Table 1: **Changes in hydroclimatic interdependence from *mid-* to *end of century*.** Dependence links detected by Granger Causality (GC; linear, $p < 0.05$) and RF-SHAP (nonlinear, $D_V > 0.015$). Arrows: $\rightarrow$ = unidirectional (GC), $\Rightarrow$ = predictive influence (RF-SHAP); $\uparrow/\downarrow$ = positive/negative influence direction. Agreement threshold: $\geq$40% of five CMIP6 models. Key structural shifts between mid- and end-of-century are highlighted.

Region	Period	SSP	GC (linear)	Agreement	RF-SHAP (nonlinear)	Driver Roles	Agreement
NSZ (JJA)	Mid	1-2.6	$T \rightarrow prw$	<50%	SM $\Rightarrow T\downarrow, prw\downarrow, Pr\uparrow$; E $\Rightarrow T\downarrow, prw\downarrow, Pr\downarrow$; $prw \Rightarrow T\uparrow, Pr\uparrow, E\downarrow$	SM, E: dominant drivers; prw: super-node	60–100%
	Mid	5-8.5	$T \leftrightarrow prw$	<50%	SM $\Rightarrow T\downarrow, prw\downarrow, Pr\uparrow$; Pr $\Rightarrow prw\uparrow, E\downarrow, q\uparrow$; $q \Rightarrow T\downarrow, prw\downarrow, Pr\uparrow$	SM: dominant driver; Pr, q: super-nodes	60–100%
	End	1-2.6	SM $\rightarrow$ Pr, SM $\rightarrow q$	<50% (weak–mod)	SM $\Rightarrow T\downarrow, prw\uparrow$ (sign reversal), $Pr\downarrow$ (sign reversal), $q\uparrow$	SM: dominant driver	60–100%
	End	5-8.5	SM $\rightarrow q$	<50% (weak–mod)	SM $\Rightarrow T\downarrow, prw\uparrow$ (sign reversal), $Pr\uparrow, q\uparrow$; E $\Rightarrow T\downarrow, prw\downarrow, Pr\downarrow$	SM, E: dominant drivers	60–100%
SSZ (JJA)	Mid	1-2.6	$T \rightarrow Pr$, $prw \rightarrow Pr$	<50%	SM $\Rightarrow prw\uparrow, Pr\uparrow, E\uparrow$	SM: dominant driver	60–100%
	Mid	5-8.5	SM $\rightarrow prw$	<50% (weak)	SM $\Rightarrow prw\uparrow, Pr\uparrow, E\uparrow$; $T \Rightarrow prw\uparrow, Pr\uparrow, E\uparrow$; $q \Rightarrow T\uparrow, prw\uparrow, Pr\uparrow, E\uparrow$	SM: dominant driver; T, q: super-nodes	60–100%
	End	1-2.6	$SM \rightarrow prw$	<50%	SM $\Rightarrow T\downarrow, prw\uparrow, Pr\uparrow, E\downarrow$ (sign reversal); $prw \Rightarrow T\uparrow, Pr\uparrow, E\downarrow$	SM: dominant driver; prw: super-node	60–100%
	End	5-8.5	$prw \rightarrow Pr$	<50%	SM $\Rightarrow T\downarrow, prw\uparrow, Pr\uparrow$; $T \Rightarrow prw\uparrow, Pr\downarrow, E\uparrow$	SM: dominant driver; T: super-node	60–100%
NMZ (DJF)	Mid	1-2.6	Few; insufficient agree.	<40%	SM $\Rightarrow T\downarrow$; $prw \Rightarrow T\uparrow, Pr\uparrow, E\downarrow$; $T \Rightarrow prw\uparrow, Pr\downarrow$	SM: dominant driver; prw, T: super-nodes	60–100%
	Mid	5-8.5	$prw \rightarrow$ SM	<50%	SM $\Rightarrow T\downarrow, Pr\uparrow, E\uparrow$	SM: dominant driver	60–100%
	End	1-2.6	Few; insufficient agree.	<40%	SM $\Rightarrow T\downarrow, Pr\uparrow, E\downarrow$; E $\Rightarrow T\downarrow$; $prw\downarrow, Pr\uparrow$; Pr $\Rightarrow q\uparrow$	SM : dominant driver; E, Pr: super-nodes	60–100%
	End	5-8.5	Few; insufficient agree.	<40%	SM $\Rightarrow T\uparrow$ (sign reversal), $prw\downarrow, Pr\uparrow, E\uparrow$; Pr $\Rightarrow T\uparrow, prw\uparrow, q\uparrow$	SM: dominant driver; Pr: super-node	60–100%
SMZ (DJF)	Mid	1-2.6	Few; insufficient agree.	<40%	E $\Rightarrow prw\downarrow, Pr\uparrow$	E: dominant driver	60–100%
	Mid	5-8.5	$q \rightarrow prw$	<50% (Weak)	No dominant driver (insufficient agreement)	None	<60%
	End	1-2.6	Few; insufficient agree.	<40%	SM $\Rightarrow prw\uparrow, Pr\uparrow$	SM: dominant driver	60–100%
	End	5-8.5	$T \rightarrow Pr$	<50%	SM $\Rightarrow prw\uparrow, Pr\uparrow, T\uparrow$; E $\Rightarrow prw\downarrow, Pr\uparrow$; $prw \Rightarrow T\uparrow, Pr\uparrow, E\uparrow$	SM, E: dominant drivers; prw: super-node	60–100%

Table 2: **Mechanistic explanations for observed shifts in hydroclimatic interdependence.** Findings classified as **New** (first reported here), **Extended** (builds on prior work with new regional/seasonal detail), or **Confirmed** (consistent with established literature). References cite supporting or contrasting studies.

