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Global escalation of more frequent and intense compound heatwave-extreme precipitation events

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Sect. S1

In this study, we used the Spearman's rank correlation coefficient (SRCC) to analyze the correlations of the attributes of CHWEP and single extreme events between the reanalysis and CMIP6 datasets. SRCC is a nonparametric statistical method used to measure the monotonic relationship between two variables (whether linear or not). It is based on the rank of the variable rather than the original data value, so it is insensitive to outliers and data distribution and is suitable for nonlinear relationships or non-normally distributed data. Its calculation formula is as follows:

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \quad \text{Eq. (S1)}$$

where ρ is SRCC, d_i is the difference in the ranks of the data corresponding to the two variables, and n is the number of samples. The SRCC value range is -1 to 1. When SRCC is 1, it indicates a complete positive correlation, and the ranks of the two variables are exactly the same; when SRCC is -1, it indicates a complete negative correlation, and the rank of one variable is completely opposite to the rank of the other variable; when SRCC is 0, it indicates no correlation, and the ranks of the two variables have no monotonic relationship. In this study, the significance level of SRCC is 5%.

Table S1 The six global climate models from CMIP6 selected in this study.

Model Name	Modeling Center / Country	Spatial Resolution	Temporal Resolution	Key Experiments Available
CanESM5	Canadian Centre for Climate Modelling and Analysis (Canada)	2.8° × 2.8°	Daily	historical, SSP2-4.5, SSP5-8.5
MRI-ESM2-0	Meteorological Research Institute (Japan)	1.1° × 1.1°	Daily	historical, SSP2-4.5, SSP5-8.5
ACCESS-CM2	CSIRO & Bureau of Meteorology (Australia)	1.9° × 1.25°	Daily	historical, SSP2-4.5, SSP5-8.5
BCC-CSM2-MR	Beijing Climate Center (China)	1.1° × 1.1°	Daily	historical, SSP2-4.5, SSP5-8.5
CESM2-WACCM	National Center for Atmospheric Research (USA)	1.9°×2.5°	Daily	historical, SSP2-4.5, SSP5-8.5
GFDL-ESM4	National Oceanic and Atmospheric Administration (USA)	1.9°×2.5°	Daily	historical, SSP2-4.5, SSP5-8.5

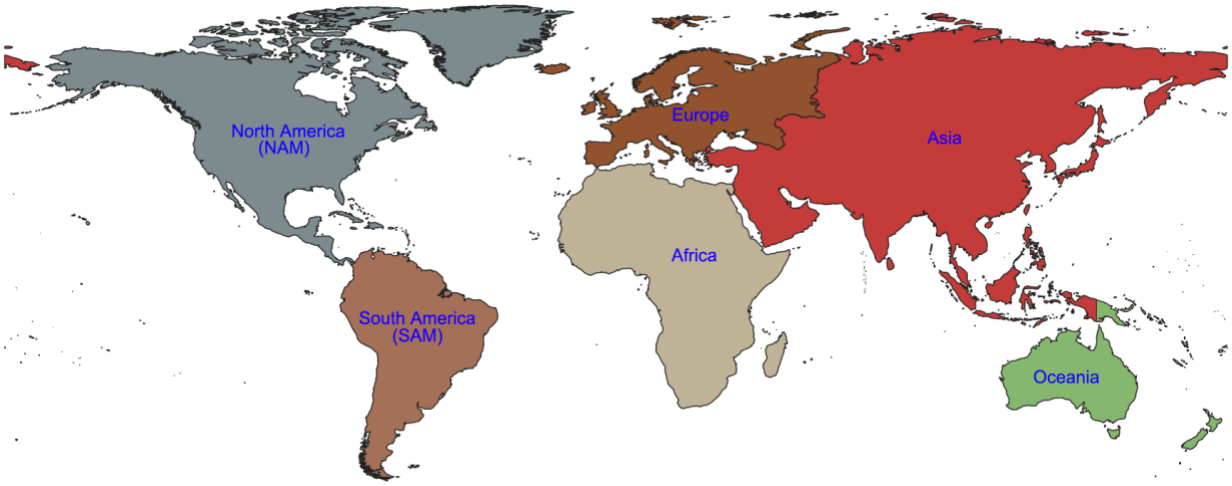

Figure S1. Regional division based on continental boundaries.

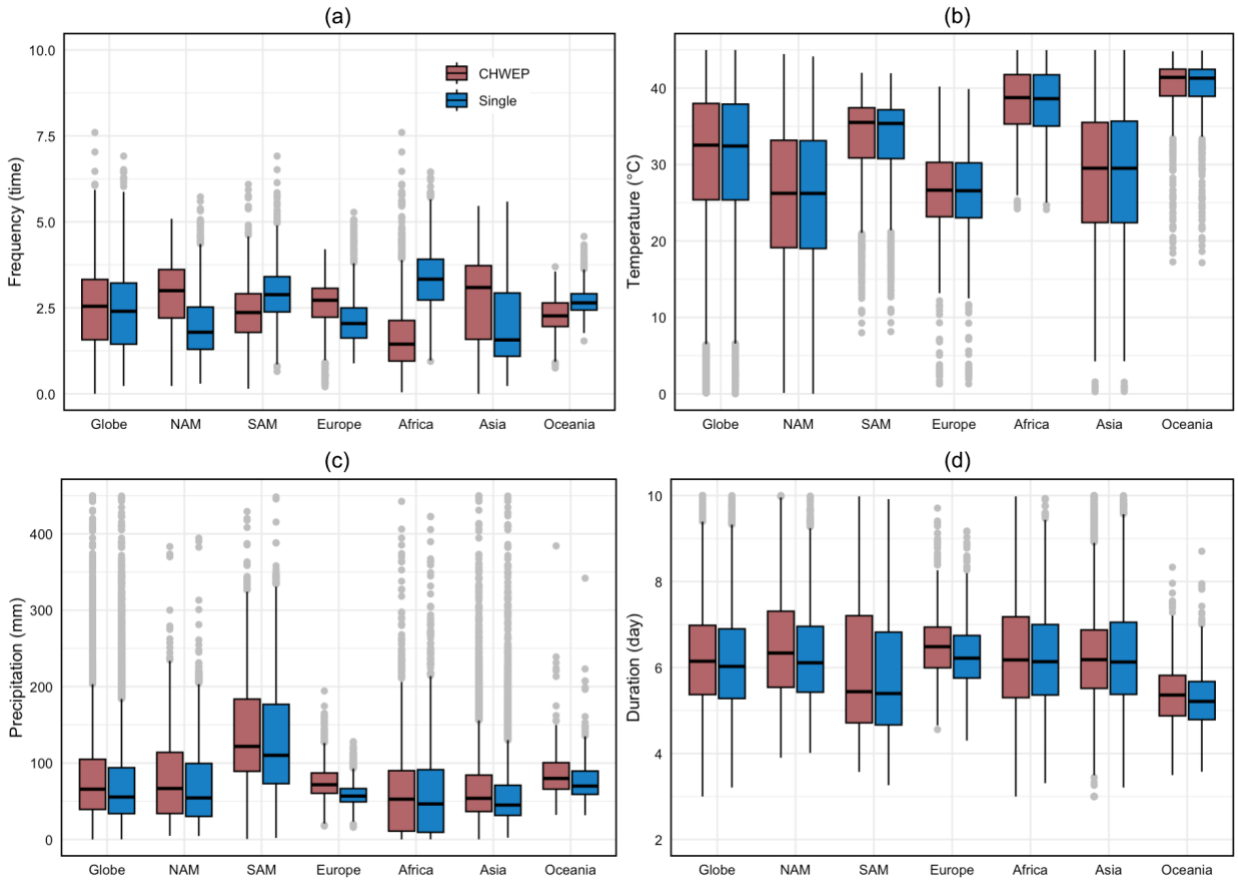

Figure S2. Box plots of the frequency (a), heatwave intensity (b), extreme precipitation intensity (c), and heatwave duration (f) for CHWEP and single extreme events.

