



Supplement of

Future intensification of compound and consecutive drought and heat-wave risks in Europe

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Contents of this file

Figure S1. Comparison of total number of drought and heatwave events between ERA5 Land and ISIMIP models across Europe

Figure S2. Binary time series of drought, heatwave, and compound event in Germany from January 2018 to December 2019.

Figure S3. Changes (future-reference periods) in drought characteristics across Europe under SSP1-2.6 based on the median ensemble of the ISIMIP models.

Figure S4. Drought hotspot regions derived from the number of drought event across Europe.

Figure S5. Changes (future-reference periods) in heatwave characteristics across Europe under SSP1-2.6 based on the median ensemble of the ISIMIP models.

Figure S6. Heatwave hotspot regions derived from the number of heatwave event across Europe.

Figure S7. Changes (future-reference periods) in compound event characteristics across Europe under SSP1-2.6 based on the median ensemble of the ISIMIP models.

Figure S8. Changes (future-reference periods) in consecutive event characteristics across Europe under SSP5-8.5.

Figure S9. Changes (future-reference periods) in consecutive event characteristics across Europe under SSP1-2.6.

Figure S10. Subregions of Europe.

Figure S11. The Relative Operating Curve (ROC) for the trained ML models to predict historical impacted sectors.

Figure S12. Simulations of drought and heatwave impacts in Germany using the ML model for reference period (1953-2014).

Table S1. Data and models used in the study

Table S2. Definition of drought and heatwave characteristics as singly and CnC

Table S3. The characteristics of drought and heatwave impacts on economic, non-economic, ecosystem, and human sectors derived from reference period and future scenarios.

Introduction

This supplementary information comprises 11 Supplementary Figures and three Supplementary Tables.

Supplementary Figure

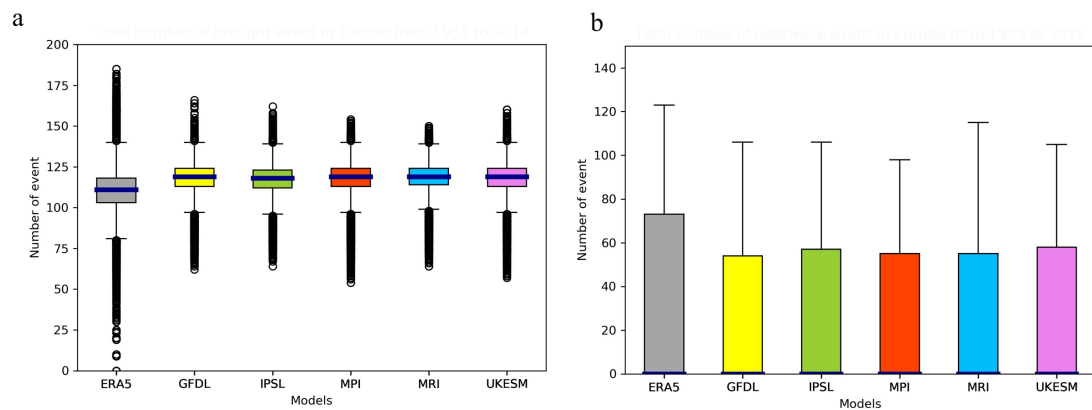


Figure S1. a) Comparison of total number of drought events between ERA5 Land and ISIMIP models across Europe from 1953 to 2014 and b) Comparison of total number of heatwave events between ERA5 Land and ISIMIP models across Europe from 1953 to 2022.

