Supplementary material for "Disentangling the anthropogenic climate change influence on recent hydroclimate whiplash events via multiple nudged model simulations"

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CEMS2	Variable	Precipitaion						PET						Event	Decision
	Timeperiod	Historic (1980-2024)			Present (2017-2024)			Historic (1980-2024)			Present (2017-2024)				
	Simulation	Nudged simulation			Nudged simulation			Nudged simulation			Nudged simulation				
Region	Index	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal		
Northern Middle East	SPEI-3	reasonable	good	reasonable	reasonable	good	reasonable	good	good	good	good	good	good	yes	yes
Southern China	SPEI-3	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	good	good	good	good	good	yes	yes
East Africa	SPEI-3	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	good	reasonable	reasonable	good	no	no
West Africa	SPEI-3	reasonable	reasonable	good	bad	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	no	no
Northern Europe	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	yes	yes
North-Central USA	SPEI-12	good	good	good	reasonable	good	good	good	good	good	good	good	good	yes	yes
Pacific Southwest	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	yes	yes
Patagonia	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	yes	yes
Southeast Australia	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	yes	yes
Central America	SPEI-12	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	good	good	reasonable	good	good	yes	yes

S1: Final results of the CESM2 model evaluation. A detailed description of the decision criteria is provided in the Methods section and Table 1. The final column “Decision” specifies whether the model is used for each region. The row “Time period” distinguishes between the event period (2017–2024) and the calibration period (1980–2024). The row “Simulation” specifies the individual climate model run with further details given in the Methods.

IFS-FESOM	Variable	Precipitaion						PET						Event	Decision
	Timeperiod	Historic (1980-2014)			Present (2017-2024)			Historic (1980-2014)			Present (2017-2024)				
	Simulation	Free running simulation			Nudged simulation			Free running simulation			Nudged simulation				
Region	Index	Anomalies	Spatial	Temporal	PearsonR	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal		
Northern Middle East	SPEI-3	bad	good	reasonable	good	good	reasonable	bad	good	reasonable	good	good	good	yes	yes
Southern China	SPEI-3	bad	good	good	good	good	good	bad	good	good	good	good	good	yes	yes
East Africa	SPEI-3	bad	reasonable	reasonable	good	reasonable	reasonable	bad	reasonable	good	good	good	good	yes	yes
West Africa	SPEI-3	bad	reasonable	good	reasonable	good	good	bad	good	good	reasonable	good	good	no	no
Northern Europe	SPEI-12	bad	good	good	good	good	good	bad	good	good	good	good	good	yes	yes
North-Central USA	SPEI-12	bad	good	good	good	good	good	bad	good	good	good	good	good	yes	yes
Pacific Southwest	SPEI-12	bad	good	good	good	good	good	bad	good	good	good	good	good	yes	yes
Patagonia	SPEI-12	bad	good	reasonable	good	good	good	bad	good	good	good	good	good	no (not in t)	no
Southeast Australia	SPEI-12	bad	good	good	good	good	good	bad	good	good	good	good	good	yes	yes
Central America	SPEI-12	bad	reasonable	good	good	reasonable	good	bad	good	good	good	good	good	yes	yes

S2: Final results of the IFS-FESM model evaluation. A detailed description is provided for S1.

AWI-CM-1	Variable	Precipitation																	
	Timeperiod	Historic (1980-2024)			Present (2017-2024)														
	Simulation	Long-nudged simulation			Short-nudged simulation														
	Ensemble	E1			E1			E2			E3			E4			E5		
Region	Index	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal
Northern Middle East	SPEI-3	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable
Southern China	SPEI-3	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good
East Africa	SPEI-3	bad	reasonable	reasonable	bad	reasonable	good	bad	reasonable	good	bad	reasonable	good	bad	reasonable	good	bad	reasonable	good
West Africa	SPEI-3	bad	reasonable	good	bad	reasonable	good	bad	reasonable	good	bad	reasonable	good	bad	reasonable	good	bad	reasonable	good
Northern Europe	SPEI-12	reasonable	good	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable
North-Central USA	SPEI-12	reasonable	good	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable
Pacific Southwest	SPEI-12	reasonable	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Patagonia	SPEI-12	reasonable	reasonable	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable
Southeast Australia	SPEI-12	reasonable	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	reasonable	reasonable	reasonable	good	reasonable	reasonable
Central America	SPEI-12	reasonable	reasonable	good	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable

S3: Final results of the AWI-CM-1 model evaluation. A detailed description is provided for S1. Part 1/3.