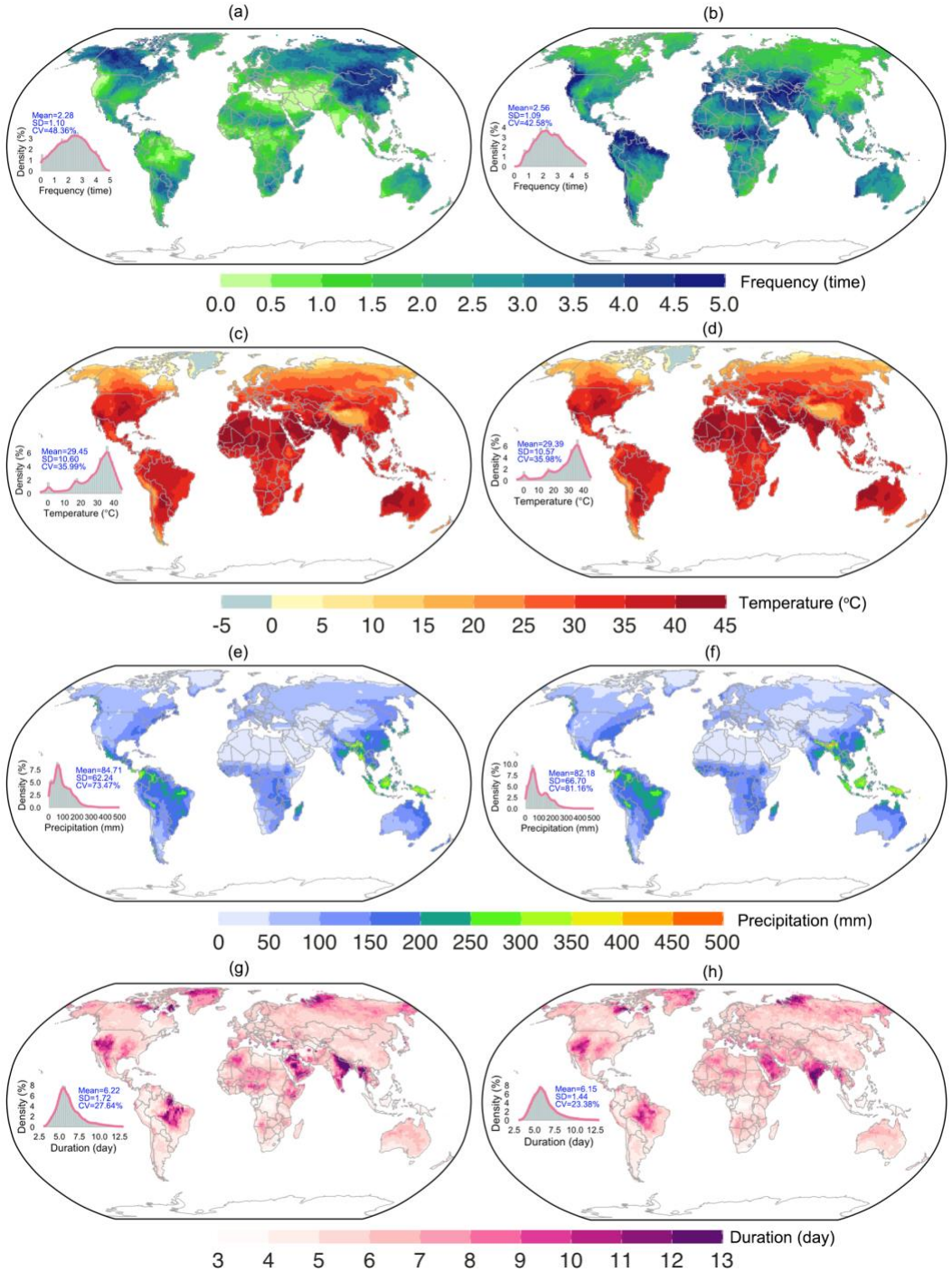

Figure S3. Spatial distribution of the mean values of the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (e and f) of CHWEP (a, c, e, and g) and single extreme events (b, d, f, and h) from 1980 to 2024 based on CMIP6 historical data.

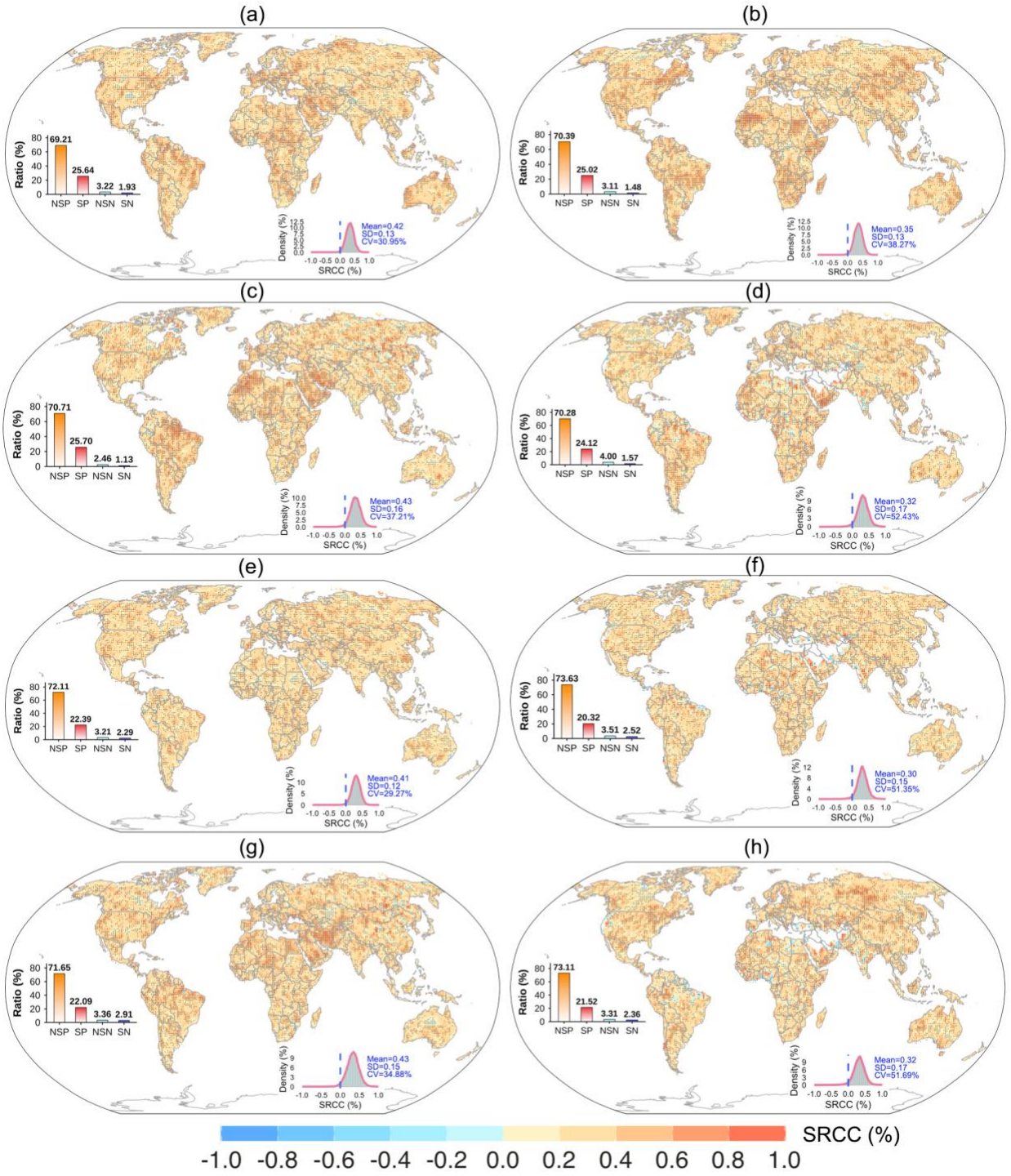

Figure S4. Spatial distribution of the SRCC values of the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (e and f) of CHWEP (a, c, e, and g) and single extreme events (b, d, f, and h) from 1980 to 2024 between reanalysis data and CMIP6 historical data.