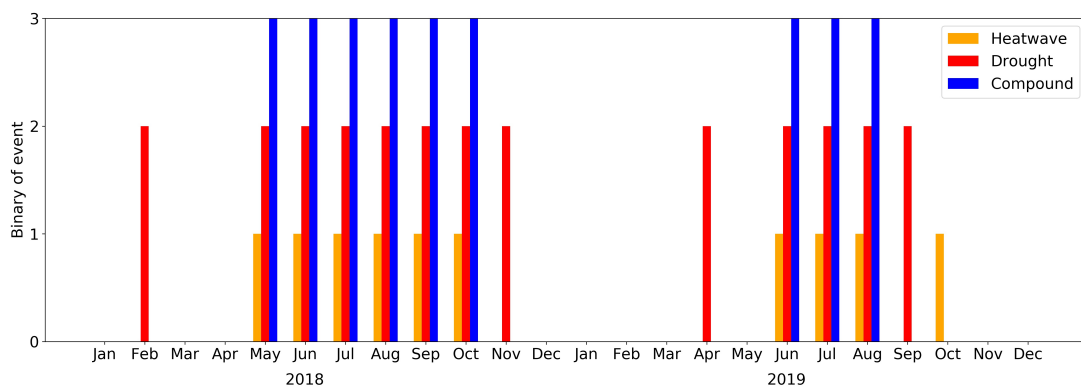


Figure S2. Binary time series of drought, heatwave, and compound event in Germany from January 2018 to December 2019.

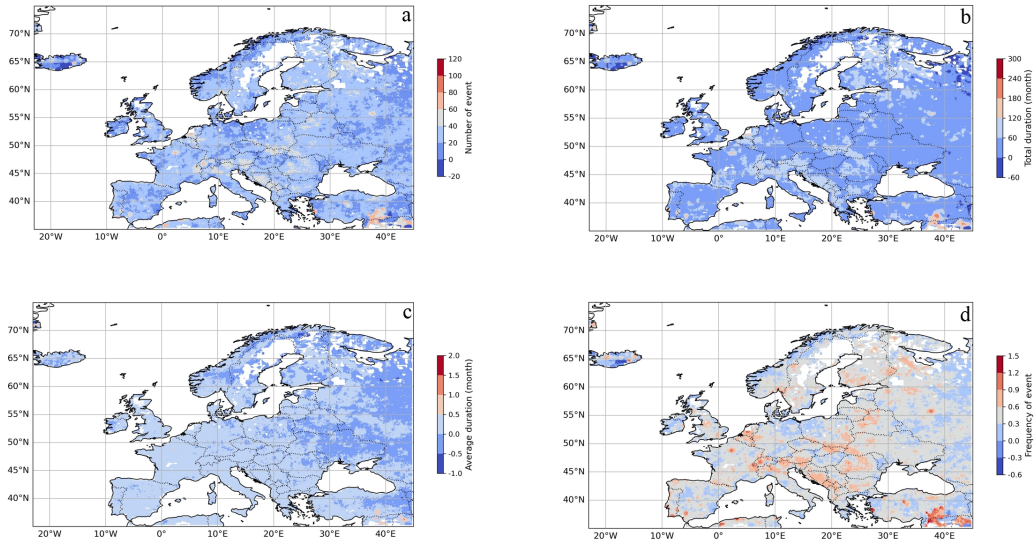


Figure S3. Changes (future-reference periods) in drought characteristics across Europe under SSP1-2.6 based on the median ensemble of the ISIMIP models. (a) Changes in the number of drought events, (b) changes in total drought duration in month, (c) changes in average drought duration in month, and (d) changes in frequency.

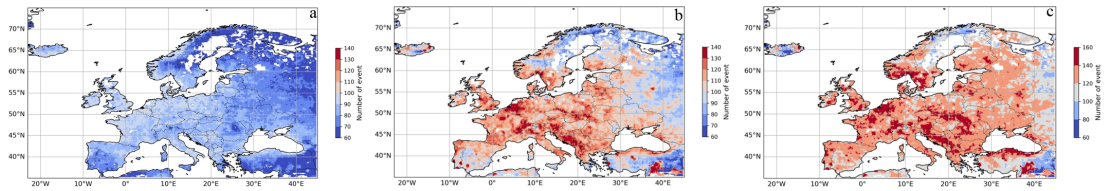


Figure S4. Drought hotspot regions derived from the number of drought event across Europe. (a) Hotspot regions based on historical period (1953-2014), (b) hotspot regions based on future period under SSP1-2.6 (2039-2100), and (c) hotspot regions based on future period under SSP5-8.5 (2039-2100). The number of drought event was obtained from the median ensemble of the ISIMIP models.