AWI-CM-1	Variable	PET																	
	Timeperiod	Historic (1980-2024)			Present (2017-2024)														
	Simulation	Long-nudged simulation			Short-nudged simulation														
	Ensemble	E1			E1			E2			E3			E4			E5		
Region	Index	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal
Northern Middle East	SPEI-3	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Southern China	SPEI-3	reasonable	good	good	reasonable	good	good	reasonable	good	good	reasonable	good	good	reasonable	good	good	reasonable	good	good
East Africa	SPEI-3	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good
West Africa	SPEI-3	reasonable	reasonable	good	reasonable	good	good	reasonable	good	good	reasonable	good	good	reasonable	good	good	reasonable	good	good
Northern Europe	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
North-Central USA	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Pacific Southwest	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Patagonia	SPEI-12	good	reasonable	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Southeast Australia	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Central America	SPEI-12	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good

S4: Final results of the AWI-CM-1 model evaluation. A detailed description is provided for S1. Part 2/3.

AWI-CM-1	Variable	Whiplash Intensity					Decision
	Timeperiod	Event Time					
	Simulation	Short-nudged simulation					
	Ensemble	E1	E2	E3	E4	E5	
Region	Index	Event	Event	Event	Event	Event	
Northern Middle East	SPEI-3	yes	yes	yes	yes	yes	yes
Southern China	SPEI-3	yes	yes	yes	yes	yes	yes
East Africa	SPEI-3	no	no	no	no	no	no
West Africa	SPEI-3	no	no	no	no	no	no
Northern Europe	SPEI-12	yes	yes	yes	yes	yes	yes
North-Central USA	SPEI-12	yes	yes	yes	yes	yes	yes
Pacific Southwest	SPEI-12	yes	yes	yes	yes	yes	yes
Patagonia	SPEI-12	yes	yes	yes	yes	yes	yes
Southeast Australia	SPEI-12	yes	yes	yes	yes	yes	yes
Central America	SPEI-12	no	no	yes	no	no	no

S5: Final results of the AWI-CM-1 model evaluation. A detailed description is provided for S1. Part 3/3.

ECHAM6	Variable	Precipitation																	
	Timeperiod	Historic (1980-2024)			Present (2017-2024)														
	Simulation	Long-nudged simulation			Short-nudged simulation														
	Ensemble	E1			E1			E2			E3			E4			E5		
Region	Index	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal
Northern Middle East	SPEI-3	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable
Southern China	SPEI-3	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good
East Africa	SPEI-3	reasonable	reasonable	reasonable	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good
West Africa	SPEI-3	bad	reasonable	good	bad	reasonable	good	bad	reasonable	good	bad	reasonable	good	bad	reasonable	good	bad	reasonable	good
Northern Europe	SPEI-12	good	good	reasonable	good	good	reasonable	good	good	reasonable	good	good	reasonable	good	good	reasonable	good	good	reasonable
North-Central USA	SPEI-12	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable
Pacific Southwest	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Patagonia	SPEI-12	reasonable	good	reasonable	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good
Southeast Australia	SPEI-12	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable	good	reasonable	reasonable
Central America	SPEI-12	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable	reasonable

S6: Final results of the ECHAM6 model evaluation. A detailed description is provided for S1. Part 1/3.

ECHAM6	Variable	PET																	
	Timeperiod	Historic (1980-2024)			Present (2017-2024)														
	Simulation	Long-nudged simulation			Short-nudged simulation														
	Ensemble	E1			E1			E2			E3			E4			E5		
Region	Index	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal	Anomalies	Spatial	Temporal
Northern Middle East	SPEI-3	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Southern China	SPEI-3	reasonable	good	good	resonable	good	good	resonable	good	good	resonable	good	good	resonable	good	good	resonable	good	good
East Africa	SPEI-3	reasonable	reasonable	good	resonable	reasonable	good	resonable	reasonable	good	resonable	reasonable	good	resonable	reasonable	good	resonable	reasonable	good
West Africa	SPEI-3	reasonable	good	good	resonable	good	good	resonable	good	good	resonable	good	good	resonable	good	good	resonable	good	good
Northern Europe	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
North-Central USA	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Pacific Southwest	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Patagonia	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Southeast Australia	SPEI-12	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good	good
Central America	SPEI-12	reasonable	good	good	resonable	reasonable	good	resonable	reasonable	good	resonable	reasonable	good	resonable	reasonable	good	resonable	reasonable	good

S7: Final results of the ECHAM6 model evaluation. A detailed description is provided for S1. Part 2/3.