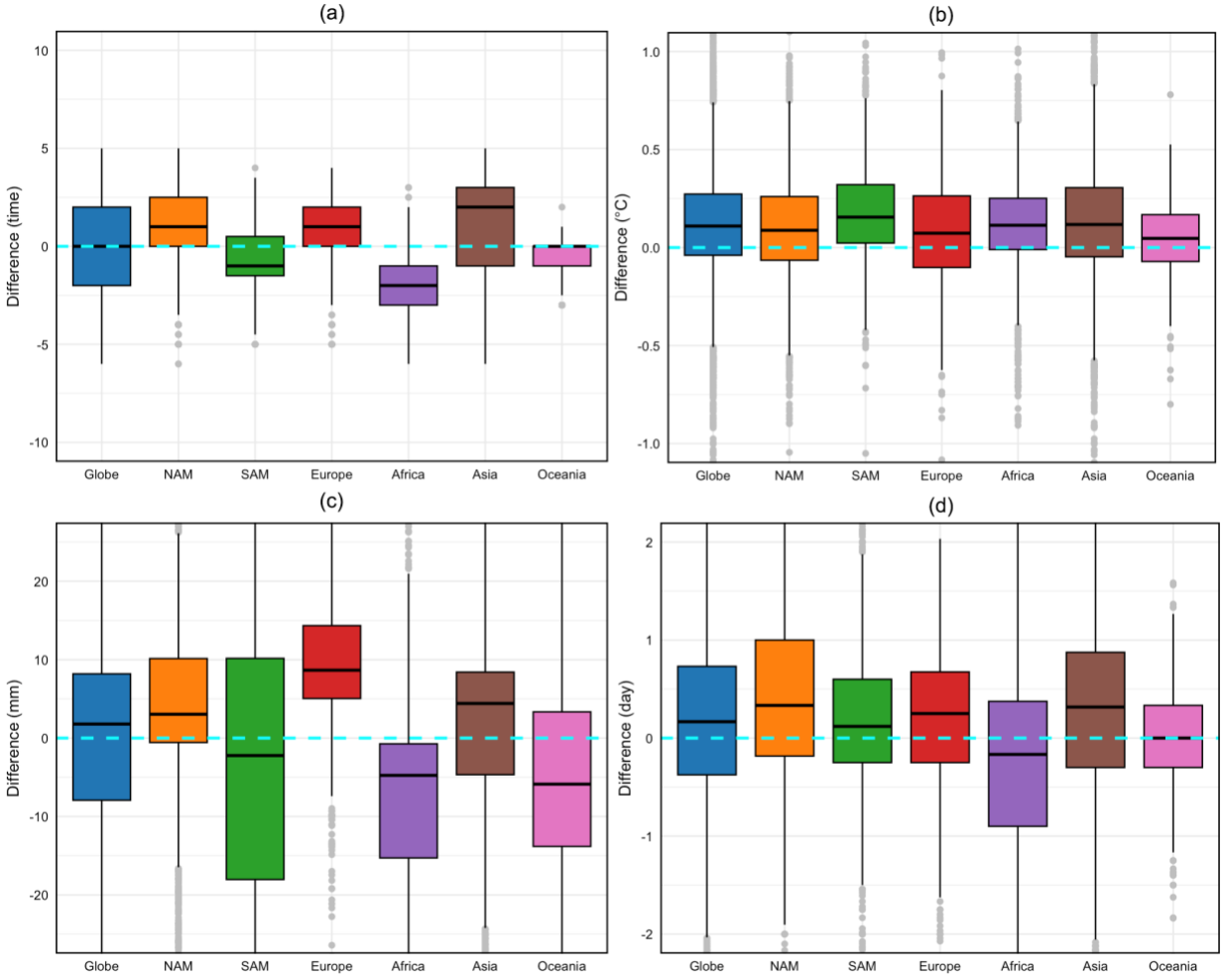

Figure S5. Box plots of median differences between CHWEP and single extreme events in frequency (a), heatwave intensity (b), extreme precipitation intensity (c), and heatwave duration (d) in historical period (1980-2024).

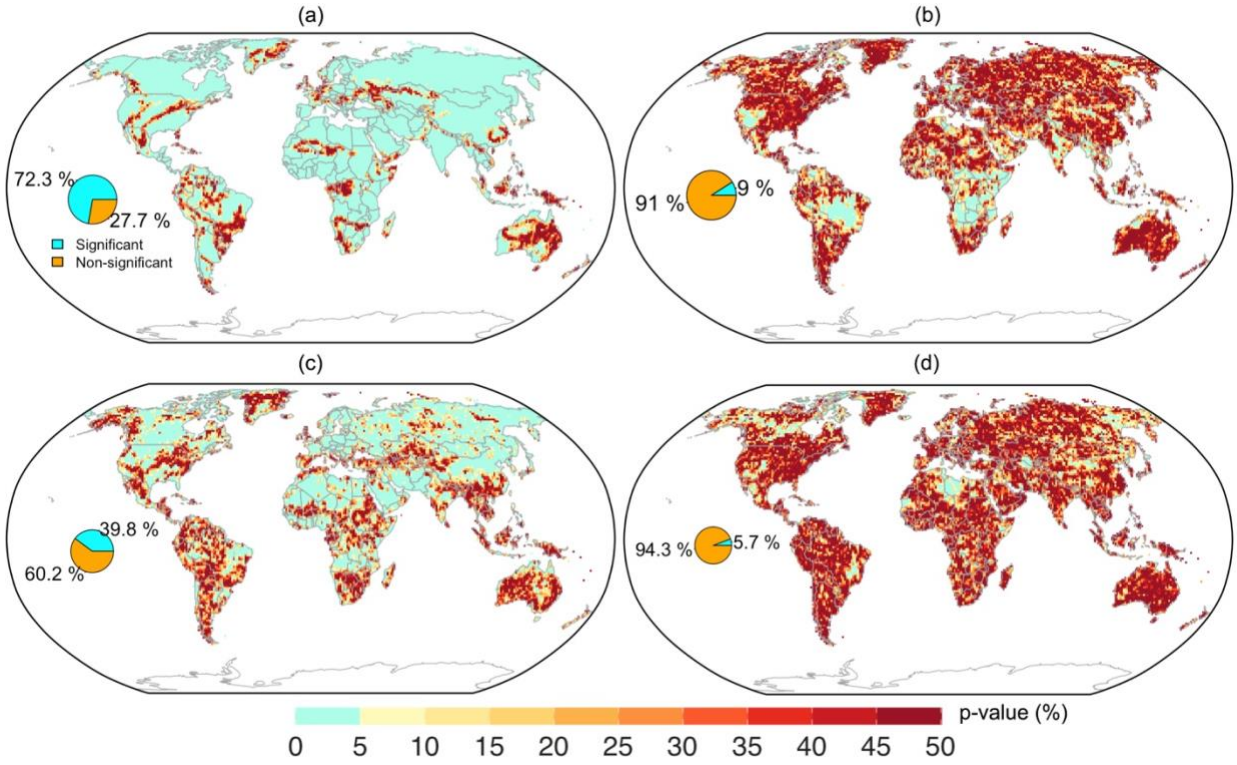

Figure S6. Spatial distribution of the p-value of median differences between CHWEP and single extreme events in frequency (a), heatwave intensity (b), extreme precipitation intensity (c), and heatwave duration (d) from 1980 to 2024 based on WRST test.

