

Regional increases in tornadic activity through midcentury due to global warming

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Abstract

An ensemble of high-resolution dynamical model simulations is used to project future tornadic activity in the United States under a high emissions scenario. The simulations are performed at 3-km grid spacings and are forced by initial and lateral boundary conditions provided by eight different GCMs sourced from CMIP6 archive. Two bi-decade epochs, 1995–2014 (historical) and 2040–2059 (SSP585), are considered. Tornado occurrence is represented by proxies based on attributes of the explicitly resolved thunderstorms. The historical simulations reproduce the geospatial distribution of EF1 + tornado reports well. Tornado proxy occurrences and outbreaks increase in the future in the region extending northward from the southeast U.S. into the Midwest. The inter-annual variability in proxy occurrences is larger in the future. Seasonally, boreal spring contributes to the largest future increase, with a seasonal cycle that peaks one to two weeks earlier. A key driver of these changes is CAPE, with particular regional and seasonal increases that appear to be linked at least in part to changes in synoptic-scale storm track. The results from this study offer a reference for emergency management, infrastructure resilience, and long-term climate adaptation strategies in the most vulnerable regions of the United States.

Introduction

To date, the effect of anthropogenic climate change on future tornado activity remains an open question. Clues about the future may, however, be revealed by a consideration of the past. Mindful of the caveats of the historical tornado database ¹, we note that: the annual number of tornado occurrences in the United States rated as (E)F1+, i.e., “tornado reports”, exhibit a positive trend over the past multiple decades; the annual number of days with at least one (E)F1 + tornado, i.e., “tornado days”, exhibit a negative trend; and the annual number of days on which large numbers of tornadoes occur, i.e., “tornado outbreak days”, exhibit a positive trend ^{2,3}, even when an additional decade of tornado reports is taken into consideration ³ (see Figure S1). An increase in the inter-annual variability of reported tornadoes, quantified as an increase in volatility ⁴, has also been found.

These temporal trends appear to have geospatial manifestations. Evidence of a geospatial shift is provided in the analysis by ref ⁵, which displays statistically significant positive trends in tornado reports — and supporting meteorological conditions — in a zone extending from Gulf of Mexico northward into the Midwest, and statistically significant negative trends in southern Texas northward into Oklahoma. Such trends are similarly depicted by ref ⁶. When further stratified by season, the trend of tornado days in southeast U.S. is positive during the cool season (November through February) and negative during the warm season (April through July) ³.

One could simply project — linearly or otherwise — these trends into the future. However, this approach does not account for the range of future greenhouse gas emission scenarios and associated range of nonlinear climatic responses ⁷. In this regard, a more reliable projection would be based on physics-constrained numerical models. Even though the effective grid resolution of typical global and regional climate models (GCMs and RCMs, respectively) is too coarse to explicitly represent tornadic thunderstorms, implicit representations are possible through analyses of the meteorological conditions that support their existence. Such conditions can be quantified using environmental parameters including convective available potential energy (CAPE), bulk vertical wind shear (VWS), and storm-relative helicity (SRH), as well as combinations of these parameters, especially the significant tornado parameter (STP) ^{8–11}; higher values generally imply a greater probability of tornado occurrence. Although environment-based projections ^{12–23} are foundational, they still have a fundamental limitation: environments alone cannot explicitly represent thunderstorm initiation, implying that projected frequencies are outer bounds ²⁴.

Convection-permitting dynamical downscaling (CPDD) of relatively coarse GCM, RCM, or reanalysis data to kilometer-scale resolution provides such explicit representations^{24,25} but when used for regional climate applications is computationally expensive. Accordingly, the relevant CPDD studies to date have only downscaled a single GCM^{26–29}, implying a susceptibility of their associated projections to model bias³⁰. This motivates our use herein of kilometer-scale simulations from an ensemble of downscaled GCMs, as generated through a prescreening, filtering, and random-sampling process termed environment-informed CPDD (EICPDD)³¹. Of equal motivation is that no CPDD study to date has specifically pursued future projections of tornadic activity. We use this EICPDD ensemble to develop such a projection for the United States.