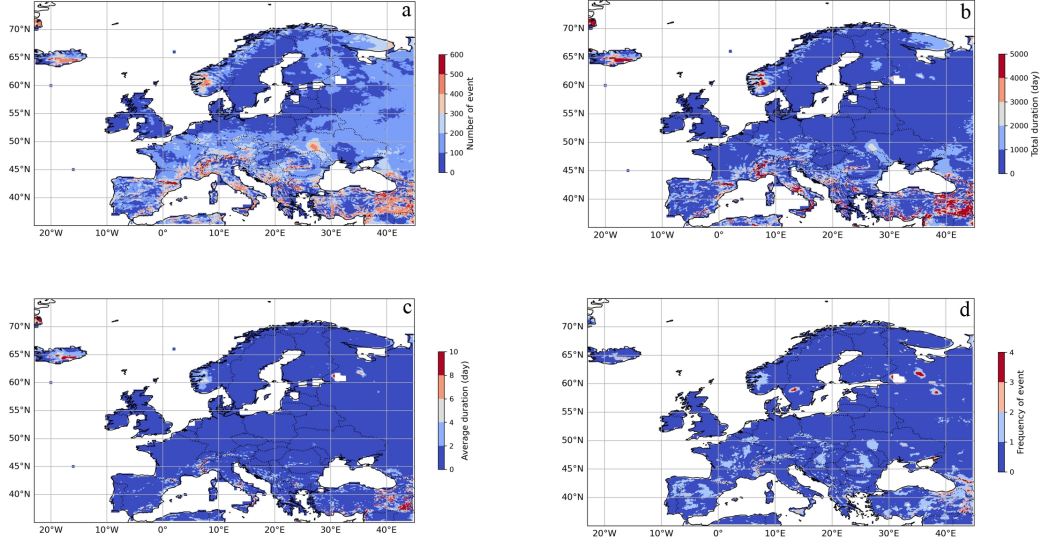


Figure S5. Changes (future-reference periods) in heatwave characteristics across Europe under SSP1-2.6 based on the median ensemble of the ISIMIP models. (a) Changes in the number of heatwave events, (b) changes in total heatwave duration in day, (c) changes in average heatwave duration in day, and (d) changes in frequency.

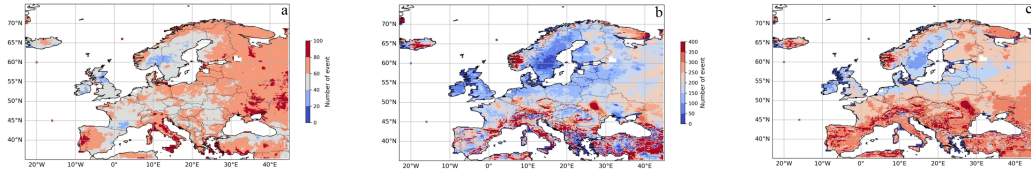


Figure S6. Heatwave hotspot regions derived from the number of heatwave event across Europe. (a) Hotspot regions based on historical period (1953-2014), (b) hotspot regions based on future period under SSP1-2.6 (2039-2100), and (c) hotspot regions based on future period under SSP5-8.5 (2039-2100). The number of heatwave event was obtained from the median ensemble of the ISIMIP models.