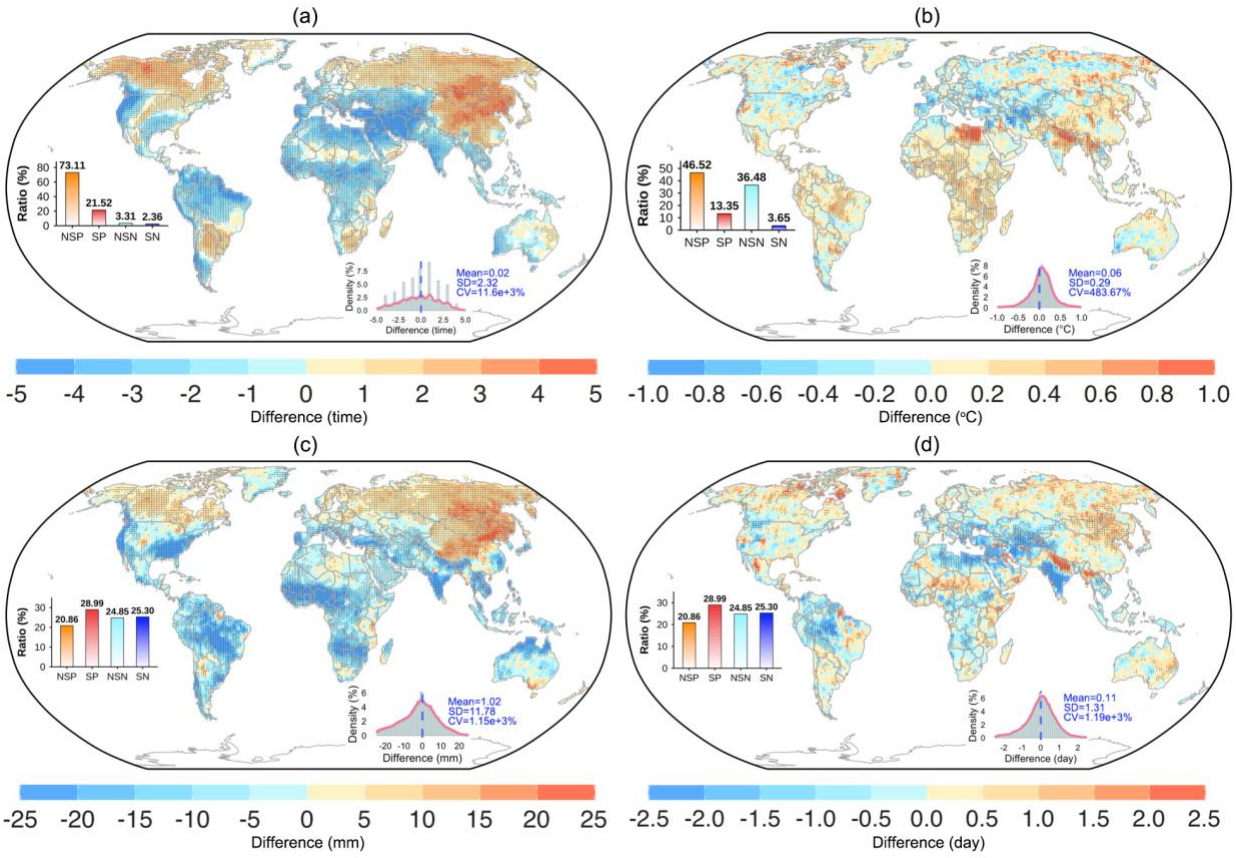

Figure S7. Spatial distribution of median differences between CHWEP and single extreme events in frequency (a), heatwave intensity (b), extreme precipitation intensity (c), and heatwave duration (d) from 1980 to 2024 based on CMIP6 data. (Note: In the left bar chart, NSP denotes Non-Significant Positive, SP denotes Significant Positive, NSN denotes Non-Significant Negative, and SN denotes Significant Negative. The same abbreviations apply hereinafter.)

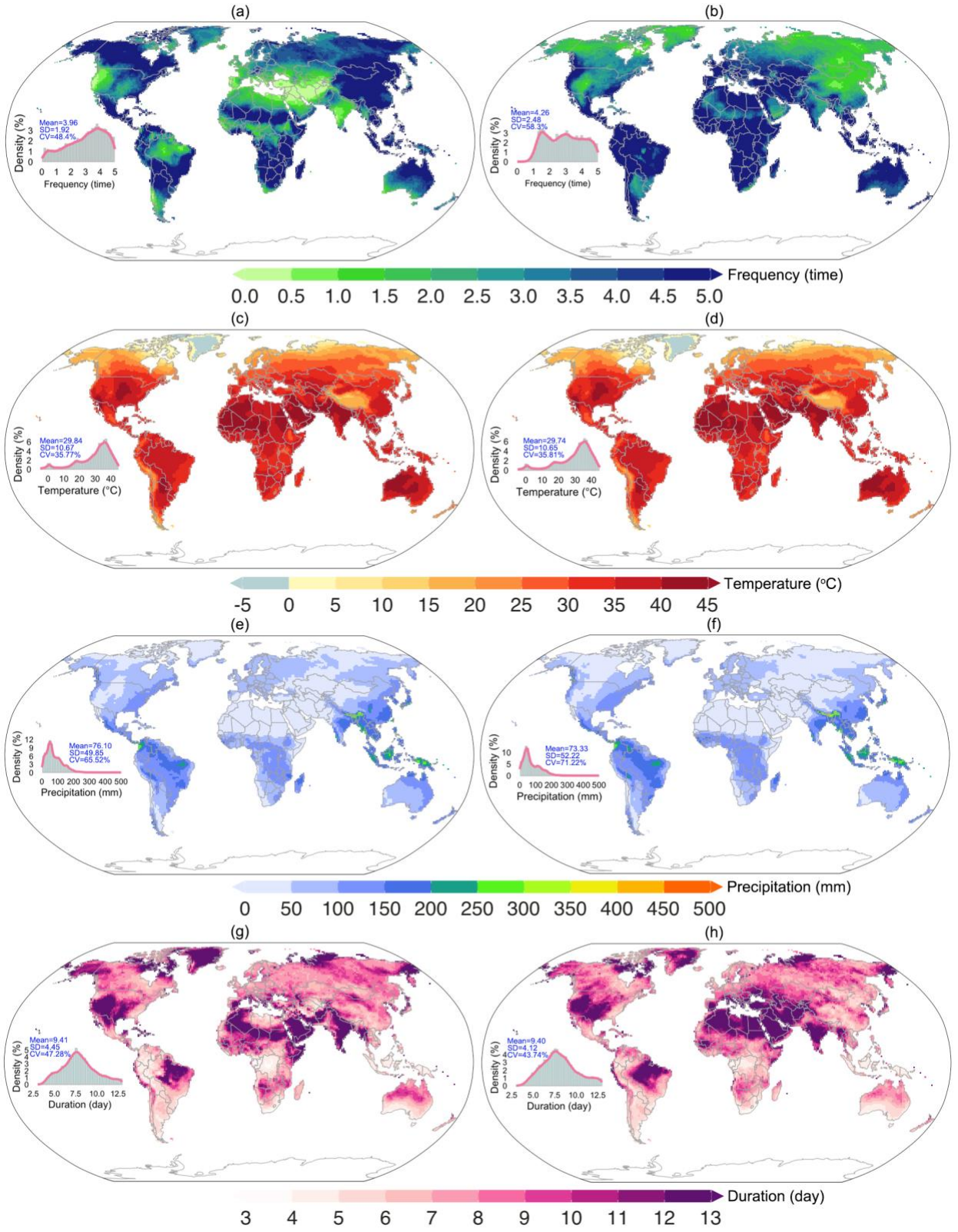
(a)
Mean=3.96
SD=1.92
CV=48.4%
Density (%)
Frequency (time)
(b)
Mean=4.26
SD=2.48
CV=58.3%
Density (%)
Frequency (time)
Frequency (time)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
(c)
Mean=29.84
SD=10.67
CV=35.77%
Density (%)
Temperature (°C)
(d)
Mean=29.74
SD=10.65
CV=35.81%
Density (%)
Temperature (°C)
Temperature (°C)
-5 0 5 10 15 20 25 30 35 40 45
(e)
Mean=76.10
SD=49.85
CV=65.52%
Density (%)
Precipitation (mm)
(f)
Mean=73.33
SD=52.22
CV=71.22%
Density (%)
Precipitation (mm)
Precipitation (mm)
0 50 100 150 200 250 300 350 400 450 500
(g)
Mean=9.41
SD=4.45
CV=47.28%
Density (%)
Duration (day)
(h)
Mean=9.40
SD=4.12
CV=43.74%
Density (%)
Duration (day)
Duration (day)
3 4 5 6 7 8 9 10 11 12 13

Figure S8. Spatial distribution of the mean values of the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (e and f) of CHWEP (a, c, e, and g) and single extreme events (b, d, f, and h) from 2056 to 2100 under SSP2-4.5 scenario.

