

Sect. S1. Mathematical formulation of monthly aggregation and secondary isotopic parameters.

Monthly precipitation-weighted isotopic compositions were calculated as:

$$\delta^{18}O_{pw} = \frac{\sum_i P_i \delta^{18}O_i}{\sum_i P_i} \quad (\text{S1})$$

and equivalently for δ^2H and $\delta^{17}O$, where P_i represents the precipitation amount associated with each individual event within a given month. All isotopic compositions are expressed in ‰ relative to VSMOW.

The d-excess parameter was calculated as:

$$d = \delta^2H - 8\delta^{18}O \quad (\text{S2})$$

The ^{17}O -excess parameter was computed using the logarithmic formulation:

$$^{17}O = \ln\left(1 + \frac{\delta^{17}O}{1000}\right) - \lambda \ln\left(1 + \frac{\delta^{18}O}{1000}\right) \quad (\text{S3})$$

with $\lambda = 0.528$.

Table S1. Seasonal PCA loading matrices for atmospheric predictors

Principal component loadings for wet (ONDJFM) and dry (AMJJAS) seasons derived from PCA applied to NAOi, WeMOi, monthly precipitation (pcp_sum), and station altitude. Values correspond to standardized loadings.

A) Wet season (ONDJFM)

Variable	PC1	PC2	PC3	PC4
NAOi	-0.707	-0.189	-0.183	0.656
WeMOi	0.707	-0.176	-0.203	0.654
pcp_sum	0.000	0.769	0.523	0.368
Altitude	0.017	-0.585	0.807	0.075

B) Dry season (AMJJAS)

Variable	PC1	PC2	PC3	PC4
NAOi	0.484	0.697	0.098	-0.520
WeMOi	-0.136	-0.218	0.935	-0.243
pcp_sum	-0.475	0.680	0.223	0.512
Altitude	0.722	-0.060	0.257	0.639

Fig. S1. Station-wise Spearman correlations between ^{17}O Excess and atmospheric predictors. Blank cells indicate station–season combinations where correlations could not be estimated due to insufficient paired observations.

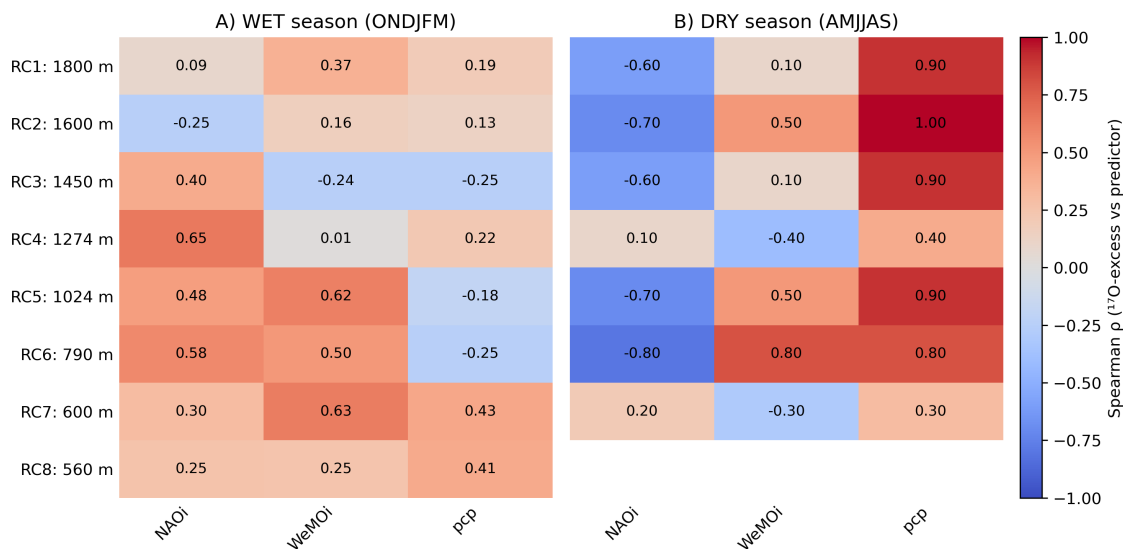


Fig. S2. Station-wise Spearman correlations between d Excess and atmospheric predictors.