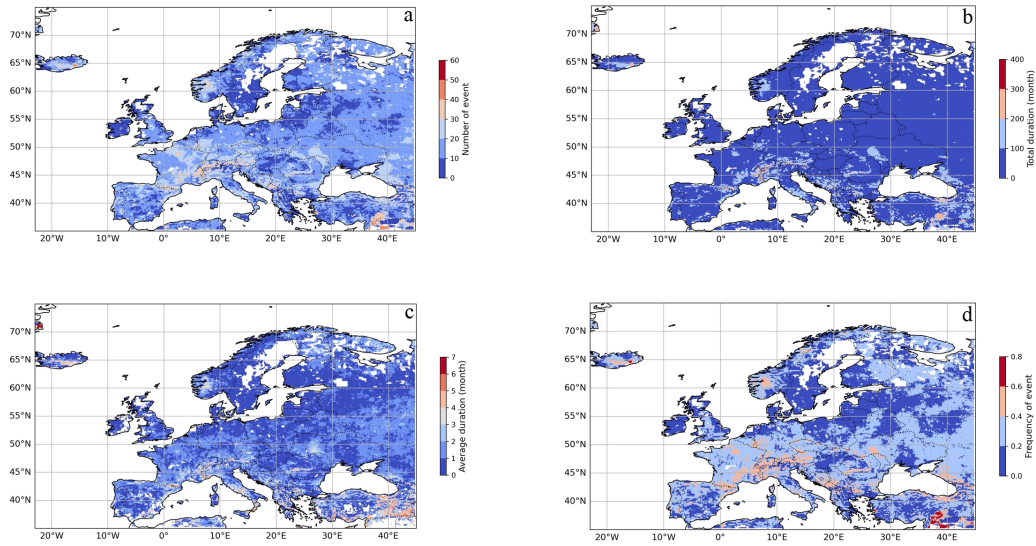


Figure S7. Changes (future-reference periods) in compound event characteristics across Europe under SSP1-2.6 based on the median ensemble of the ISIMIP models. (a) Changes in the number of compound events, (b) changes in total compound duration in day, (c) changes in average compound duration in day, and (d) changes in compound frequency.

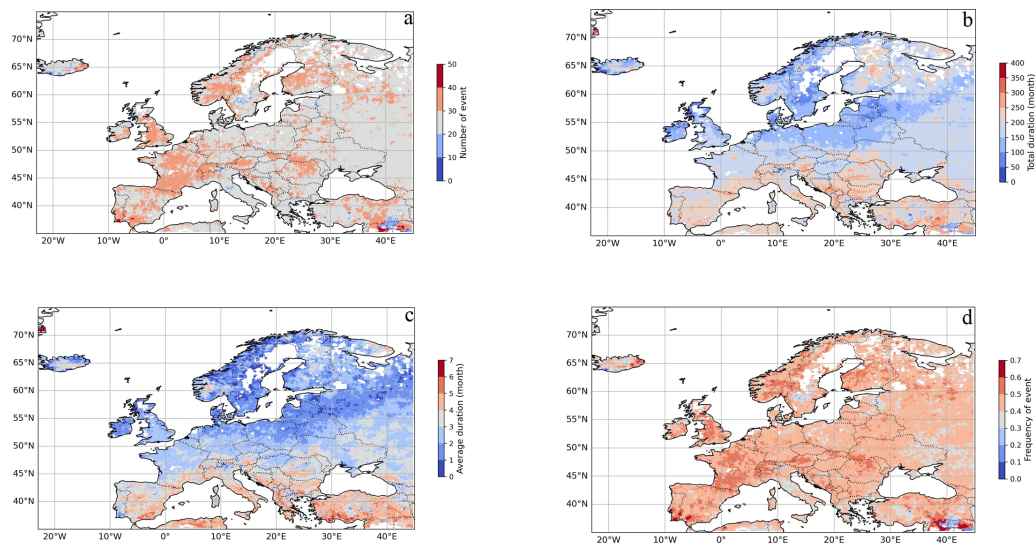


Figure S8. Changes (future-reference periods) in consecutive event characteristics across Europe under SSP5-8.5. (a) Changes in the number of consecutive events, (b) changes in total consecutive duration in day, (c) changes in average consecutive duration in day, and (d) changes in consecutive frequency.