Region	Status	Finding	Mechanistic Explanation	References
NSZ (JJA)	[Confirmed]	SM→ T negative coupling consistent across periods	SM decline → ↓latent heat → ↑sensible heat flux → surface warming (well-established land–atmosphere feedback)	Seneviratne et al. (2006, 2010)
	[New]	SM→Pr sign reversal under SSP5-8.5 (neg → pos at end-century)	Under sustained warming, SM enhances atmospheric moisture via evaporation; thermodynamic moisture-availability pathway persists. Under SSP1-2.6 stabilized forcing, circulation-mediated negative feedback dominates	Zhou et al. (2019); Hsu & Dirmeyer (2023)
	[New]	E emerges as co-dominant driver at end-century SSP5-8.5	Shift from memory-driven (SM storage) to flux-driven (soil–water–atmosphere exchange) dynamics under intensified radiative forcing	Seneviratne et al. (2010); Sun et al. (2025)
	[Extended]	prw super-node: enhances T, Pr but suppresses E	Thermodynamic control: ↑prw → ↑T (greenhouse) + ↑Pr (moisture supply) but ↓E (reduced VPD under humid conditions)	Fujita & Sato (2017); Wentz et al. (2007)
	[Extended]	Super-CC scaling (8–13%/°C) vs global ∼7%/°C	Land-dominated hemisphere: enhanced surface warming → greater moisture capacity divergence from ocean-dominated regions	Silva & Haerter (2025); Douville et al. (2022)
	[Confirmed]	↓Pr despite ↑prw	Hadley cell expansion shifts subtropical highs poleward → increased aridity despite greater column moisture	Grise & Davis (2020); Schmidt & Grise (2017)
SSZ (JJA)	[New]	SM→E sign reversal (pos → neg at end-century)	Regime shift: SM crosses critical threshold → E decouples from SM and becomes controlled by VPD; transition from energy-limited to moisture-limited regime	Hsu & Dirmeyer (2023); Seneviratne et al. (2010)
	[New]	Hemispheric phase lag: SSZ mid-century ≈ NSZ end-century	Asynchronous transition toward moisture-limited coupling; temporally staggered structural reorganization across hemispheres	**Not previously reported**
	[Extended]	Sub-CC scaling (3–4%/°C)	Ocean-dominated hemisphere: weaker surface warming → limited moisture capacity divergence vs. land-dominated NH	Feulner et al. (2013); Douville et al. (2022)
	[Confirmed]	Largest P–E deficit (∼11.8 km^3/day JJA)	Hadley expansion + enhanced evaporative demand → Budyko steady-state breakdown; E/Pr → 1 violated	Budyko (1958); Konapala et al. (2020)
	[Extended]	T as persistent super-node under SSP5-8.5	T enhances prw and E through thermodynamic scaling; T→Pr shifts pos → neg reflecting strengthened SM–T coupling	Seneviratne et al. (2006, 2010)
NMZ (DJF)	[New]	SM→ T sign reversal (neg → pos under SSP5-8.5 end-century)	months with soil moisture also shows high temperature indicating enhanced long wave radiation influenced warming	Seneviratne et al. (2006); **sign reversal is new**
	[Confirmed]	SM consistently enhances Pr (SM→Pr positive)	Positive soil moisture–precipitation feedback: SM → ↑E → ↑boundary-layer moisture → ↑convective triggering	Sun et al. (2025); Seneviratne et al. (2010)
	[Extended]	SM–E sensitivity to radiative forcing	Under SSP1-2.6 (stabilized): E decouples from SM; under SSP5-8.5 (sustained): E remains SM-coupled due to persistent moisture demand	Hsu & Dirmeyer (2023)
	[New]	q variance ≫ mean shifts (ΔDJF: q = 51.46% vs SM = −2.42%)	SM decline + Pr increase → reduced infiltration + enhanced surface runoff → flood hazard amplification concurrent with drought	Ghajarnia et al. (2020); **divergence is new**
	[Confirmed]	T→prw positive but T→Pr negative (mid SSP1-2.6)	Thermodynamic scaling: warming increases moisture capacity but Pr constrained by dynamic moisture convergence	Wentz et al. (2007)
SMZ (DJF)	[New]	SM emerges as driver only at end-century	Southern Ocean cooling buffers warming → delayed crossing of SM-coupling thresholds relative to NH regions	Kang et al. (2023); **first reported for SM coupling**
	[Extended]	E→prw negative but E→Pr positive	Increased precipitation efficiency potentially influenced by wind dynamics; E reduces atmospheric moisture but enhances convective triggering	Gao et al. (2026)
	[New]	No super-nodes at mid-century SSP5-8.5	Insufficient inter-model agreement suggests inherently high structural uncertainty in ocean-dominated regions under high forcing	**Not previously reported**
	[Confirmed]	Weakest hemispheric coupling response	Higher ocean fraction → greater thermal inertia → subdued land–atmosphere feedbacks relative to NH	Xu & Ramanathan (2012); Armstrong (2013)