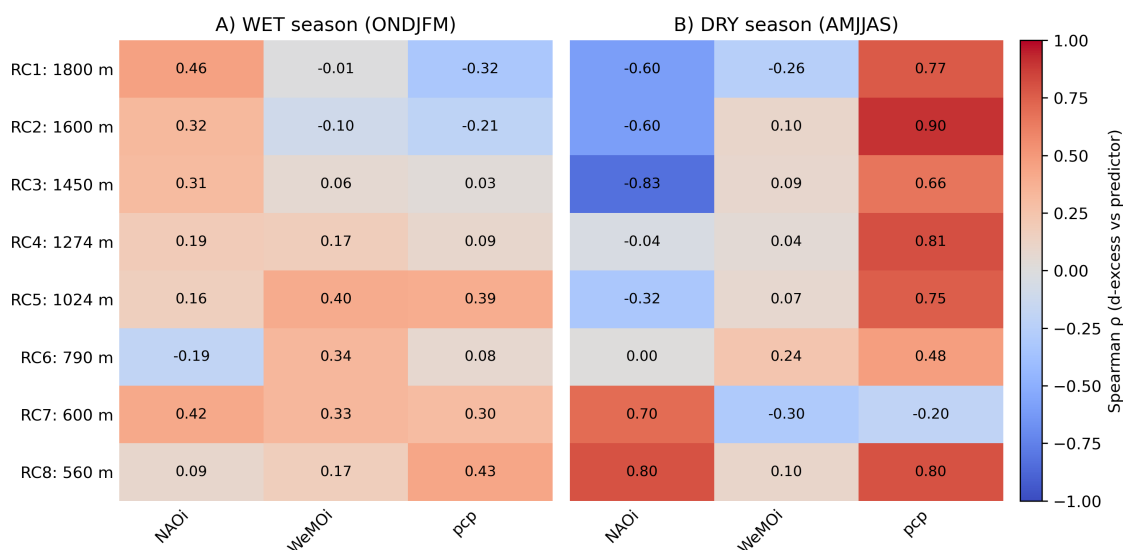


Table S2. List of regionally coherent precipitation event days coincident with isotope sampling and retained for backward trajectory analysis. “Days with rainfall” were identified using the spatial consistency criterion described in Section 4.6, requiring measurable precipitation at a minimum of four monitoring stations on the same day. Events are classified by hydroclimatic season (wet: ONDJFM; dry: AMJJAS). The table reports the event date, season, number of stations with measurable precipitation, and associated monthly NAOi and WeMOi values used for circulation stratification. These 52 event days (40 wet, 12 dry) constitute the basis for all HYSPLIT trajectory simulations and subsequent clustering analyses.

date_str	season	n_stations_rain	fraction_stations	pcp_sum_mm	pcp_mean_mm	pcp_max_mm
25/12/2017	WET	4	0.67	144.4	24	36.1
21/04/2019	DRY	3	0.50	189.2	32	63.2
15/05/2020	DRY	3	0.50	261.9	44	99
03/10/2020	WET	6	1.00	106.8	18	17.8
31/10/2020	WET	5	0.83	99.5	17	19.9
07/11/2020	WET	6	1.00	189.3	32	59.5
28/11/2020	WET	5	0.83	85.8	14	17.2
13/12/2020	WET	6	1.00	211.1	35	56.5
31/12/2020	WET	4	0.67	89.2	15	22.3
23/01/2021	WET	4	0.67	89.7	15	22.7
24/01/2021	WET	5	0.83	97	16	37
29/01/2021	WET	3	0.50	75.2	13	41
15/02/2021	WET	4	0.67	172.9	29	74
26/02/2021	WET	5	0.83	104.2	17	29
21/03/2021	WET	3	0.50	60.2	10	20.2
16/04/2021	DRY	4	0.67	34.4	6	13.1
25/04/2021	DRY	6	1.00	49.2	8	10
26/04/2021	DRY	6	1.00	60	10	10
18/09/2021	DRY	6	1.00	39.6	7	6.6
05/11/2021	WET	6	1.00	474.2	79	79.1
22/11/2021	WET	5	0.83	242.8	40	50
29/11/2021	WET	5	0.83	100	17	20
03/12/2021	WET	3	0.50	53.3	9	17.8
05/12/2021	WET	3	0.50	49	8	18
22/12/2021	WET	5	0.83	46.5	8	9.3
28/12/2021	WET	5	0.83	85.6	14	17.6
08/01/2022	WET	3	0.50	48.2	8	16.2
18/02/2022	WET	6	1.00	26.4	4	4.4
25/02/2022	WET	6	1.00	42	7	7
28/02/2022	WET	5	0.83	21.7	4	9.7
07/03/2022	WET	6	1.00	174.4	29	29.2
18/03/2022	WET	3	0.50	75.4	13	25.4
26/03/2022	WET	3	0.50	90	15	30
27/03/2022	WET	3	0.50	90	15	30
02/04/2022	DRY	5	0.83	220	37	44

