

Supplementary Information for
Regional increases in tornadic activity through midcentury due to global warming

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Introduction

The document includes 15 figures and two tables as the supplementary data for the paper.

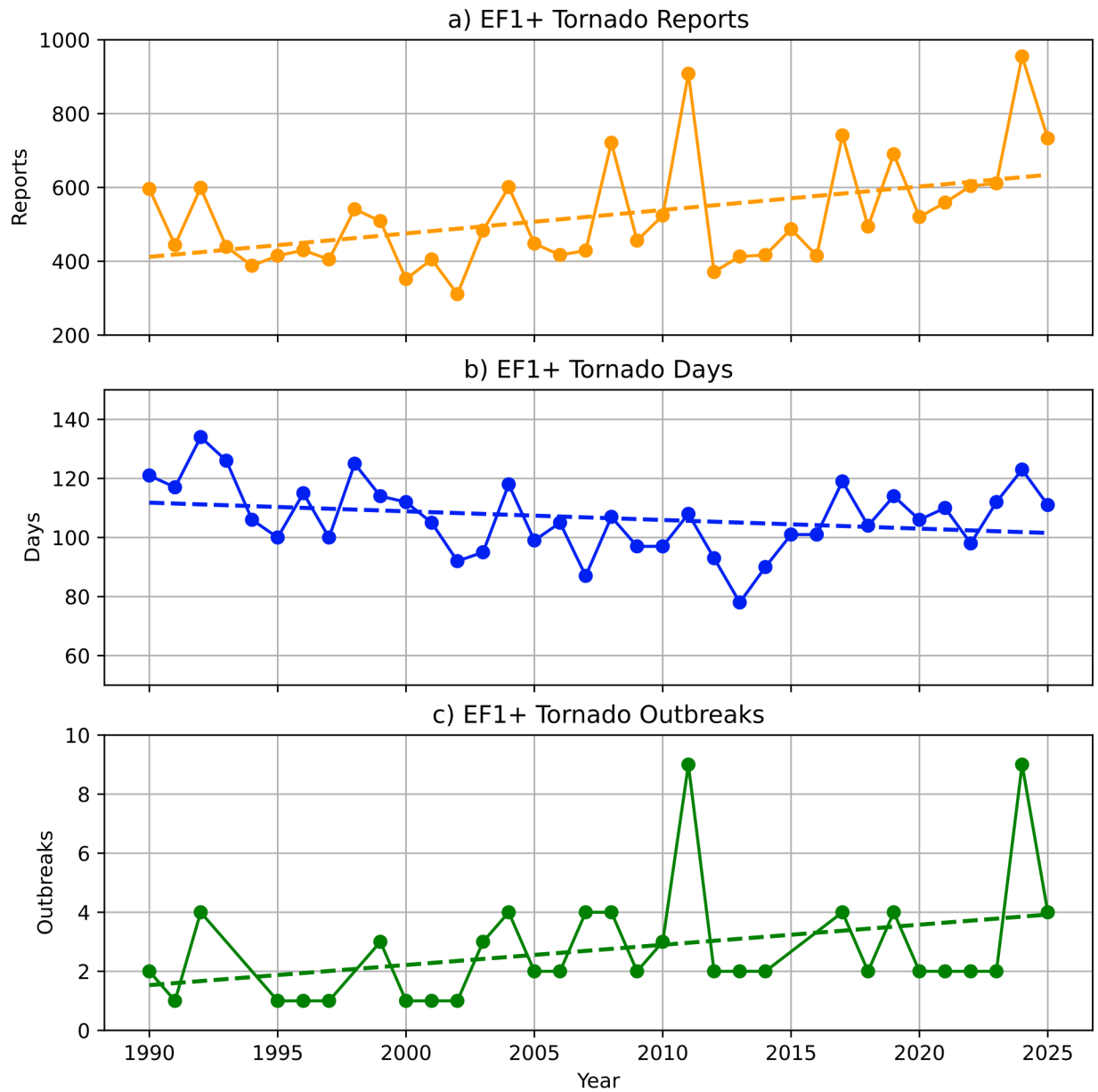


Figure S1. Historical tornado climatology from 1990 to 2025. Time series of annual a) EF1+ tornado reports, b) EF1+ tornado days, and c) tornado outbreaks (with 30 or more EF1+ tornadoes), based on data from the NOAA Storm Prediction Center (SPC). Dashed lines represent linear fits.