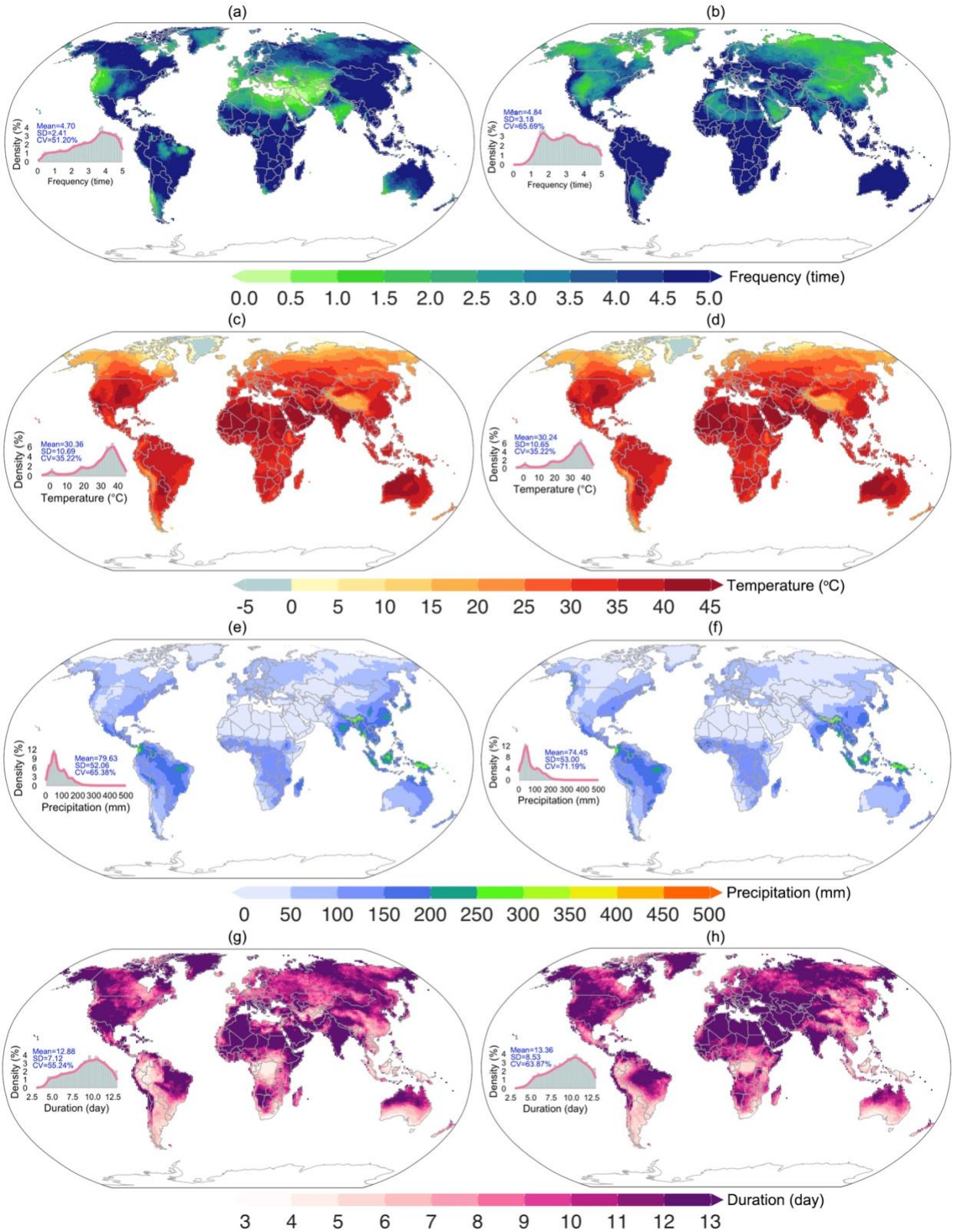
(a)
(b)
Mean=4.70
SD=2.41
CV=61.20%
Mean=4.84
SD=3.18
CV=65.69%
Density (%)
Frequency (time)
Frequency (time)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
(c)
(d)
Mean=30.36
SD=10.69
CV=35.22%
Mean=30.24
SD=10.65
CV=35.22%
Temperature (°C)
Temperature (°C)
-5 0 5 10 15 20 25 30 35 40 45
(e)
(f)
Mean=79.63
SD=52.06
CV=65.38%
Mean=74.45
SD=53.00
CV=71.19%
Precipitation (mm)
Precipitation (mm)
0 50 100 150 200 250 300 350 400 450 500
(g)
(h)
Mean=12.88
SD=7.12
CV=55.24%
Mean=13.36
SD=8.53
CV=63.87%
Duration (day)
Duration (day)
3 4 5 6 7 8 9 10 11 12 13

Figure S9. Spatial distribution of the mean values of the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (e and f) of CHWEP (a, c, e, and g) and single extreme events (b, d, f, and h) from 2056 to 2100 under SSP5-8.5 scenario.

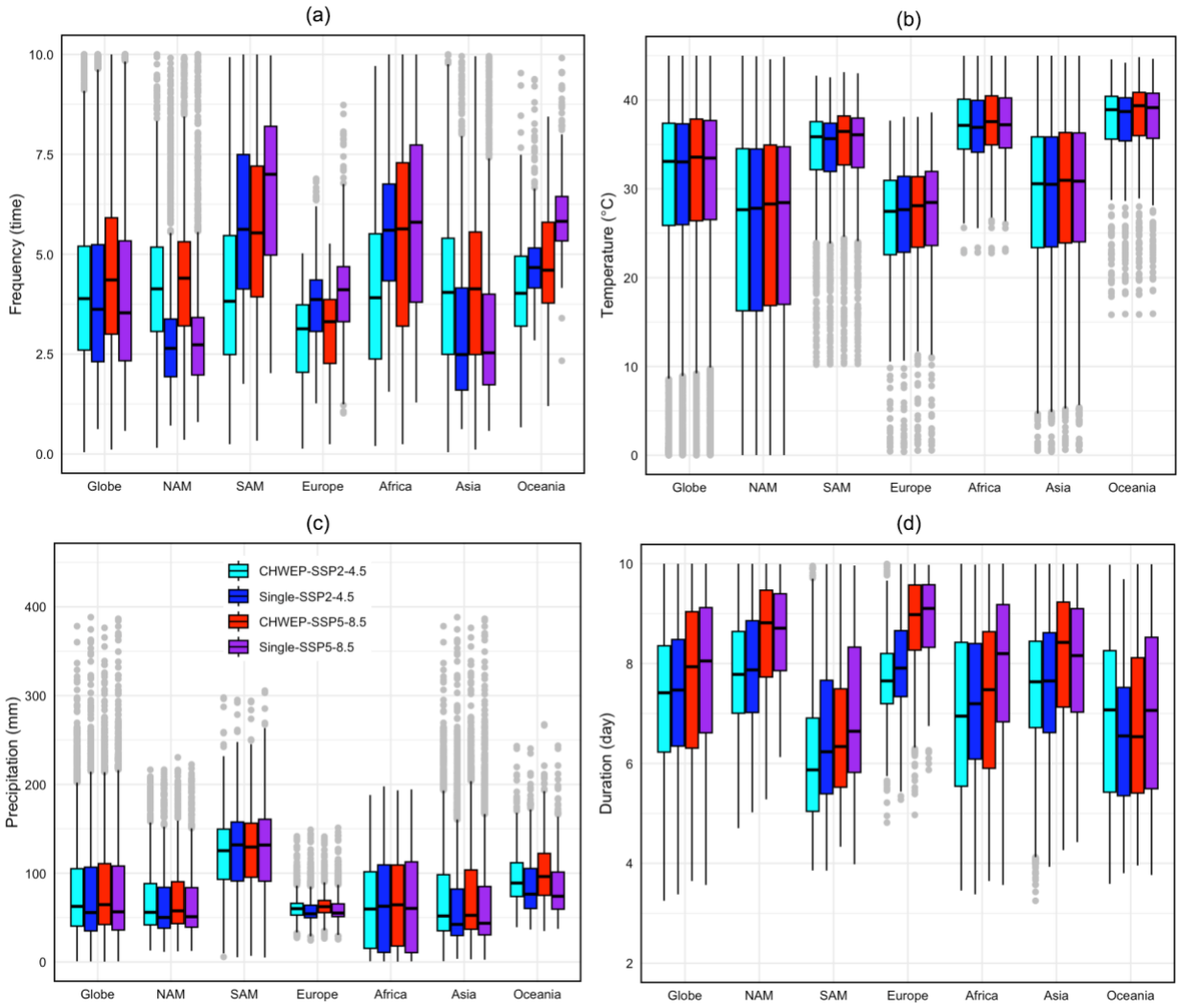

Figure S10. Box plots of the mean values of the frequency (a), heatwave intensity (b), extreme precipitation intensity (c), and heatwave duration (d) for CHWEP and single extreme events from 2056 to 2100 under the SSP2-4.5 and SSP5-8.5 scenarios.