10/04/2022	DRY	5	0.83	152.4	25	30.6
18/04/2022	DRY	5	0.83	97.5	16	35.7
31/08/2022	DRY	4	0.67	17	3	5
16/09/2022	DRY	6	1.00	35.5	6	6
23/09/2022	DRY	5	0.83	116.8	19	23.6
01/10/2022	WET	6	1.00	42	7	7
04/10/2022	WET	6	1.00	78	13	13
15/10/2022	WET	3	0.50	43	7	17
08/11/2022	WET	6	1.00	92.2	15	21
14/11/2022	WET	4	0.67	65.4	11	17
30/11/2022	WET	3	0.50	105.6	18	35.2
07/12/2022	WET	6	1.00	109.8	18	18.3
17/12/2022	WET	6	1.00	1062	177	177
18/12/2022	WET	6	1.00	60	10	10
10/01/2023	WET	5	0.83	50	8	10
21/01/2023	WET	5	0.83	90	15	18
26/03/2023	WET	3	0.50	39	7	13

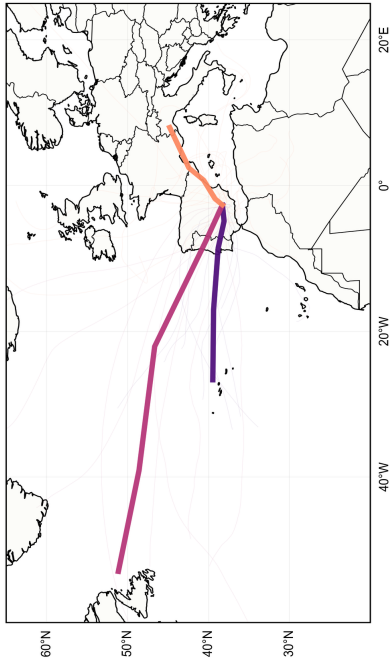
Table S3. Clustering diagnostics for backward air-mass trajectories associated with regionally coherent “days with rainfall”. Trajectories were computed for three arrival heights (500, 1500, and 3000 m above ground level) and clustered separately for wet (ONDJFM) and dry (AMJJAS) seasons using k-means applied to reduced trajectory vectors (longitude–latitude positions at fixed 24-hour lags). The table reports the initial number of requested clusters (K_{initial}), the final number retained after merging poorly populated clusters (K_{final}), the mean silhouette score, and cluster sizes. Silhouette scores are reported only when more than one regime was retained.

Season	Arrival height (m)	n trajectories	K_{initial}	K_{final}	Silhouette	Cluster sizes
WET	500	40	4	3	0.227	15 / 14 / 11
WET	1500	40	4	3	0.393	16 / 13 / 11
WET	3000	40	4	4	0.301	12 / 10 / 9 / 9
DRY	500	12	3	2	0.410	7 / 5
DRY	1500	12	3	1	-	12
DRY	3000	12	3	2	0.325	6 / 6