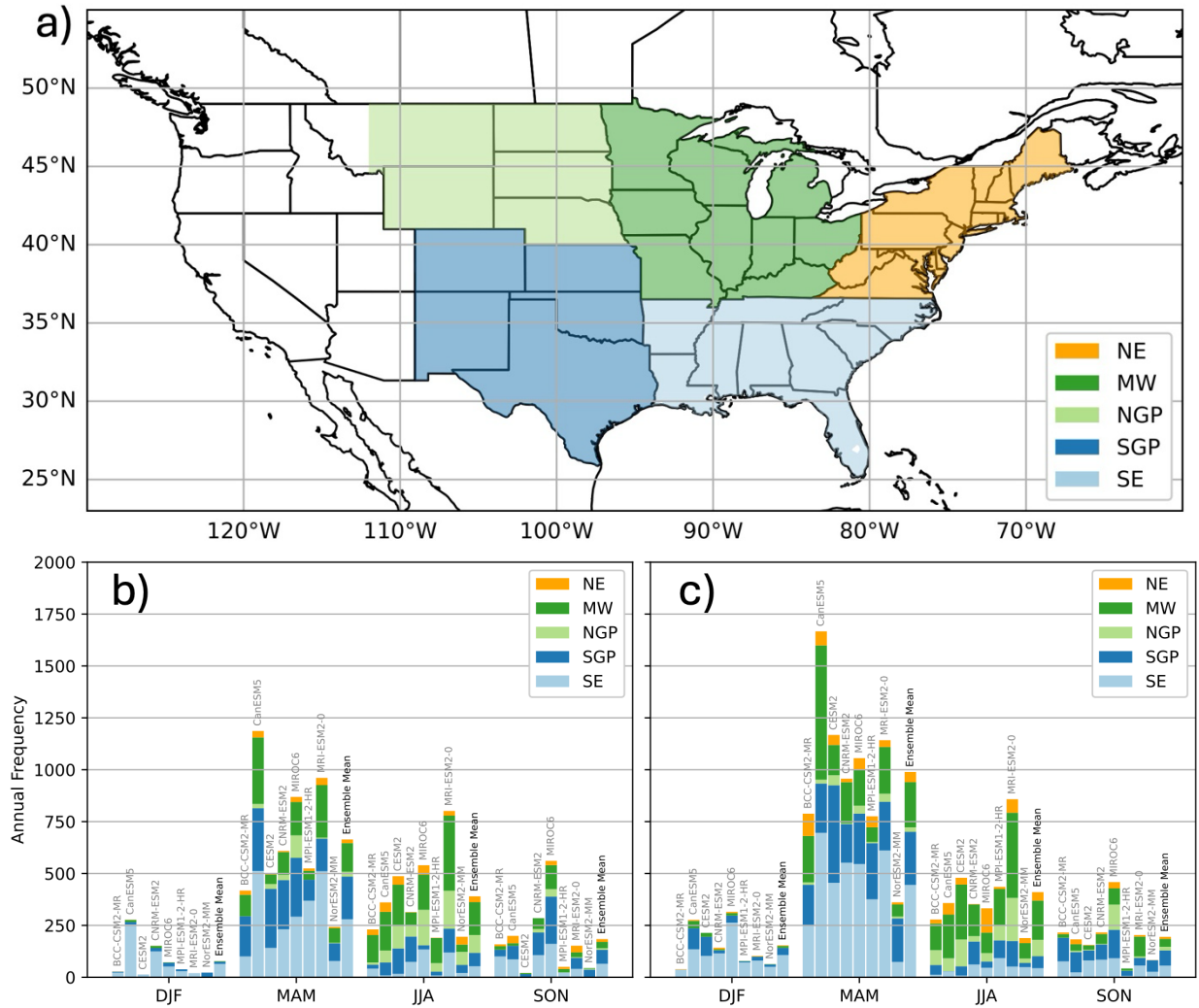


Figure S2. Region definition and seasonal and regional frequency of tornado proxy occurrences for the historical and future periods. Graphical depiction of the U.S. regions for the regional analysis is shown in a) (NE: northeast U.S.; MW: Midwest U.S.; NGP: Northern Great Plains; SGP: Southern Great Plains; SE: southeast U.S.; the westernmost boundary of all WRF simulations is 112°W.). Frequencies are represented as the number of tornado proxy occurrences for each GCM. Individual bars show frequencies from each GCM that was downscaled or the ensemble mean of eight downscaled GCMs. Two periods are b) the historical period (1995–2014), and c) the future (SSP585) period (2040–2059).

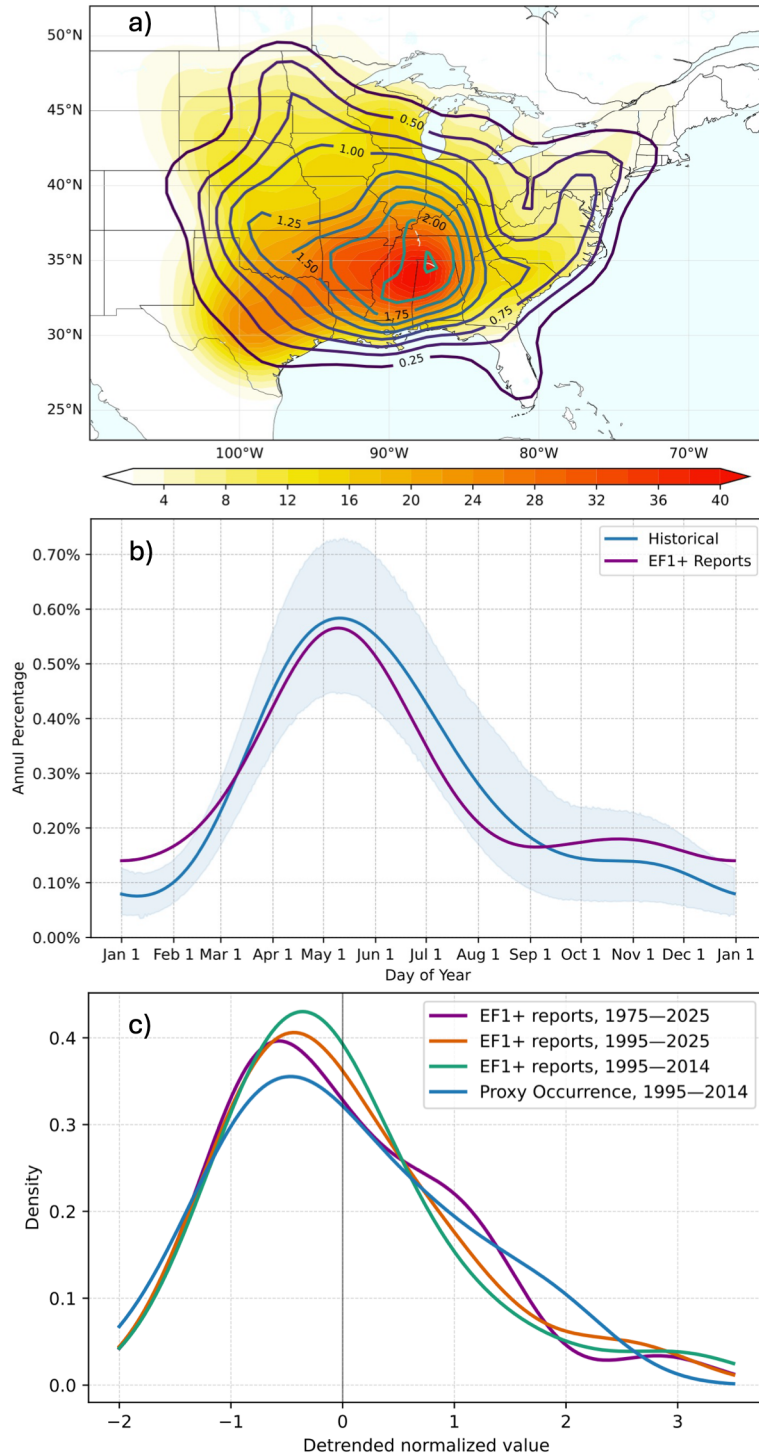


Figure S3. Comparison between CPDD results and historical tornado climatology. a) Geospatial distribution (smoothed by a two-dimensional Gaussian filter with $\sigma=1.5$) of tornado proxy occurrences (color fill) and NOAA SPC EF1+ reports (lines); b) annual cycle (smoothed by a Gaussian filter with $\sigma=30$) of the annual percentage of EF1+ tornado reports and CPDD proxy occurrence during 1995–2014; c) the comparison between the variability of the normalized detrended tornado proxy occurrences and EF1+ tornado reports over three different periods.