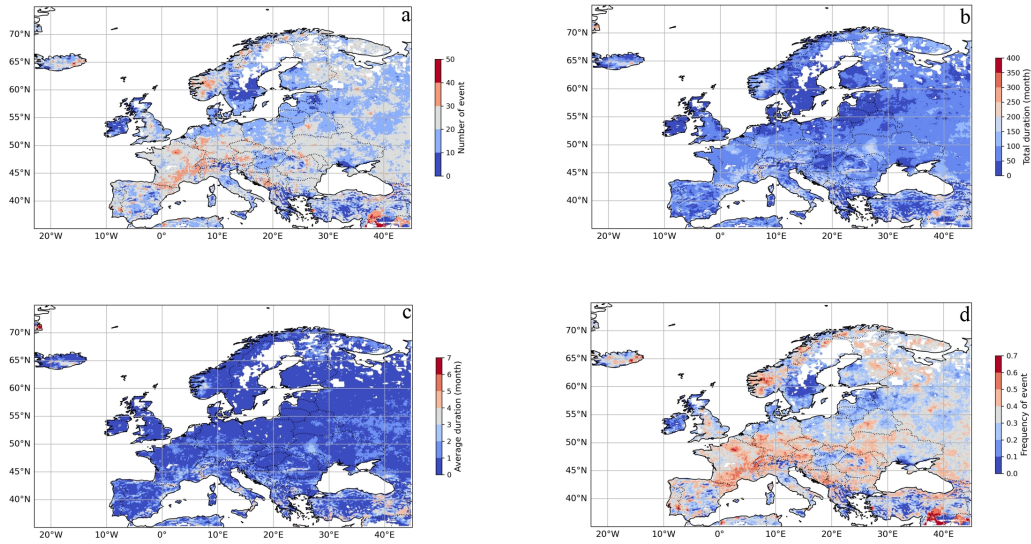


Figure S9. Changes (future-reference periods) in consecutive event characteristics across Europe under SSP1-2.6. (a) Changes in the number of consecutive events, (b) changes in total consecutive duration in day, (c) changes in average consecutive duration in day, and (d) changes in consecutive frequency.

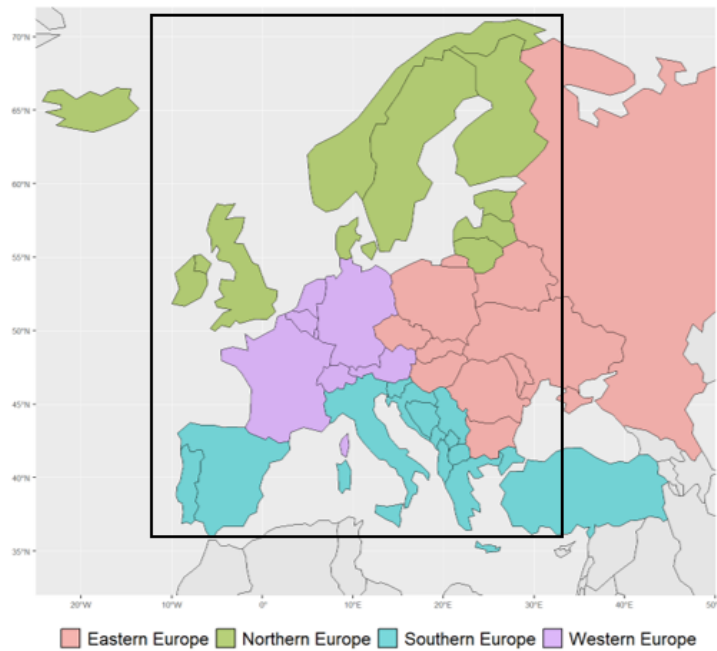


Figure S10. Subregions of Europe. Light red color is eastern Europe, green color is northern Europe, blue color is southern Europe, and purple color is western Europe.