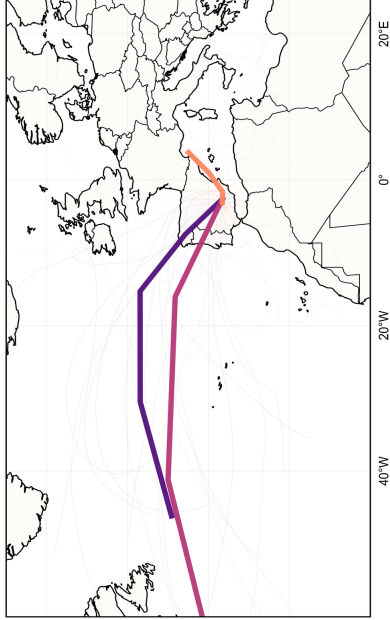
Fig. S3. Centroid trajectories of backward air-mass clusters for all season–altitude combinations. Panels show wet (ONDJFM) and dry (AMJJAS) seasons at arrival heights of 500, 1500, and 3000 m above ground level. Colored lines represent cluster-mean trajectories; faint lines indicate individual event-day

trajectories. The number of events (N) and final number of retained clusters (K_{final}) are indicated in each panel.

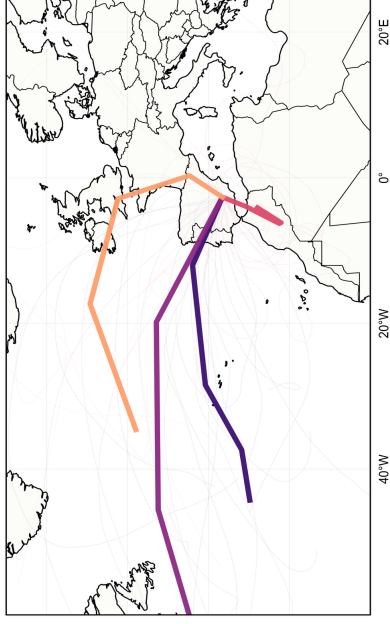
WET | 500 m | N=40 | K=3



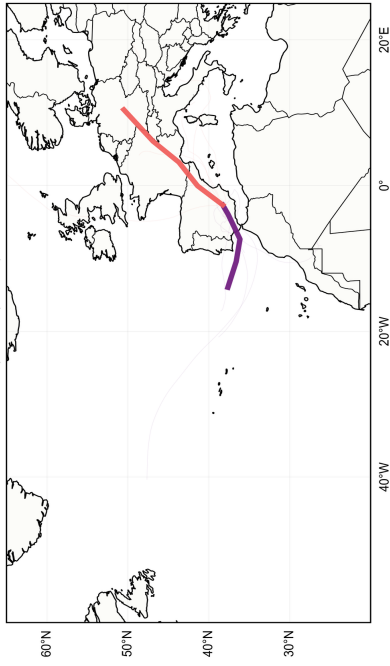
WET | 1500 m | N=40 | K=3



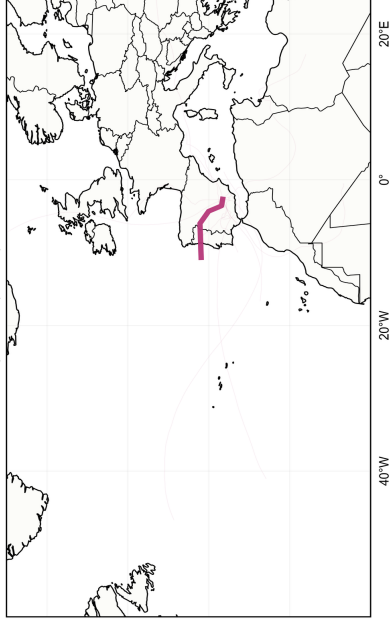
WET | 3000 m | N=40 | K=4



DRY | 500 m | N=12 | K=2



DRY | 1500 m | N=12 | K=1



DRY | 3000 m | N=12 | K=2

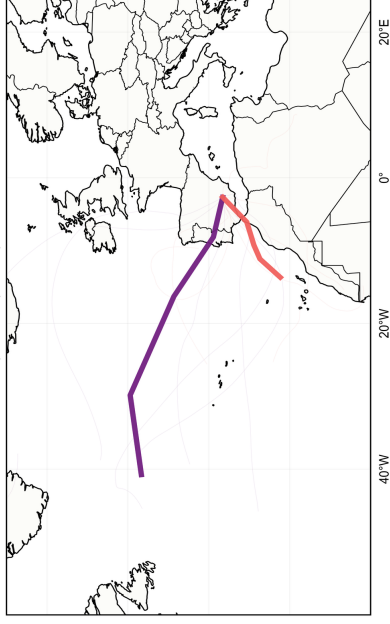


Fig. S4. Relative frequency of transport regimes across terciles of the North Atlantic Oscillation (NAOi) and Western Mediterranean Oscillation (WeMOi), computed exclusively from the subset of regionally coherent isotope-sampling event days. Bars are normalized within each tercile. Panels are organized by season (ONDJFM and AMJJAS) and arrival height (500, 1500, 3000 m).