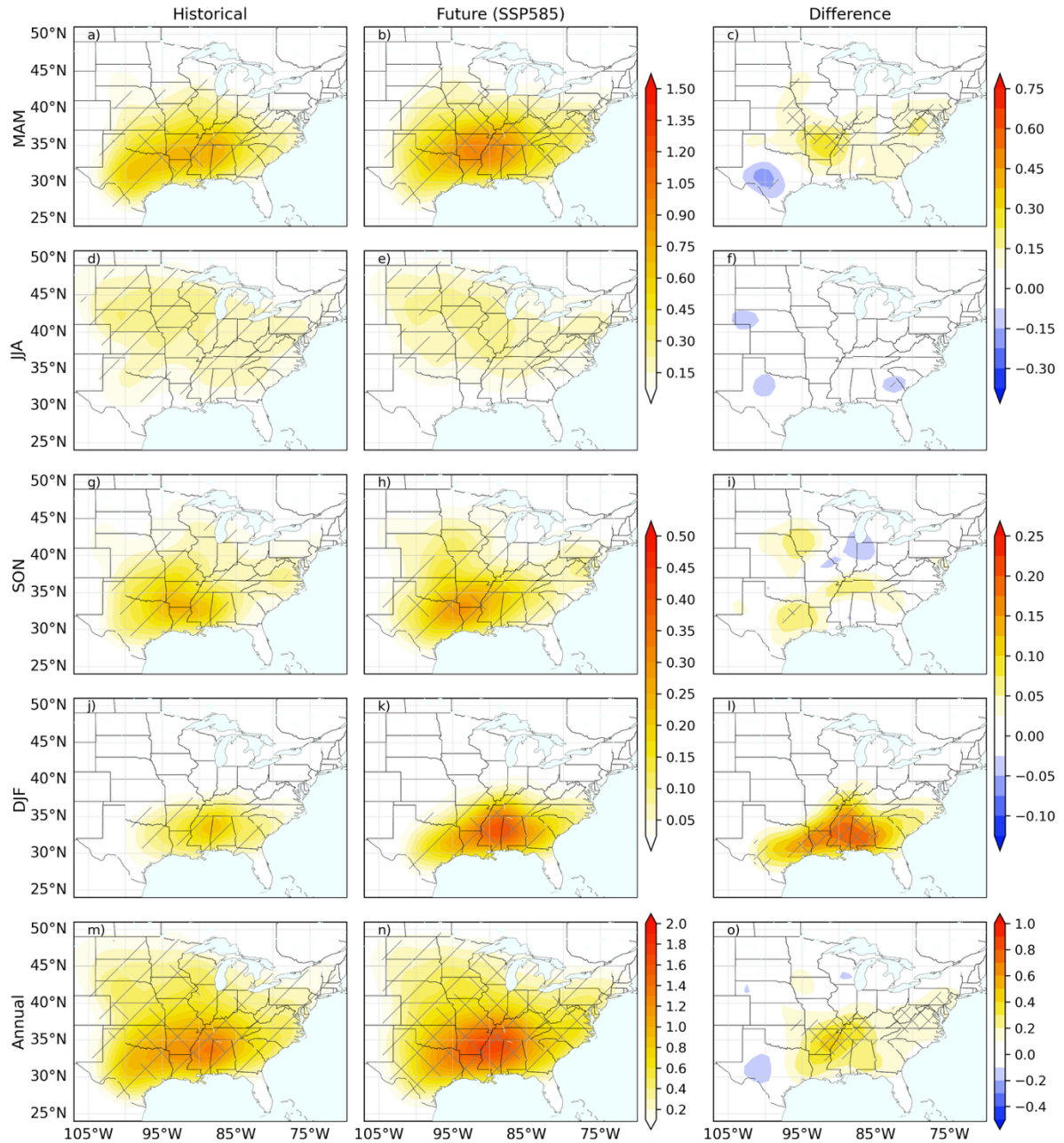


Figure S4. Geospatial analyses of annual and seasonal ensemble mean tornado proxy days over 2-d maps for the historical and future periods and their differences. Values are smoothed by a two-dimensional Gaussian filter with $\sigma=1.5$. Regional distributions are shown for for spring (MAM, a–c), summer (JJA, d–f), fall (SON, g–i), winter (DJF, j–l), and the whole year (m–o). Historical occurrences are represented in the left column, future occurrences in the middle column, and the difference in the right column. The hatching in the historical and future panels indicates robustness: ensemble mean > ensemble std is marked with forward slashes; ensemble mean > twice ensemble std is marked with backslashes. The hatching in the response plots indicates the significance of a t-test: p-value < 0.10 is marked with forward slashes; and p-value < 0.05 is marked with backslashes. Note that the color scale is not the same for

different panels due to large variations in seasonal frequency. The unit of the scale is average number of tornado proxy days per season (or year).

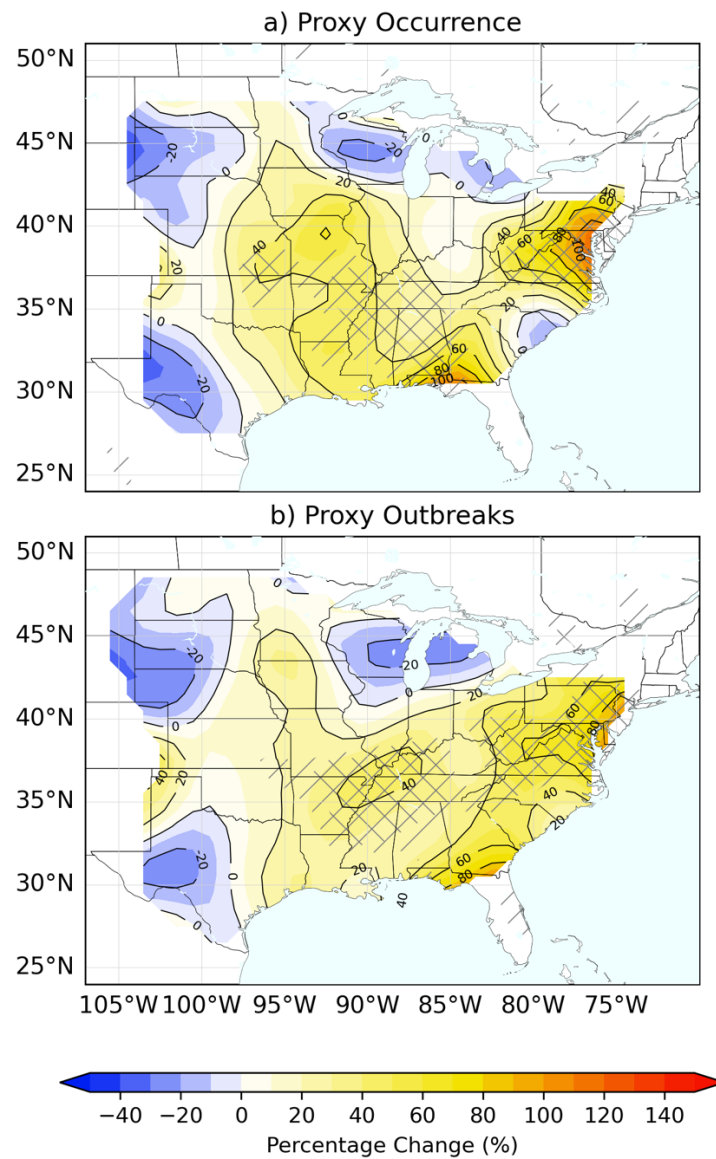


Figure S5. Percentage change of the annual ensemble mean future-minus historical differences. Percentages are calculated relative to the local historical values for a) tornado proxy occurrence and b) tornado proxy outbreaks at each grid points. The hatching indicates the significance of a t-test on the absolute change values: $p\text{-value} < 0.10$ is marked with forward slashes; and $p\text{-value} < 0.05$ is marked with back slashes.