Results

Assessment of tornado proxies using historical reports

We first assess the EICPDD over the historical period (1995–2014) by comparing tornado reports from the NOAA Storm Prediction Center database to *tornado proxy occurrences* based on attributes of explicitly resolved rotating thunderstorms in the downscaled GCMs (see Methods). Despite the inherent differences between human-based reporting¹ and simulated storm-based detection (see Methods), the GCM-forced ensemble proxy occurrences in each season and region (see Figure S2a) has a similar percentage to that of tornado reports (Fig. 1a). In addition, the geospatial distributions of the reports and the modelled proxies are well aligned (Figure S3a): both show a maximum in the southeast (SE) U.S. extending westward into the southern Great Plains (SGP) and northward into the Midwest (MW). Likewise, the seasonal cycle of the tornado proxies corresponds well to that of the tornado reports over the historical period (Figure S3b), as does the interannual variability (Figure S3c; Table S1). Indeed, Figures S3a–c clearly demonstrate the capability of our EICPDD ensemble to represent the historical tornado climatology, at least in a bulk sense.

Tornado proxy occurrences over historical and future periods

The ensemble mean of seasonal and annual tornado proxy occurrence is presented in Fig. 2 for the historical as well as future (2040–2059; SSP585) periods. In both periods, proxies are maximized during boreal spring in the southeast U.S. Proxy maxima of lesser amplitudes are shown during: summer in the upper Midwest, fall in the southern Great Plains, and winter in the southeast. This implied cycle, which is also represented in Fig. 1 as well as in geospatial analyses of tornado proxy *days* (Figure S4), corresponds to the known seasonal migration of tornadic storm forcing in the United States³².

The future minus historical differences (right column of Fig. 2) are considered the response of proxy occurrences to anthropogenic climate change; the possible effects of internal climate variability are also acknowledged (see the discussion below). There is a future increase of up to 16.4 (95% CI: 4.7–29.5) proxies per 1°×1° grid box in the region from Gulf of Mexico extending through the Midwest, and around 7.1 (95% CI: 3.9–10.0) in the northeast U.S.; on average these represent increases of 28.7% and 53.4%, respectively, relative to the local historical occurrences (see also Figure S5). Decreases of up to 5.7 (95% CI: -2.1–13.6) proxies per 1°×1° grid box occur in western Texas (Fig. 2c), which is on average 7.98% decrease relative to the local historical occurrence. The response in spring contributes most to the changes in annual frequency in areas south of ~40°N latitude, including the statistically significant increases in the southeast and Midwest, and the decreases over Texas (Fig. 2f). For summer and fall the response lacks significant signals over large areas (Fig. 2i&l). In winter, the response is positive and statistically

significant along the Gulf coast (Fig. 2o). Such regional responses can also be confirmed by Fig. 1. The overall conclusion is that under the high emissions scenario described by SSP585, tornado occurrence is projected to increase in the future, especially during the spring and winter seasons, over a broad area extending to 45° N latitude, and generally east of 95° W longitude.

Within both the historical and future periods the seasonal and regional distribution of proxy occurrences for all ensemble members (Fig. 1) show that the percentages of proxy occurrences are clearly different across the GCMs. This is especially reflected in larger differences within the future period for spring and summer; the numbers of proxy occurrences per season and region also have a large deviation across the GCMs (Figure S2b&c). The season and region of largest future increase depend on the individual GCMs. For example, in spring the largest increase for CanESM5 is in the Midwest, while for CNRM-ESM2 this signal is found in the southeast U.S., despite being of similar magnitudes. As computed from all GCMs, the largest standard deviations of proxy occurrences are found in the southeast during the spring season (Figure S6). Spatial distribution of the future-minus-historical change can also have differences in detail (Figure S7). Such variability across GCMs testifies to the utility of a multi-model ensemble approach.