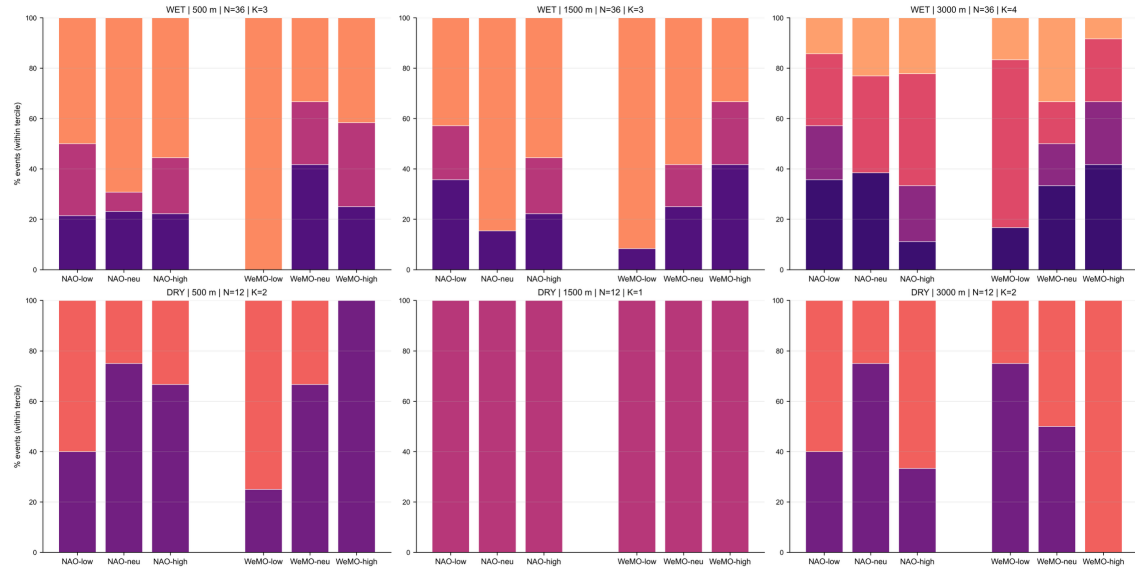


Table S4. Monte Carlo cross-validation metrics for seasonal Random Forest models. Performance statistics (mean \pm standard deviation across 200 shuffle-split iterations; 80/20 partition) for $\delta^{18}\text{O}$, d-excess (dex), and ^{17}O -excess (O17ex) models trained separately for wet (ONDJFM) and dry (AMJJAS) seasons. Metrics are computed from the full seasonal subsets after filtering complete cases.

A) $\delta^{18}\text{O}$

Season	n	R ² _mean	R ² _std	RMSE_mean (‰)	RMSE_std (‰)	MAE_mean (‰)	MAE_std (‰)
WET (ONDJFM)	145	0.481418	0.134589	1.432248	0.229698	1.095292	0.172097
DRY (AMJJAS)	52	0.602335	0.251697	1.459088	0.396206	1.095192	0.296274

B) d-excess (dex)

Season	n	R ² _mean	R ² _std	RMSE_mean (‰)	RMSE_std (‰)	MAE_mean (‰)	MAE_std (‰)
WET (ONDJFM)	145	0.430496	0.138091	2.342140	0.438665	1.702713	0.296442
DRY (AMJJAS)	52	0.347925	0.356473	3.633653	0.888150	2.760388	0.671739