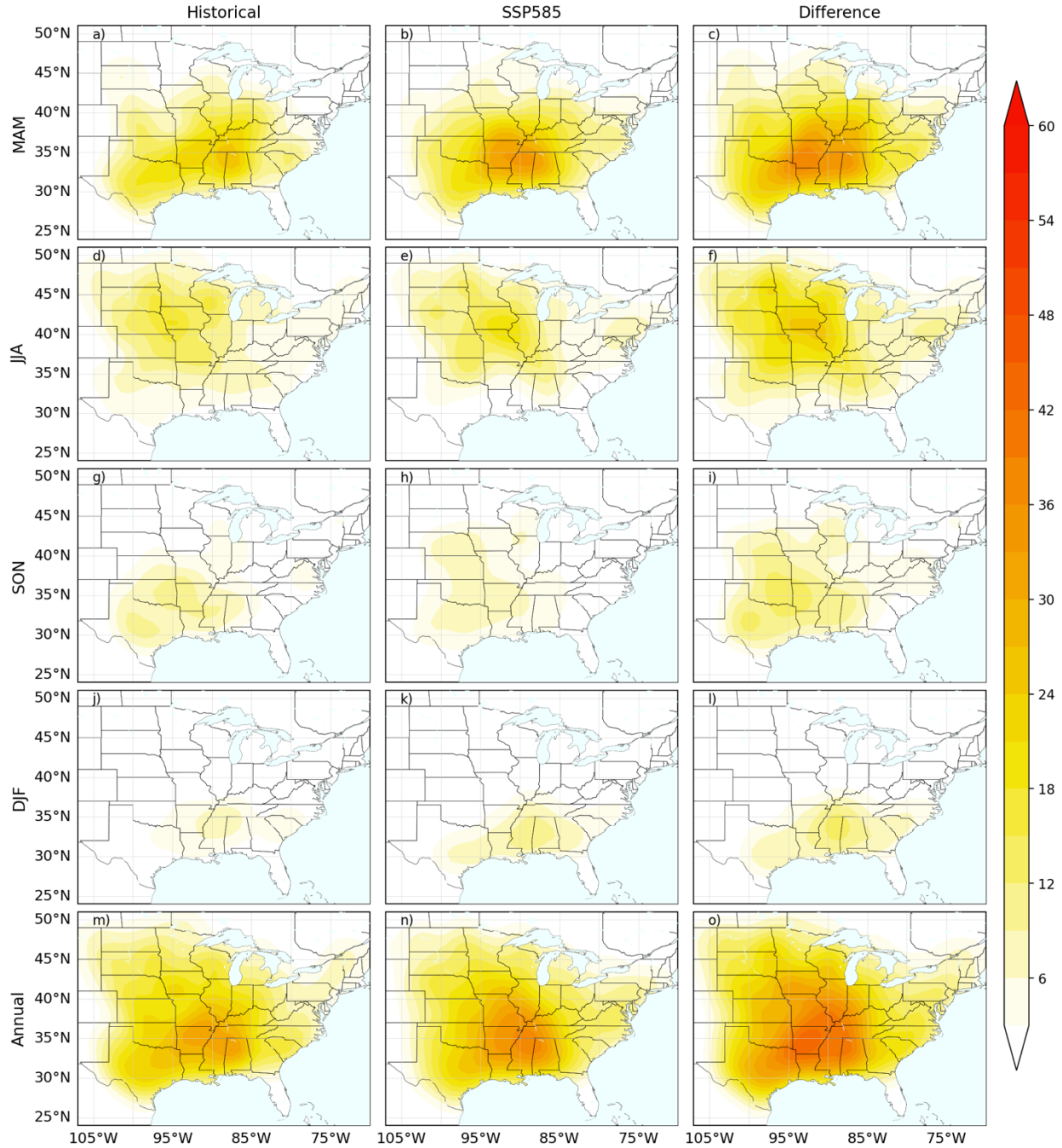


Figure S6. Geospatial analyses of annual and seasonal ensemble standard deviation of tornado proxy occurrences for the historical, future period and their difference. Values are smoothed by a two-dimensional Gaussian filter with $\sigma=1.5$. Regional distributions are shown for spring (MAM, a–c), summer (JJA, d–f), fall (SON, g–i), winter (DJF, j–l), and the whole year (m–o). The standard deviation of historical occurrences is represented in the left column, future occurrences in the middle column, and the response (difference) in the right column. The unit of the scale is average number of tornado proxy occurrences per season (or year).