ECHAM6	Variable	Whiplash Intensity					Decision
	Timeperiod	Event Time					
	Simulation	Short-nudged simulation					
	Ensemble	E1	E2	E3	E4	E5	
Region	Index	Event	Event	Event	Event	Event	
Northern Middle East	SPEI-3	yes	yes	yes	yes	yes	yes
Southern China	SPEI-3	yes	yes	yes	yes	yes	yes
East Africa	SPEI-3	no	no	no	no	no	no
West Africa	SPEI-3	no	no	no	no	no	no
Northern Europe	SPEI-12	yes	yes	yes	yes	yes	yes
North-Central USA	SPEI-12	yes	yes	yes	yes	yes	yes
Pacific Southwest	SPEI-12	yes	yes	yes	yes	yes	yes
Patagonia	SPEI-12	yes	yes	yes	yes	yes	yes
Southeast Australia	SPEI-12	yes	yes	yes	yes	yes	yes
Central America	SPEI-12	no	no	no	no	no	no

S8: Final results of the ECHAM6 model evaluation. A detailed description is provided for S1. Part 3/3.

Supplementary Discussion

The Hargreaves and Samani (1985) formulation is commonly written as:

$$PET = K * R_a * (T + 17.8) * \sqrt{\Delta T} \quad (1)$$

where K is a coefficient, R_a the extraterrestrial radiation, T the mean daily temperature (in °Celcius) and ΔT the daily diurnal temperature range. Given that only T_{min} and T_{max} is provided, T and ΔT is defined via:

$$T = \frac{T_{max} + T_{min}}{2} \quad (2)$$

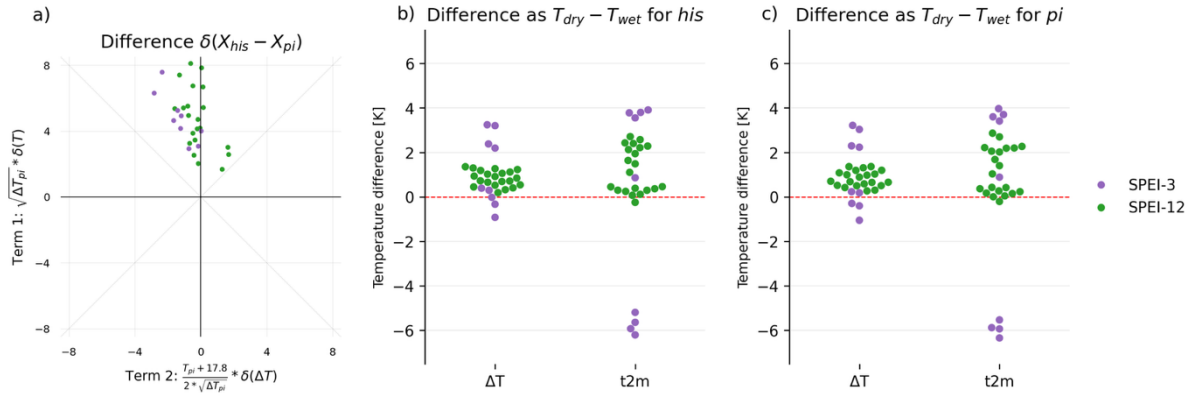
$$\Delta T = T_{max} - T_{min} \quad (3)$$

To identify the dominant contributions to the change δ between the factual (his) and counterfactual (pi) simulations, we approximate δPET using a first-order Taylor expansion based on the partial derivatives of PET (Eq 1) with respect to T and ΔT:

$$\delta PET \approx K * R_a * \left[\sqrt{\Delta T_{pi}} * \delta T + \frac{T_{pi} + 17.3}{2 * \sqrt{\Delta T_{pi}}} * \delta(\Delta T)\right] \quad (4)$$

Figure S9a compares the contributions of the two terms, and clearly shows that the first term clearly dominates changes in PET and global warming predominantly affects mean temperature. This supports the conclusion presented in the main text that the larger baseline ΔT during dry phases (Figure S9 b,c) leads to stronger PET increases compared to the wet phase.

However, absolute differences in PET do not directly translate into comparabel changes in SPEI, as the underlying log-logistic distribution is calibrated individually for each grid cell and month. At the annual timescale (SPEI-12), this effect has only a minor influence, as variability in the distribution is reduced. For SPEI-3, however, the recalibration could potentially lead to different responses, although this does not appear to be the case for the events shown in figure 3 in the main text.



S9: Details about the driving factors of changes in PET under the hargeaves formulation. Dots represent all model-event combinations that pass the evaluation and are retained for the analysis. Purple dots correspond to the three SPEI-3 events; green dots correspond to the six SPEI-12 ones. T_{min} and T_{max} are computed as aggregated rolling means matching the respective SPEI accumulation period. All values are spatially averaged over the event

region. **a** shows the two terms of equation (4) on the x- and y-axis, comparing the historical and pre-industrial simulation. The input values are temporally averaged over the event period. **b** shows the difference in T and ΔT between the dry and wet phases for the historical simulation. The phases are derived by the start and end dates of the event period. **c** shows the same than b), but for the pre-industrial simulation.