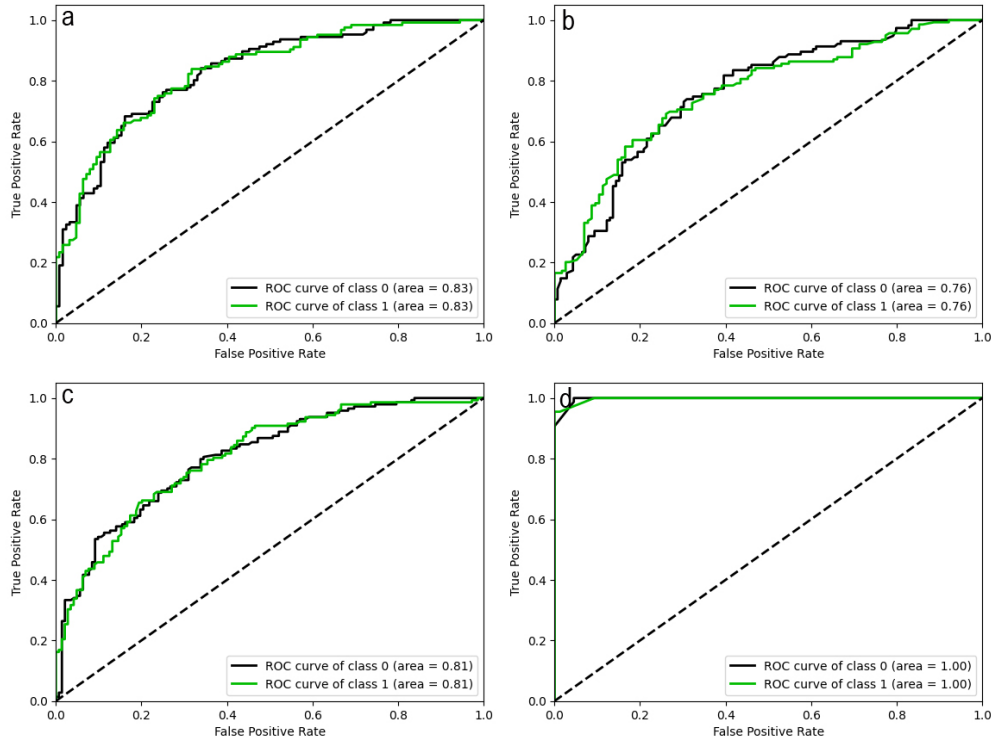


Figure S11. The Relative Operating Curve (ROC) for the trained ML models to predict historical impacted sectors. (a) ROC for drought impact on economic sector, (b) ROC for drought impact on non-economic sector, (c) ROC for drought impact on ecosystem sector, and (d) ROC for heatwave impact on human.