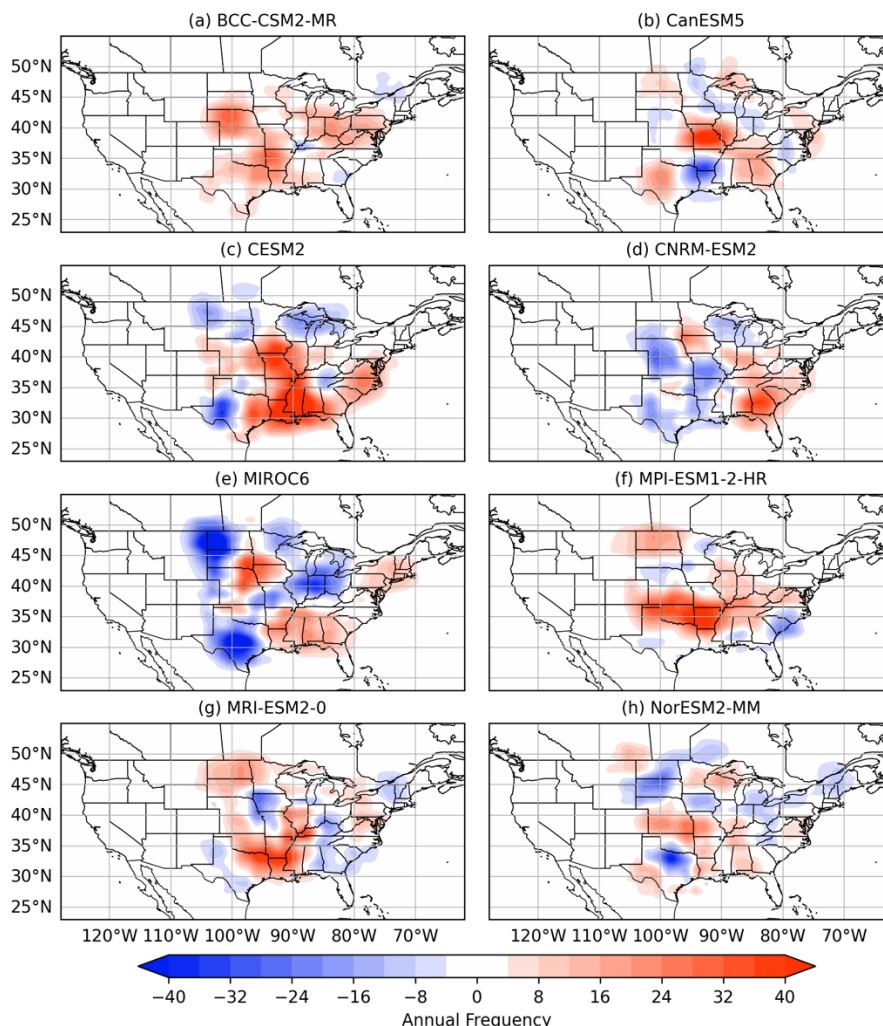


Figure S7. Future-minus-historical difference of annual tornado proxy occurrences for each GCM driver in the ensemble. The members of the ensemble are a) BCC-CSM2-MR, b) CanESM5, c) CESM2, d) CNRM-ESM2, e) MIROC6, f) MPI-ESM1-2-HR, g) MRI-ESM2-0, and h) NorESM2-MM.

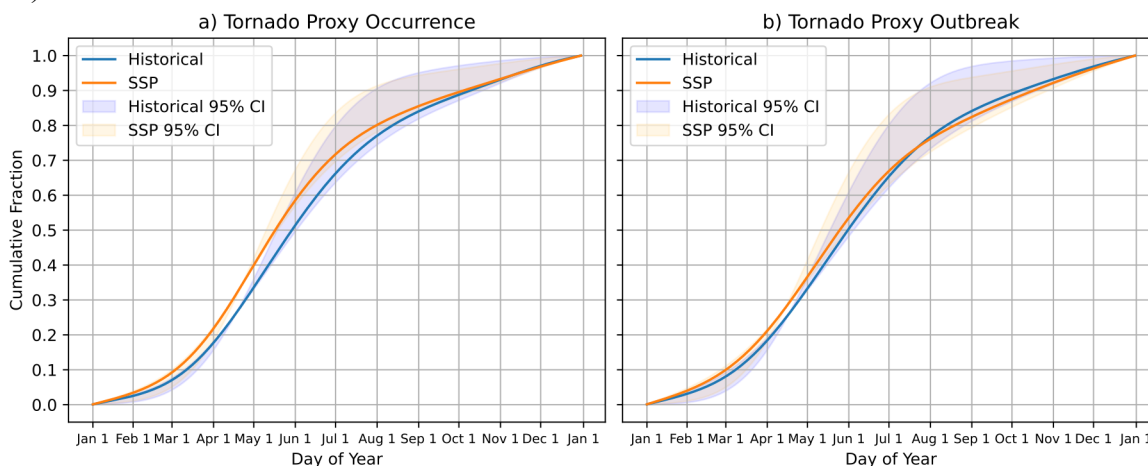


Figure S8. Cumulative fraction of tornadic activities in an annual cycle. Distributions are presented for a) tornado proxy occurrences and b) tornado proxy outbreaks.

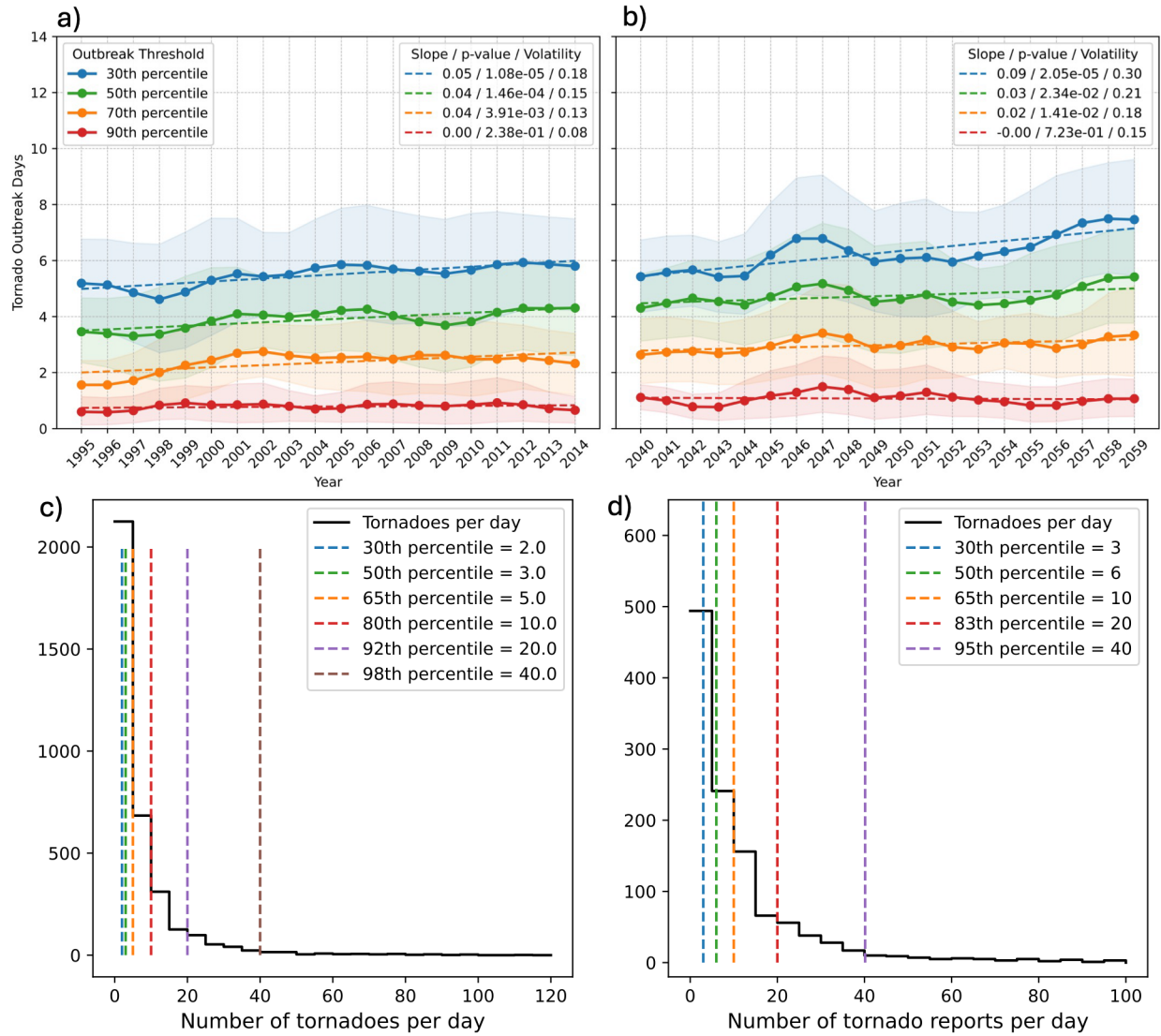


Figure S9. Ensemble mean tornado outbreak trends for the historical and future periods and threshold definitions. Ensemble mean tornado outbreak trends (smoothed by a Gaussian filter with $\sigma=1$) with different percentile thresholds (as defined in panel c) are presented for a) historical and b) future time periods. The distribution and the values of different percentiles are presented for c) daily tornado proxy occurrences during the historical period and d) daily tornado reports on our candidate days (ERA5-forced simulations).