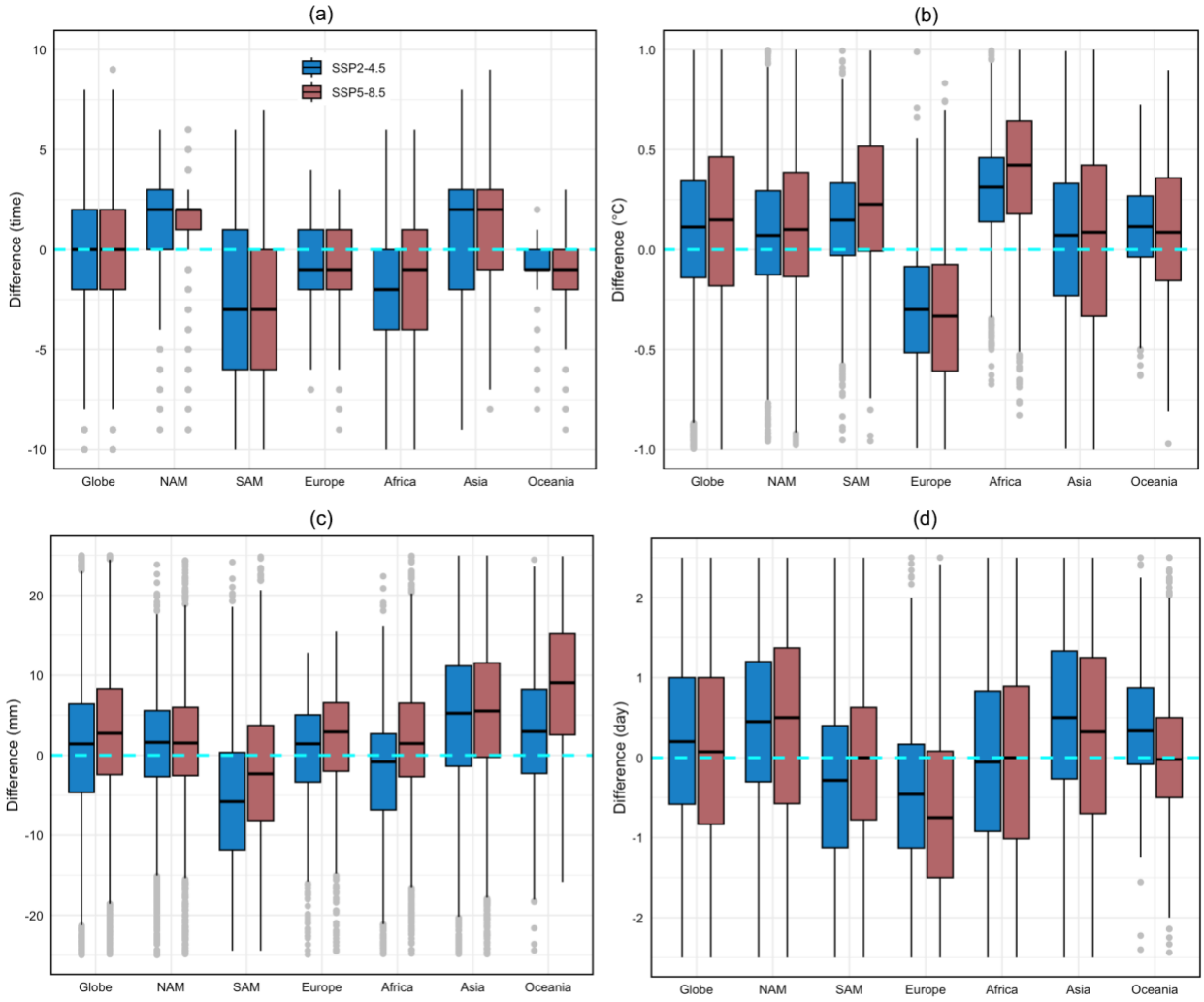

Figure S11. Box plots of median differences between CHWEP and single extreme events in frequency (a), heatwave intensity (b), extreme precipitation intensity (c), and heatwave duration (d) from 2056 to 2100 under the SSP2-4.5 and SSP5-8.5 scenarios.

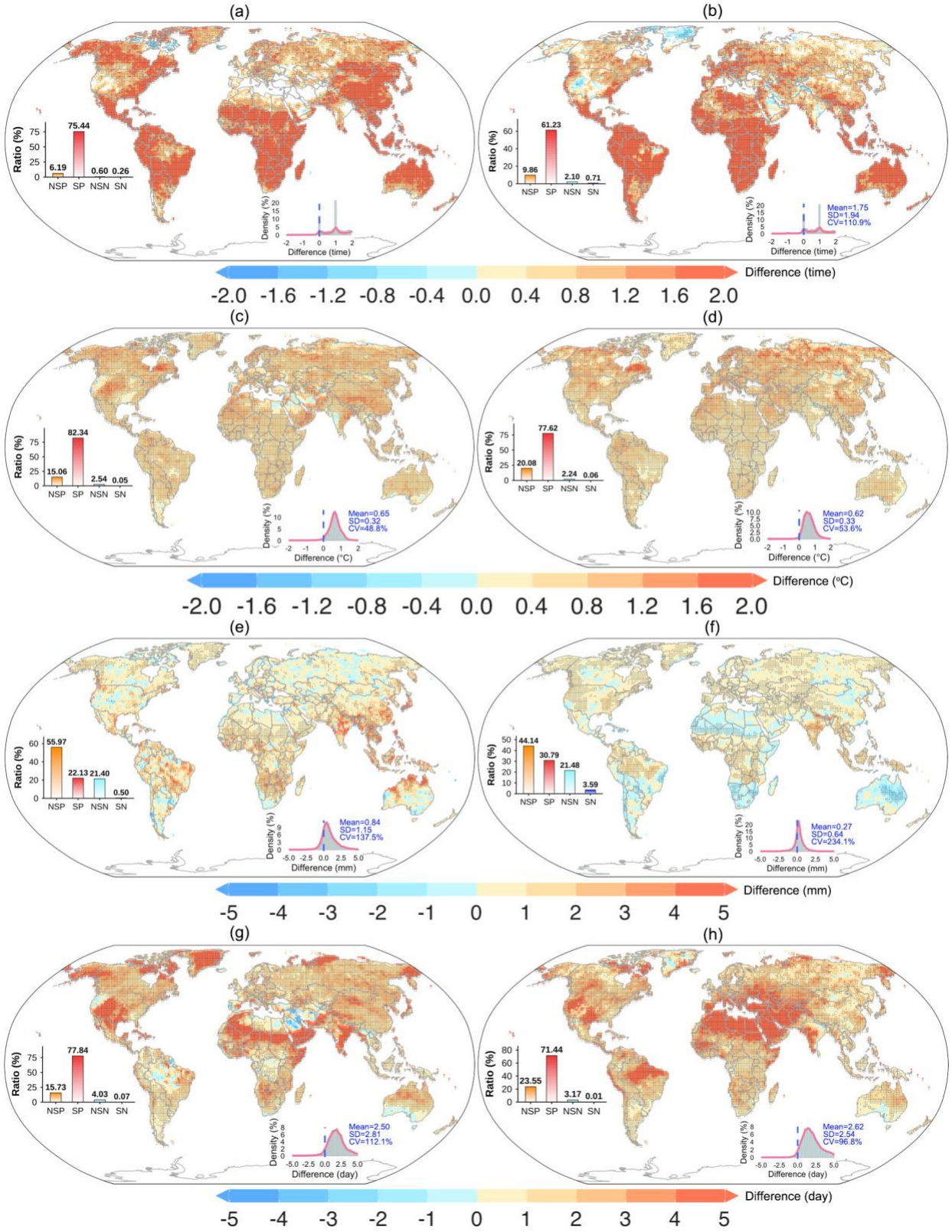
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Ratio (%)
NSP SP NSN SN
6.19 75.44 0.60 0.26
9.86 61.23 2.10 0.71
15.06 82.34 2.54 0.05
20.08 77.62 2.24 0.06
55.97 22.13 21.40 0.50
44.14 30.79 21.48 3.59
15.73 77.84 4.03 0.07
23.55 71.44 3.17 0.01
Density (%)
Difference (time)
Mean=1.75 SD=1.94 CV=110.9%
Difference (°C)
Mean=0.65 SD=0.32 CV=48.8%
Mean=0.62 SD=0.33 CV=53.6%
Difference (mm)
Mean=0.84 SD=1.15 CV=137.5%
Mean=0.27 SD=0.64 CV=234.1%
Difference (day)
Mean=2.50 SD=2.81 CV=112.1%
Mean=2.62 SD=2.54 CV=96.8%
-2.0 -1.6 -1.2 -0.8 -0.4 0.0 0.4 0.8 1.2 1.6 2.0
-5 -4 -3 -2 -1 0 1 2 3 4 5

Figure S12. Spatial distribution of the median differences in the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (g and h) of CHWEP (a, c, e and g) and single extreme events (b, d, f, and h) in the future period under the SSP2-4.5 scenario compared with the historical period. (Note: In the left bar chart, NSP denotes Non-Significant Positive, SP denotes Significant Positive, NSN denotes Non-Significant Negative, and SN denotes Significant Negative. The same abbreviations apply hereinafter.)