C) ^{17}O -excess (O17ex)

Season	n	R ² _mean	R ² _std	RMSE_mean	RMSE_std	MAE_mean	MAE_std
WET (ONDJFM)	88	0.195460	0.231071	9.706677	1.737611	7.749563	1.392844
DRY (AMJJAS)	37	0.395831	0.404389	10.822799	2.700140	8.660346	2.216742

Fig. S5. $\delta^{18}\text{O}$ impurity-based feature importance and permutation importance (ΔR^2) for wet (ONDJFM) and dry (AMJJAS) seasonal $\delta^{18}\text{O}$ models.

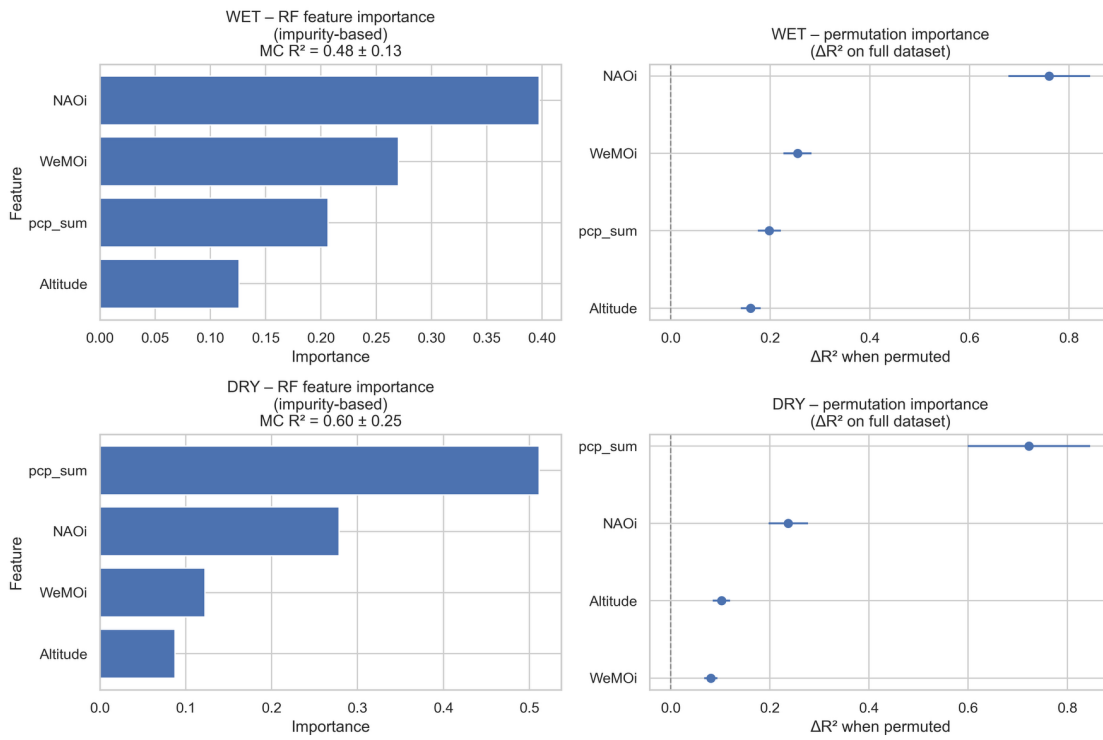


Fig. S6. d-excess impurity-based feature importance and permutation importance (ΔR^2) for wet (ONDJFM) and dry (AMJJAS) seasonal models.