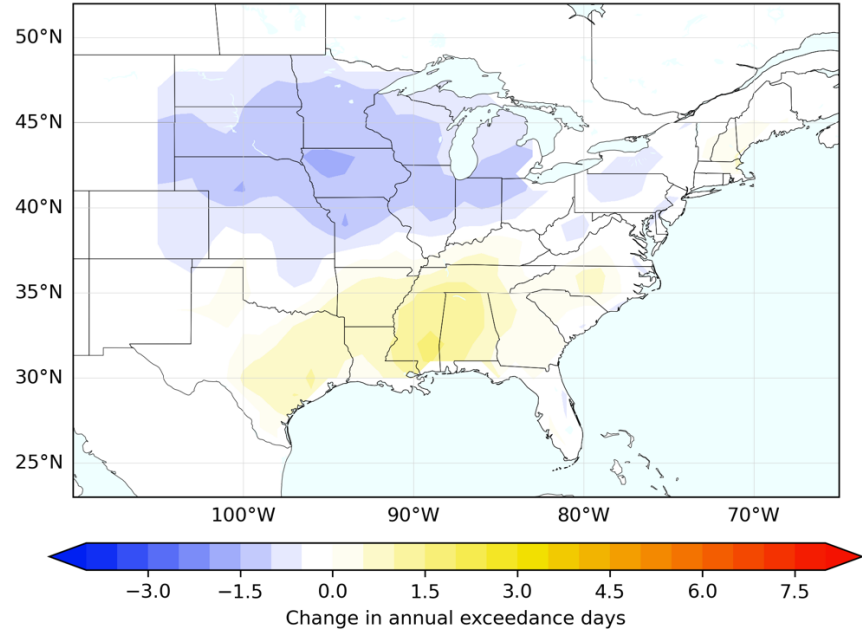


Figure S10. Ensemble mean future-minus-historical change of the number of tornado favorable days for SSP245. Tornado favorable days are defined with daily maximum STP ≥ 1 . The change is the difference between the future periods of 2040–2059 and the historical period of 1995–2014 (performed with the same GCMs except MRI-ESM2-0 due to data unavailability).

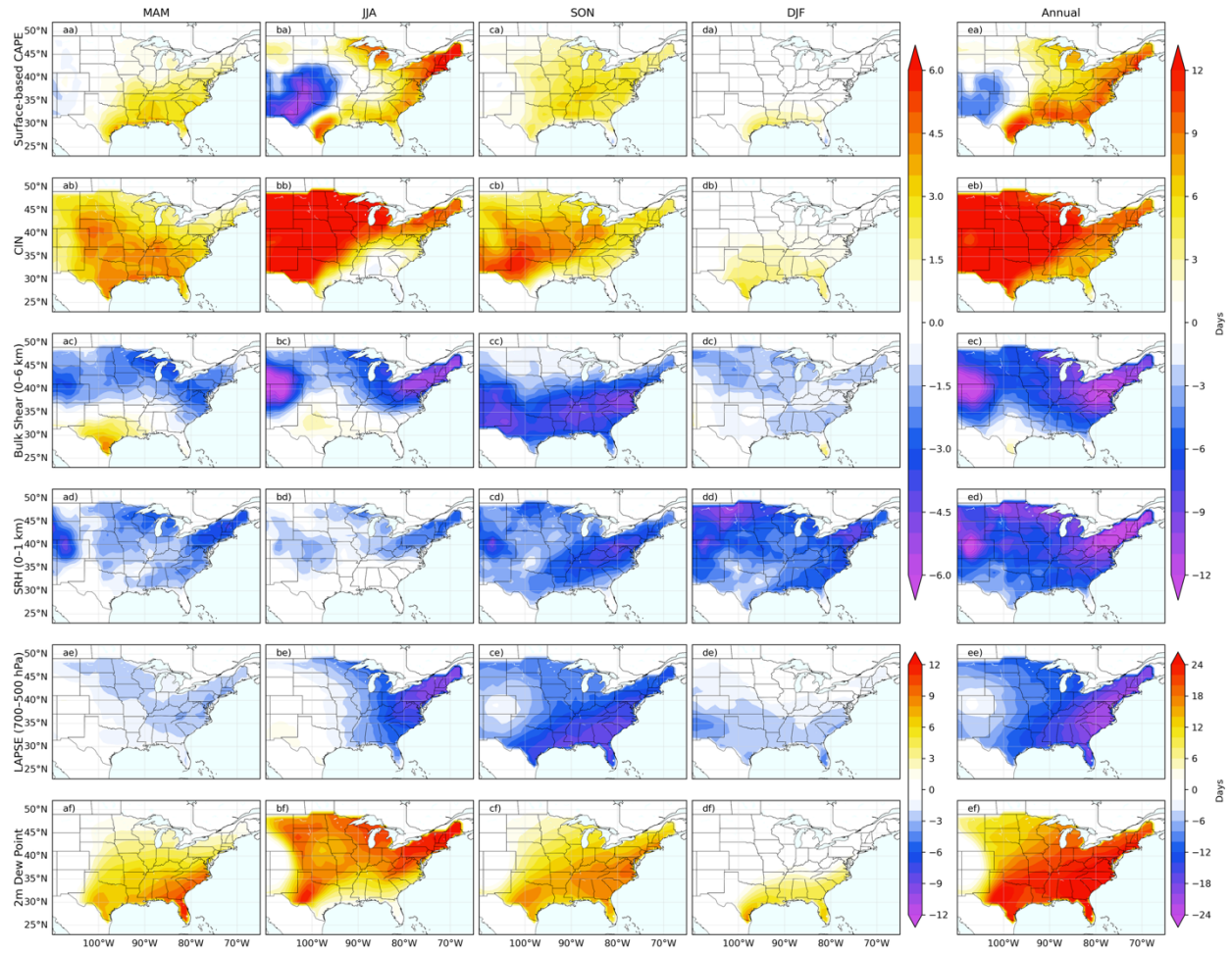


Figure S11. Geospatial analyses of annual and seasonal ensemble mean future-minus-historical difference of tornado-related environments. Environmental variables climatology is presented for spring (MAM, aa–af), summer (JJA, ba–bf), fall (SON, ca–cf), winter (DJF, da–df), and the whole year (ea–ef). Shaded contours are the change in the number of days with daily maximum CAPE > 1500 J/kg (aa–ea), daily maximum CIN > 150 J/kg (ab–eb), daily maximum 0–6 km bulk shear > 20 m/s (ac–ec), daily maximum 0–1 km SRH > 150 m²/s² (ad–ed), daily maximum 700–500 hPa lapse rate > 6°C/km (ae–ee), and daily maximum 2m dew point > 60°F (af–ef).

