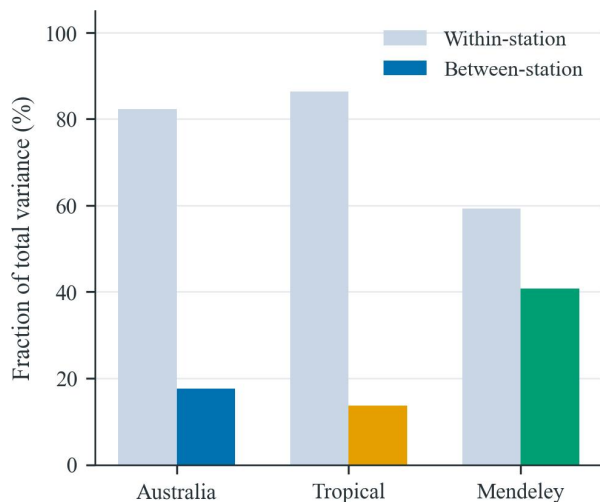


(A) Nepal d-excess MAE

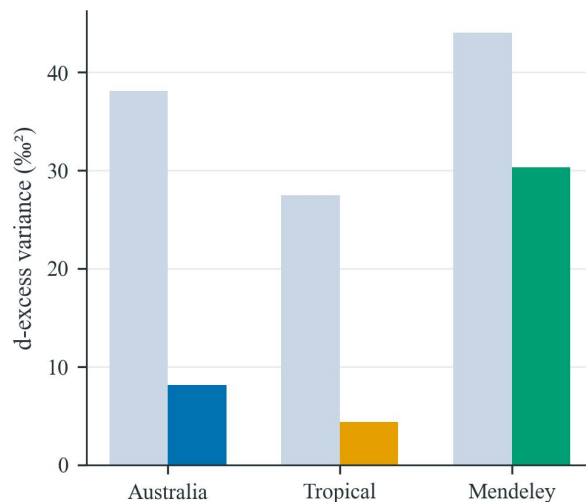


(B) Nepal d-excess RMSE

Figure S1. Derived d-excess error across IsoRole and five Nepal transfer comparators. Bars show equal-station MAE and RMSE for 175 queries from Kathmandu and Lete.



(A) Relative d-excess variance



(B) Absolute d-excess variance

Figure S2. Within- and between-station d-excess variance across three isotope archives. Panels show relative fractions and absolute components; colors identify the archive-specific between-station contribution.

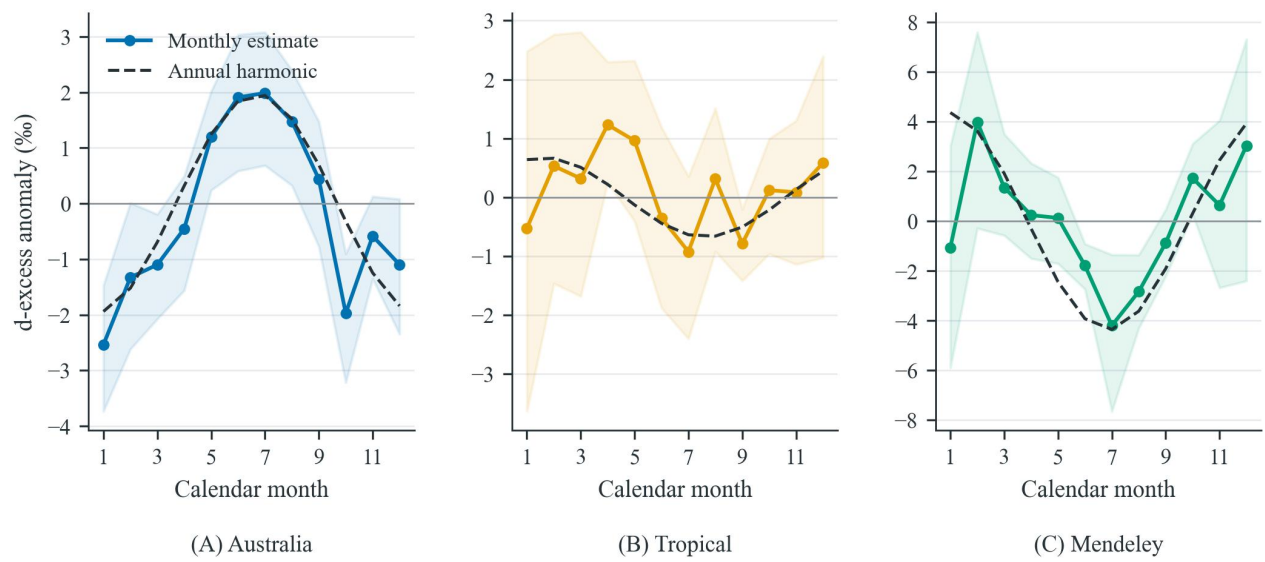


Figure S3. Archive-specific annual cycles and harmonic structure of measured precipitation d-excess. Monthly equal-station anomalies, station-bootstrap intervals, and annual harmonic fits are shown for all three archives.

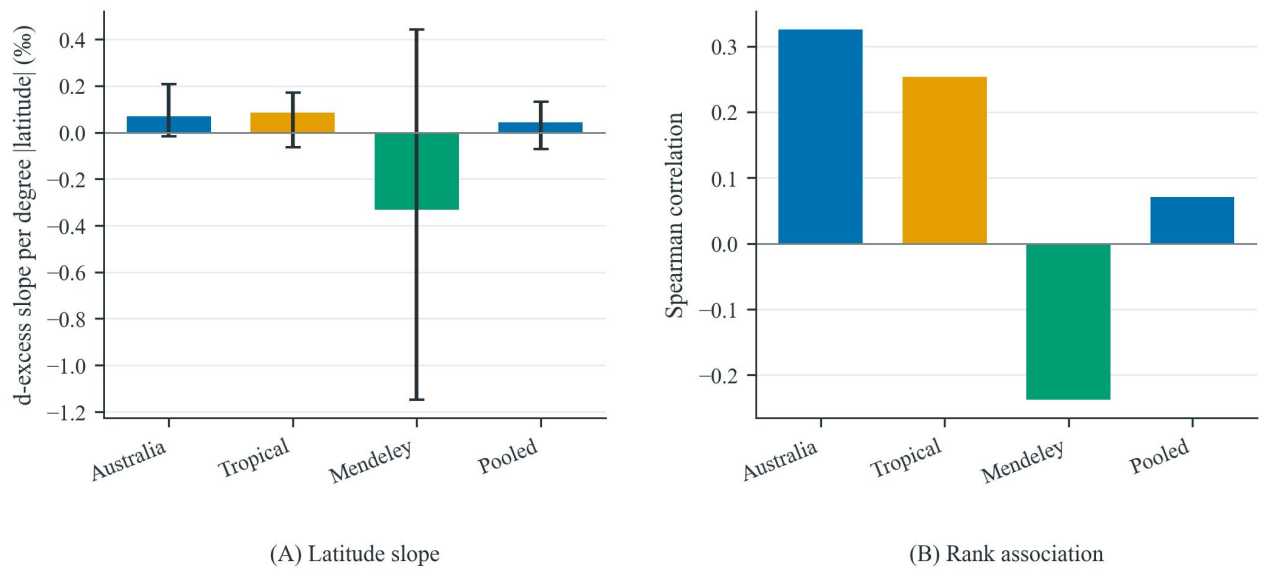


Figure S4. Latitude relations of measured d-excess across archives and the pooled network. Panels show station-bootstrap slopes and Spearman associations for the same source-specific and source-adjusted scopes.