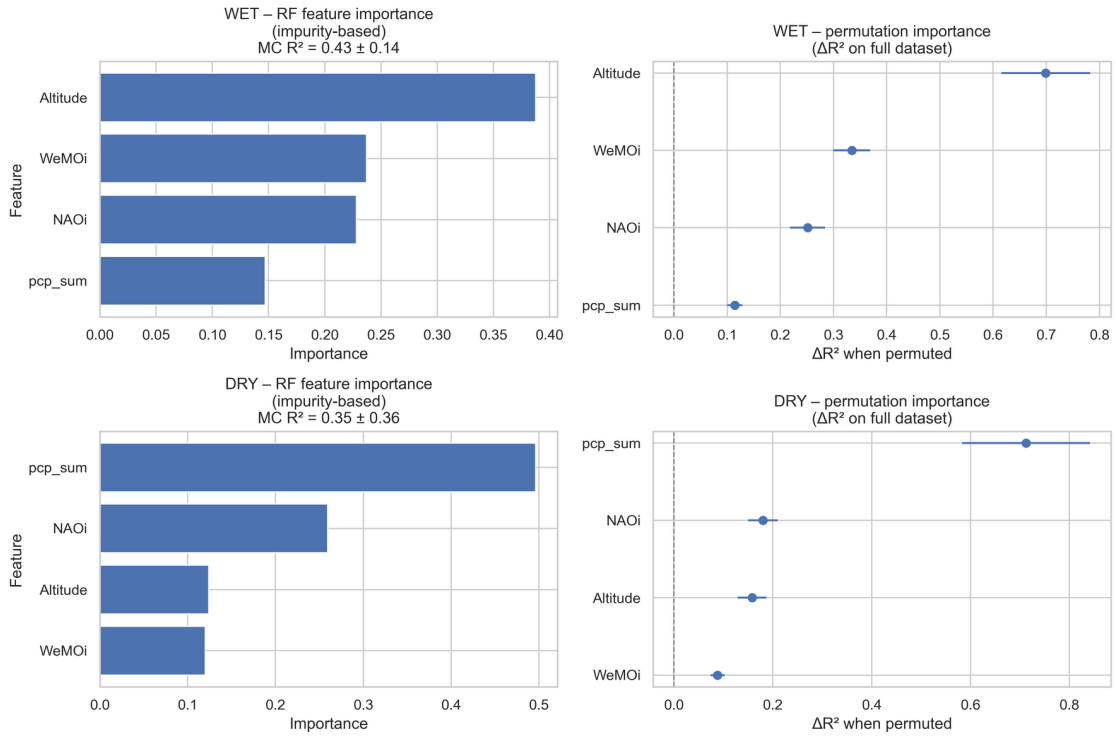


Fig. S7. ^{17}O -excess impurity-based feature importance and permutation importance (ΔR^2) for wet (ONDJFM) and dry (AMJJAS) seasonal models.