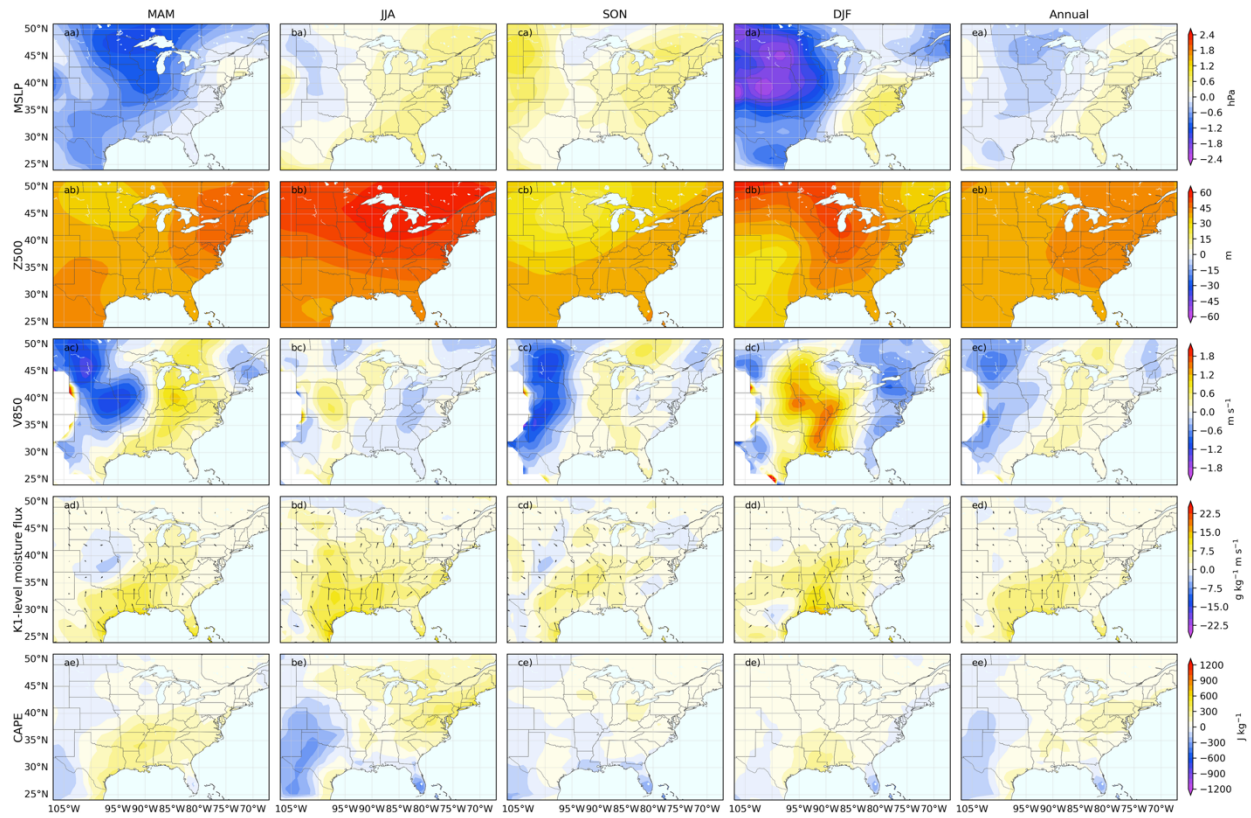


Figure S12. Geospatial analyses of annual and seasonal ensemble mean future-minus-historical difference of synoptic-scale environments on simulation days. Ensemble mean differences are presented for mean sea-level pressure (aa–ea), 500 hPa geopotential height (ab–eb), 850 hPa meridional wind (ac–ec), lowest-model level moisture flux (ad–ed, arrows showing directions of the $q \cdot \vec{V}$ vector), and CAPE (ae–ee) on the simulated days in spring (MAM, aa–ae), summer (JJA, ba–be), fall (SON, ca–ce), winter (DJF, da–de) and all simulated days (Annual, ea–ee).

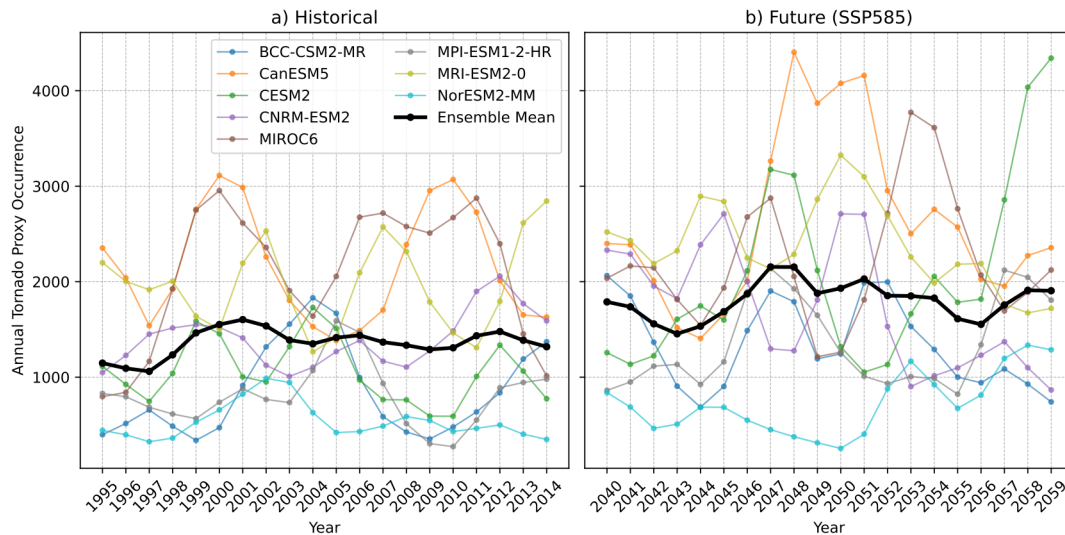


Figure S13. Time series of annual tornado proxy occurrence of the ensemble mean and all members for the historical and future periods. a) Historical and b) future (SSP585) time series are presented for 1995–2014 and 2040–2059, respectively.