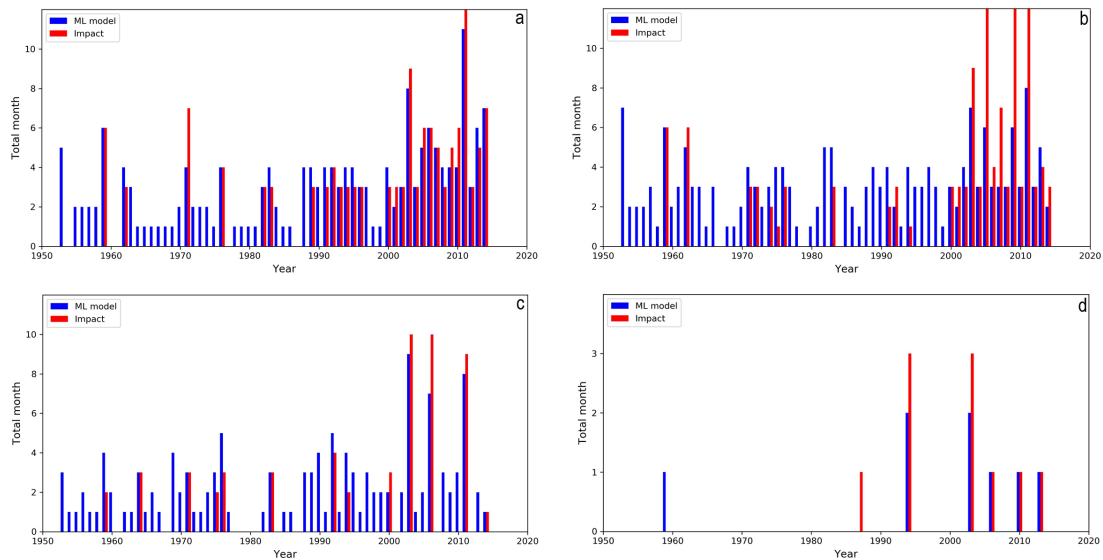


Figure S12. Simulations of drought and heatwave impacts in Germany using the ML model for reference period (1953-2014). (a) Simulation of drought impact on economic sector, (b) simulation of drought impact on non-economic sector, (c) simulation of drought impact on ecosystem sector, and (d) simulation of heatwave impact on human.

Supplementary Table

Table S1. Data and models used in the study

Variable	Unit	Time scale	Spatial resolution	Model	Period
Maximum near-surface temperature (Tmax)	K	Daily	ISIMIP: 0.5° x 0.5° ERA5 Land: 0.1° x 0.1°	ISIMIP (GFDL, IPSL, MPI, MRI, UKESM), ERA5 Land	ISIMIP: Extended summer period from 1953 to 2014 and from 2015 to 2100 ERA5 Land: 1953-2019
Minimum near-surface temperature (Tmin)	K	Daily	ISIMIP: 0.5° x 0.5° ERA5 Land: 0.1° x 0.1°	ISIMIP (GFDL, IPSL, MPI, MRI, UKESM), ERA5 Land	ISIMIP: Extended summer period from 1953 to 2014 and from 2015 to 2100 ERA5 Land: 1953-2019
Moisture in the upper portion of the soil column (SM)	Kg m ⁻²	Monthly	ISIMIP: 0.5° x 0.5° ERA5 Land: 0.1° x 0.1°	ISIMIP (CWatM), ERA5 Land	ISIMIP: from 1953 to 2014 and from 2015 to 2100 ERA5 Land: 1953-2019

Table S2. Definition of drought and heatwave characteristics as singly and CnC

	Total number of events	Total duration of events	Average duration of events	Frequency of events
Heatwave	Total number of heatwaves in the considered period	Total number of heatwave days during the analyzed period	Division of total heatwave duration by the total number of heatwave events	Frequency of heatwave events in a year, which is the total number of heatwave events divided by total years
Drought	Total number of drought events in the considered period	Total number of drought months during the analyzed period	Division of total drought events duration by the total number of drought events	Frequency of drought events in a year, which is the total number of drought events divided by total years
CnC	Total number of compound/consecutive events in the considered period	Total number of compound/consecutive months during the analyzed period	Division of total compound/consecutive events duration by the total number of events	Frequency of compound/consecutive events in a year, which is the total number of compound/consecutive events divided by total years

Table S3. The characteristics of drought and heatwave impacts on economic, non-economic, ecosystem, and human sectors derived from reference period and future scenarios

Impact sector	Scenario	Characteristics			
		Total number of impact	Total duration	Average duration	Frequency
Drought Economic	Reference	36	128	3.5	2.1
	SSPI1.2-6	65	216	3.3	3.5
	SSP5-8.5	66	248	3.8	4
Non-economic	Reference	45	126	2.8	2
	SSPI1.2-6	54	183	3.4	2.9
	SSP5-8.5	65	224	3.5	3.6
Ecosystem	Reference	24	75	3.1	1.2
	SSPI1.2-6	57	165	2.9	2.7
	SSP5-8.5	66	209	3.2	3.4
Heatwave Human	Reference	7	8	1.1	0.2
	SSPI1.2-6	63	96	1.5	1.5
	SSP5-8.5	71	203	2.9	3.3