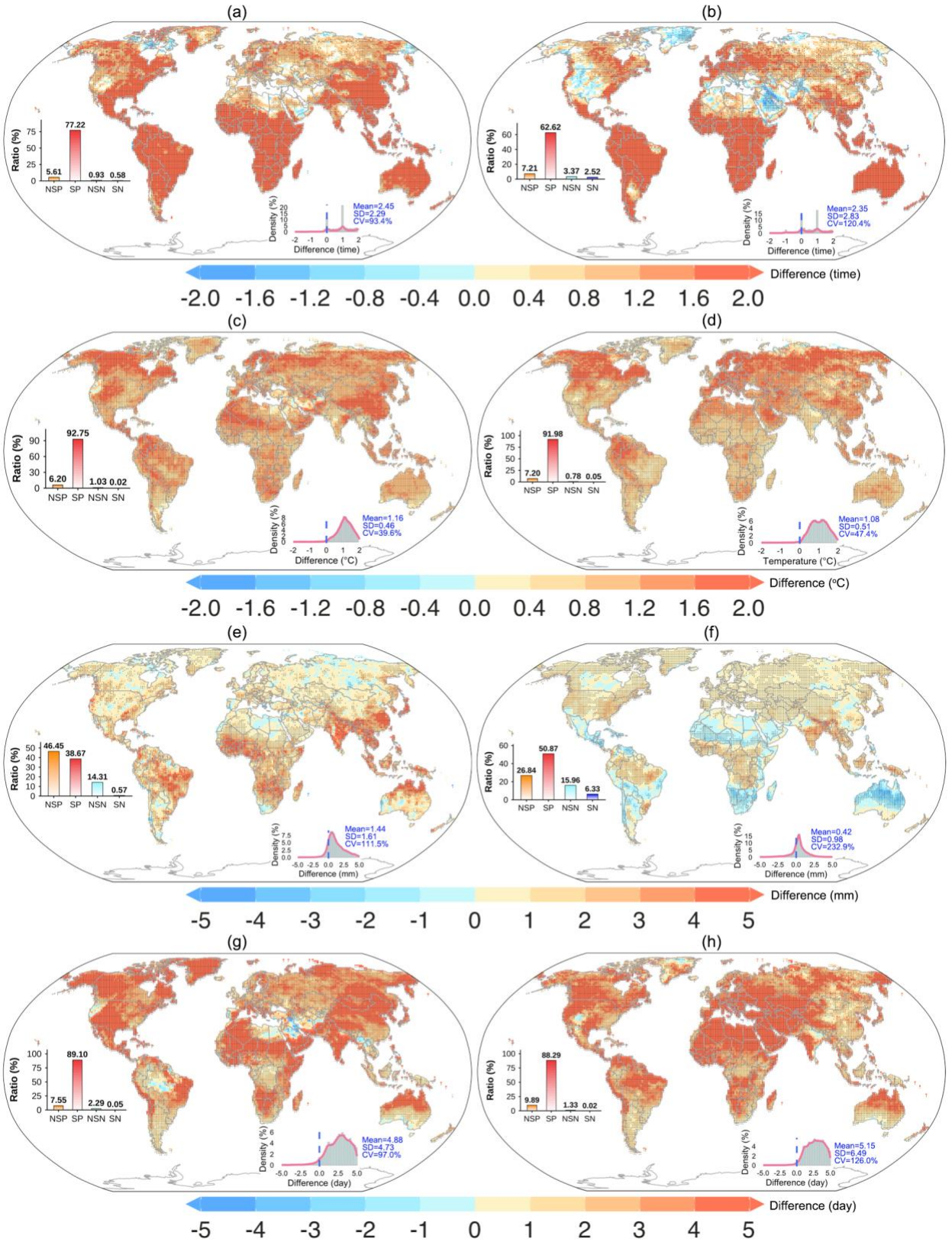
(a)
(b)
Ratio (%)
77.22
5.61
0.93
0.58
62.62
7.21
3.37
2.52
NSP SP NSN SN
Density (%)
Mean=2.45
SD=2.29
CV=93.4%
Mean=2.35
SD=2.83
CV=120.4%
Difference (time)
Difference (time)
-2.0 -1.6 -1.2 -0.8 -0.4 0.0 0.4 0.8 1.2 1.6 2.0
(c)
(d)
92.75
6.20
1.03
0.02
91.98
7.20
0.78
0.05
Mean=1.16
SD=0.46
CV=39.6%
Mean=1.08
SD=0.51
CV=47.4%
Difference (°C)
Temperature (°C)
Difference (°C)
-2.0 -1.6 -1.2 -0.8 -0.4 0.0 0.4 0.8 1.2 1.6 2.0
(e)
(f)
46.45
38.67
14.31
0.57
26.84
50.87
15.96
6.33
Mean=1.44
SD=1.61
CV=111.5%
Mean=0.42
SD=0.98
CV=232.9%
Difference (mm)
Difference (mm)
-5 -4 -3 -2 -1 0 1 2 3 4 5
(g)
(h)
89.10
7.55
2.29
0.05
88.29
9.89
1.33
0.02
Mean=4.88
SD=4.73
CV=97.0%
Mean=5.15
SD=6.49
CV=126.0%
Difference (day)
Difference (day)
-5 -4 -3 -2 -1 0 1 2 3 4 5

Figure S13. Spatial distribution of the median differences in the frequency (a and b), heatwave intensity (c and d), extreme precipitation intensity (e and f), and heatwave duration (g and h) of CHWEP (a, c, e and g) and single extreme events (b, d, f, and h) in the future period under the SSP5-8.5 scenario compared with the historical period.

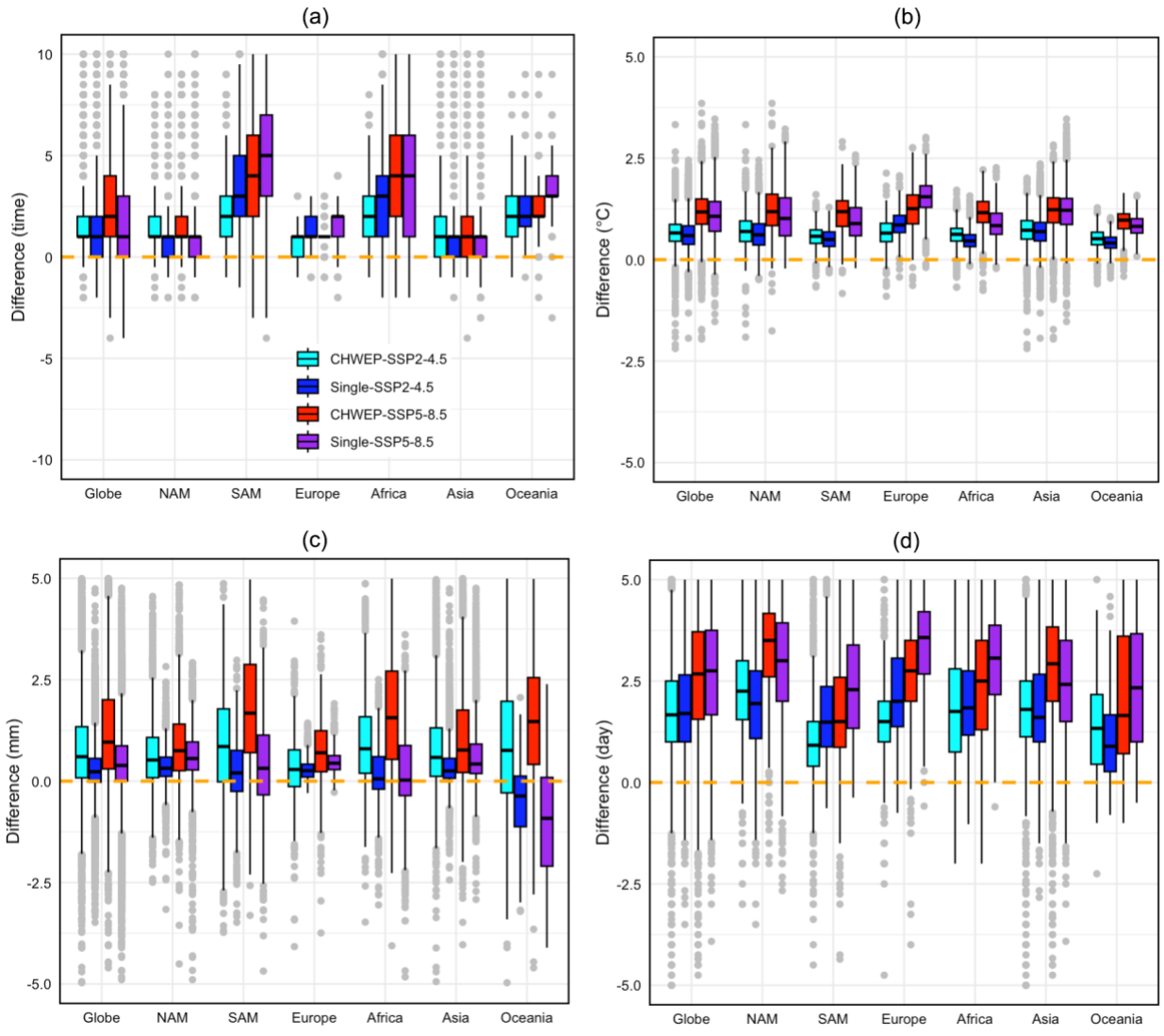

Figure S14. Box plots of the median differences in the frequency (a), heatwave intensity (b), extreme precipitation intensity (d), and heatwave duration (e) of CHWEP and single extreme

events during the future period (2056–2100) under the SSP2-4.5 and SSP5-8.5 scenarios compared with the historical period (1980–2024).