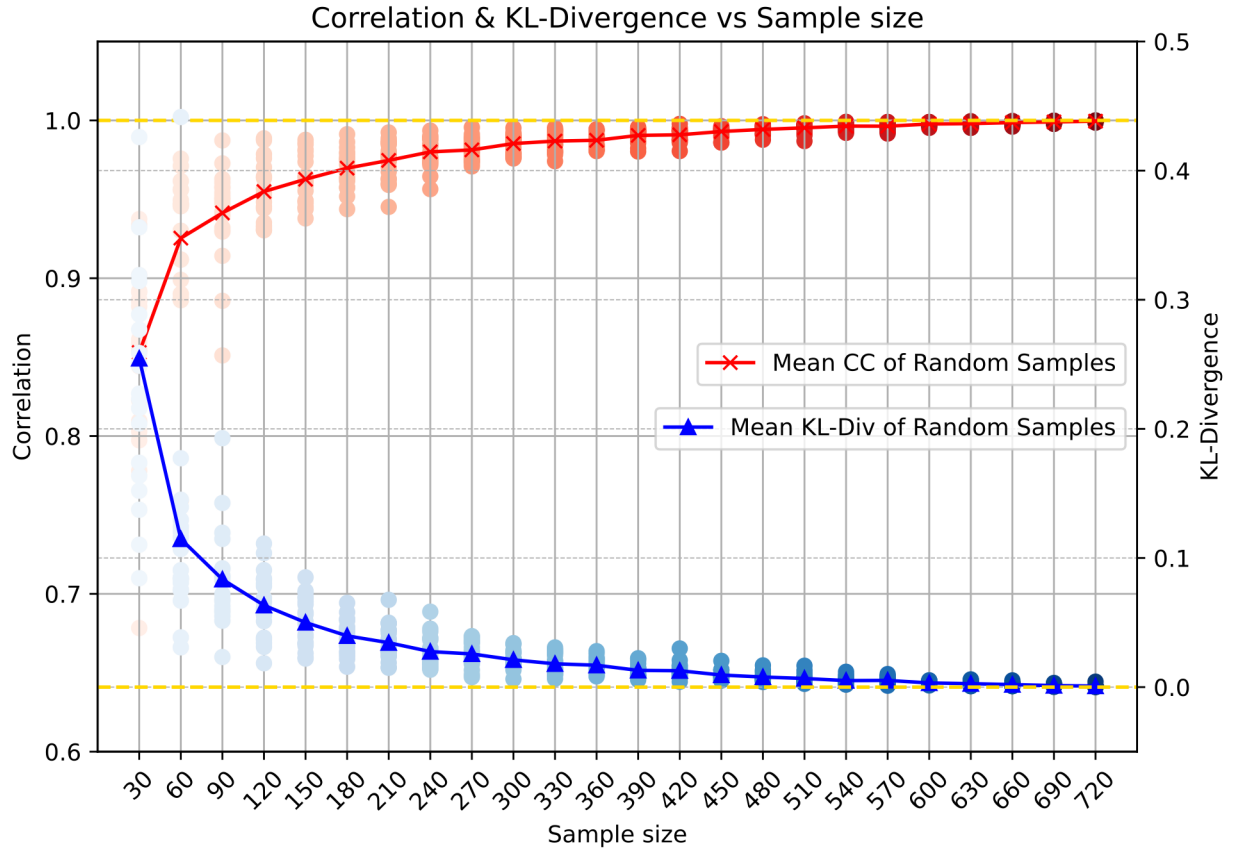


Figure S14. Bootstrapping test of sample size in the random sampling process. Samples with different sizes are randomly drawn from the 750-case dataset of CPDD simulations driven by ERA5. Pattern correlation coefficient (CC) and Kullback-Leibler (KL) divergence are marked in red and blue, respectively. Each scatter point represents the CC (red dots) and KL divergence (blue dots) of one bootstrap sample. The red crosses and blue triangles represent, respectively, the mean CC and KL divergence of the 20 bootstrap samples for each size of subsets.

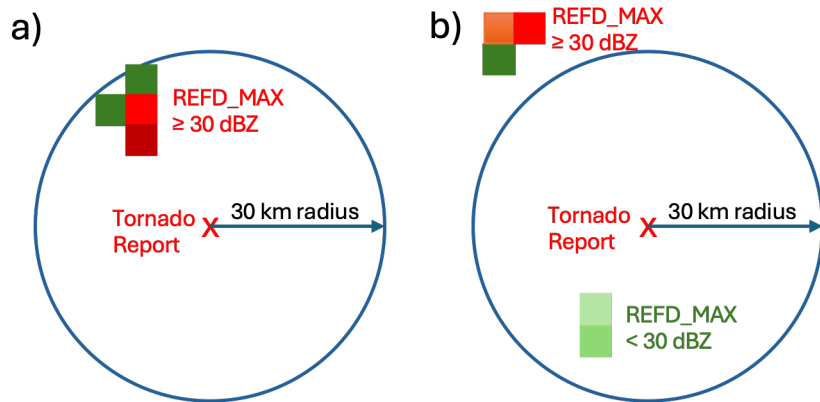


Figure S15. Illustration of storm searching process. Examples of a) matched tornado report and b) unmatched tornado report are presented.

Table S1. Two-sample KS-test between normalized detrended proxy occurrence of our CPDD simulation and normalized detrended EF1+ tornado reports during three different periods.

Report period	n	KS statistic	P-value
EF1+ reports, 1975-2025	51	0.1127	0.9796
EF1+ reports, 1995-2025	31	0.1484	0.9064
EF1+ reports, 1995-2014	20	0.1500	0.9831

Table S2. Two-sample KS-test results on the distributions of tornado proxy swath metrics in two periods.

Metric	GCM	Historical Swaths	Future Swaths	P-value
Proxy Swath length (km)	BCC-CSM2-MR	1497	2843	0.0600
	CanESM5	3123	3995	0.5196
	CESM2	3356	4205	0.0000
	CNRM-ESM2	2578	3014	0.1667
	MIROC6	4432	4647	0.0041
	MPI-ESM1-2-HR	1617	2250	0.1511
	MRI-ESM2-0	2560	3333	0.9856
	NorESM2-MM	3218	3175	0.3500
	All models pooled	22381	27462	0.5734
Proxy Swath Area (km ²)	BCC-CSM2-MR	1497	2843	0.4646
	CanESM5	3123	3995	0.9969
	CESM2	3356	4205	0.0062
	CNRM-ESM2	2578	3014	0.6277
	MIROC6	4432	4647	0.0293
	MPI-ESM1-2-HR	1617	2250	0.1497
	MRI-ESM2-0	2560	3333	0.6212
	NorESM2-MM	3218	3175	0.8097
	All models pooled	22381	27462	0.9591