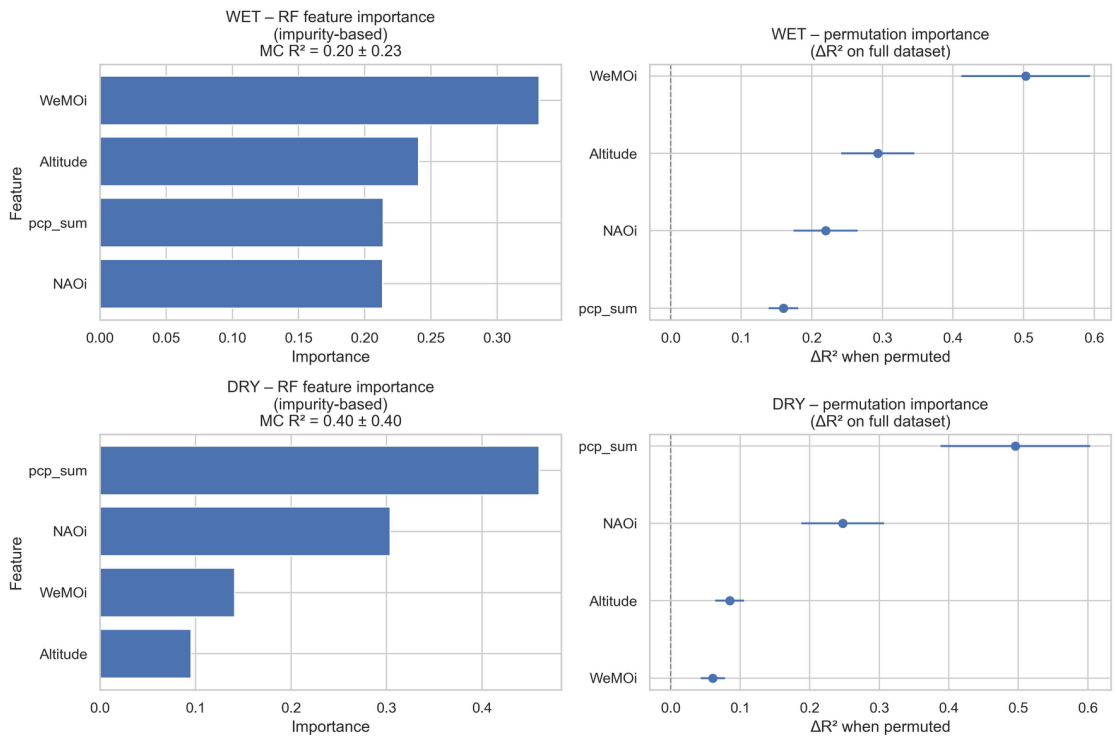


Fig. S8. SHAP interpretation of seasonal d-excess models.

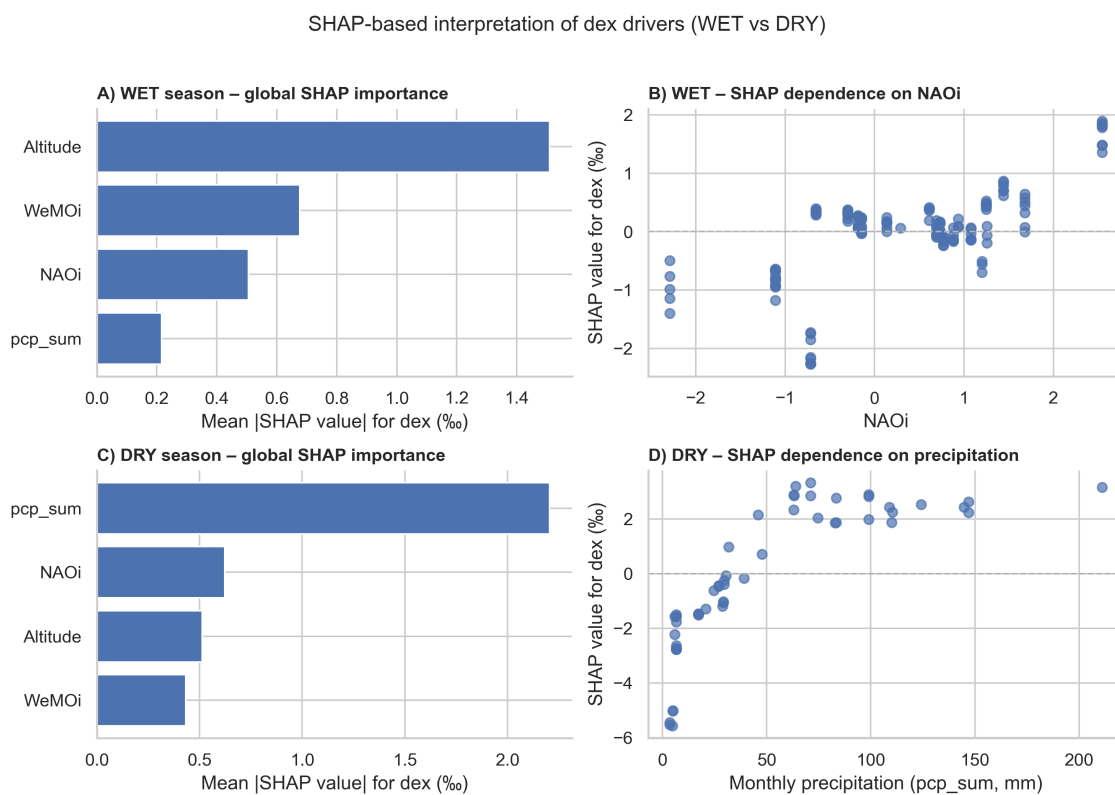


Fig. S9. SHAP interpretation of seasonal ^{17}O -excess models.

SHAP-based interpretation of O17ex drivers (WET vs DRY)