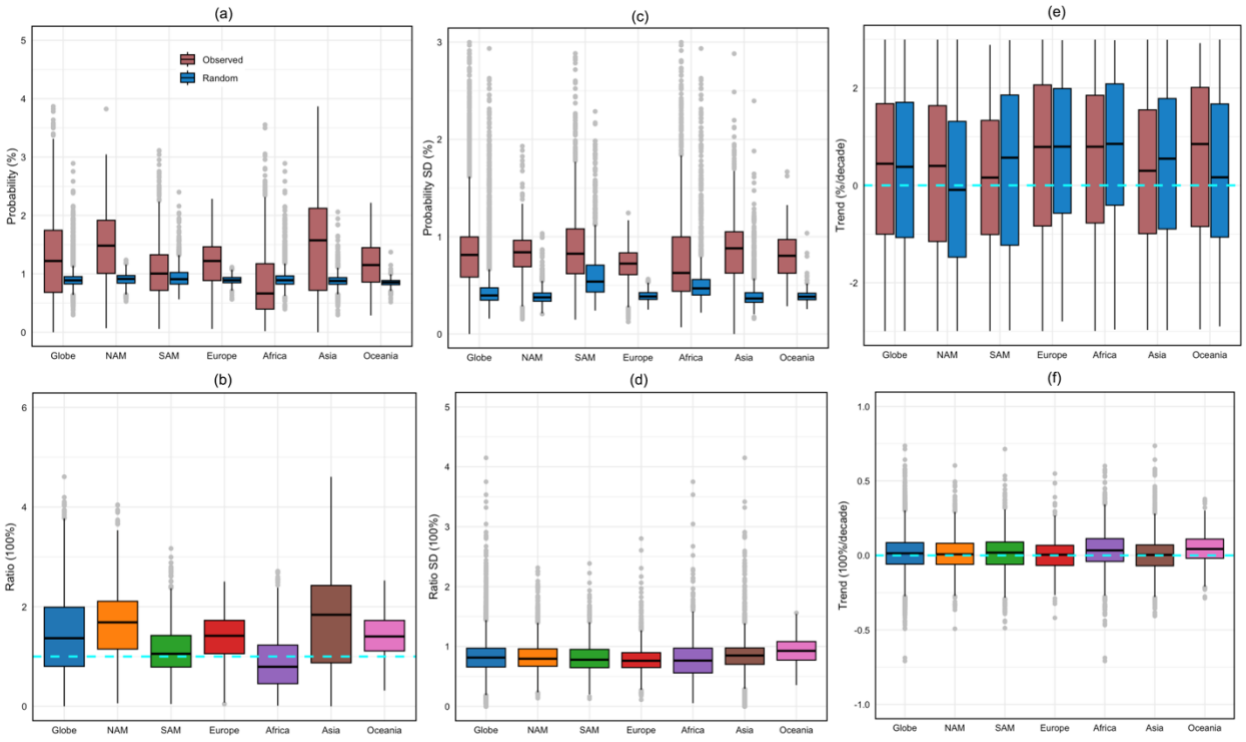

Figure S15. Box plots of the observed probability and the mean of random probabilities (a), along with their ratio (b), box plots of the standard deviations of the observed probability and random probabilities (c), along with the standard deviation of their ratio (d), and box plots of the trends in the observed probability and random probabilities (e), along with the trend of their ratio (f), during the historical period (1980-2024).

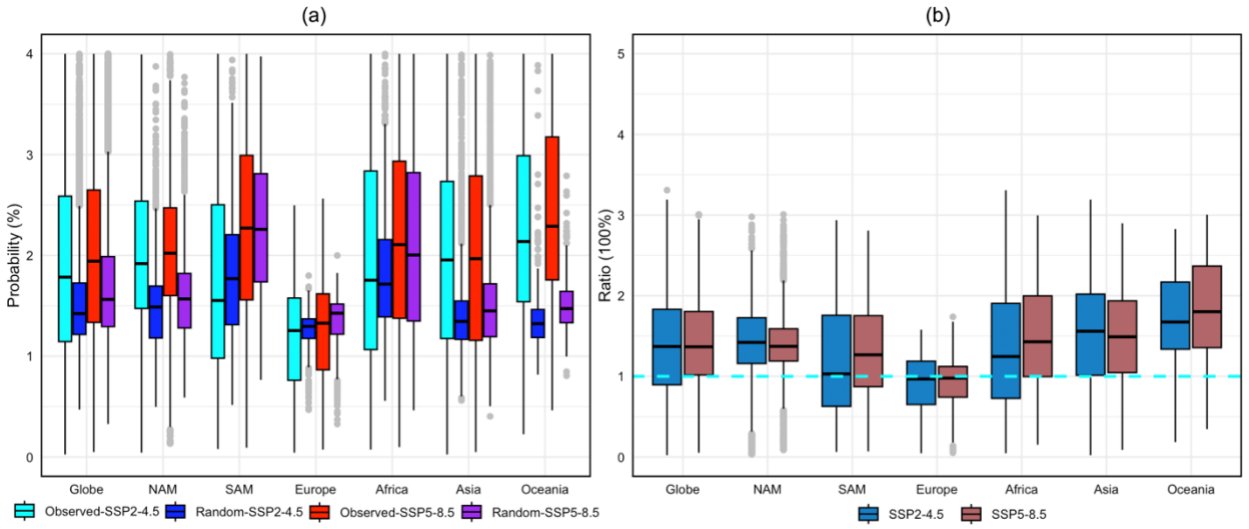

Figure S16. Box plots of the mean observed probability and mean coincidence probability (a), and the mean ratio of observed probability to coincidence probability (b) under the SSP2-4.5 and SSP5-8.5 scenarios for the period 2056–2100.

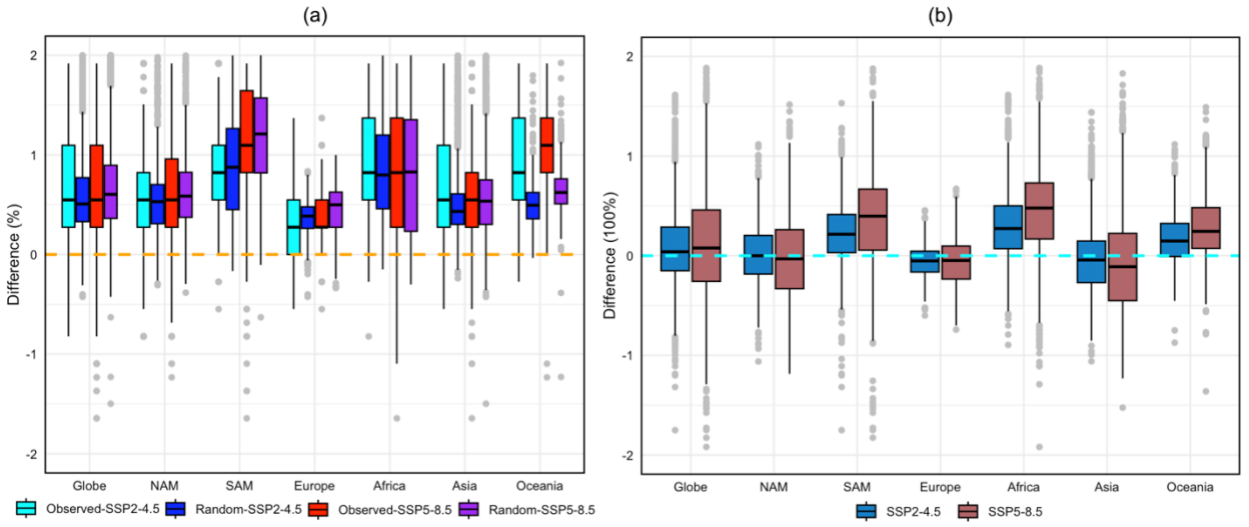

Figure S17. Box plots of the differences in median values of observed probability and coincidence probability (a), and their ratio (b) for the co-occurrence of heatwaves and extreme precipitation between the future period (under the SSP2-4.5 and SSP5-8.5 scenarios) and the historical period.