Over the eastern contiguous United States (ECONUS; see Figure S2a), the time series of ensemble mean tornado proxy occurrences within the 20-year historical and future periods exhibit positive trends, but with low significance (Fig. 3a). However, the one-sided two-sample t-test between the historical and future period has a p-value of 0.00076, providing evidence that the proxy occurrences are significantly greater in the future period. In addition, the volatility⁴ of the occurrences in the future is also larger, which means there is more inter-annual variability of the tornado proxy in the future period.

The increase in global mean temperature during the historical period (1995–2014) and future period (2040–2059; SSP585) is ~ 0.5°C and ~ 1°C respectively, for the GCMs downscaled in this study²³. Over these two periods, the occurrence frequency of tornado proxies increases annually by ~ 12% and ~ 8% respectively, over the ECONUS. Acknowledging the lack of statistical significance with the associated trends (Fig. 3a), the rate of proxy increase per degree of global warming would appear to be relatively less in the future, which is consistent with the rate of increase in the frequency of days with tornado-supportive environments (0.6 days/year in historical period and 0.3 days/year in the future period).

As suggested in Figs. 1–2, the seasonal cycle of the tornado proxies (Fig. 3b; see also Figure S3b) is amplified in the future under SSP585, especially during spring. Embedded within this amplification is a shift of annual peak from 10 May (day 130; 129–133, 95% CI) to 29 April (day 119; 118–123, 95% CI). Mean occurrences from June to the end of the year remain approximately the same for the future, but the start of the tornado season, characterized by 10% of annual occurrences^{2,28}, shifts from 12 March (day 71; 61–79, 95% CI) to 4 March (day 63; 61–76, 95% CI) (see Figure S8a). We recognize that the seasonality as well as the interannual variability of tornado activity can also be related to modes of internal climate variability^{33–36}. Although the 95% confidence interval of the annual peak of proxy occurrences do not overlap, the future shift of the seasonal cycle in Fig. 3 is still within the bounds of internal climate variability in ref.³³.

Tornado proxy outbreaks and spatial metrics

Instances of relatively large numbers (> 50th percentile) of tornado proxies on given days are quantified as outbreaks (see Methods). As shown in the time series of tornado proxy outbreaks (Fig. 3c), the annual trend is

significantly positive during the historical period (Fig. 3c), which is consistent with the trend of observed outbreaks in the United States^{2,3}. The trend in the future is also significantly positive, but with a slope that is less steep than in the past (Fig. 3c, Figure S9a&b). Thus, the rate of proxy outbreaks per degree of global warming would also appear to be relatively less in the future ($\sim 11\%/1^\circ\text{C}$), compared to that in the historical period ($\sim 23\%/0.5^\circ\text{C}$). Nevertheless, on average, there are more outbreak days in the future period under SSP585, as supported by a p-value of 0.00016 from a one-sided two-sample t-test. The lesser significance of the trend and larger volatility in the future period compared to the historical period indicate that the future tornado outbreak activity is more uncertain.

A shift and amplification in the seasonal cycle of tornado proxy outbreaks are also observed (Fig. 3d). The annual peak shifts from 16 May (day 136; 130–138, 95% CI) to 9 May (day 129; 125–131, 95% CI). The uncertainty of outbreak seasonal cycle is, however, much larger than that of the proxy occurrences, likely due to the lower number of outbreak events. In addition, our prior statement regarding the contributions of modes of internal climate variability also applies here to outbreaks.

The geospatial distribution of tornado proxy outbreaks (Fig. 4) is quite similar to that of tornado proxy occurrence (Fig. 2) and proxy days (Figure S4). Likewise, the seasonal migrations of areas affected by outbreaks in historical and future period are similar, as are the future expansions of outbreak areas, especially in fall and winter (Fig. 4j, 4k, 4m, & 4n). The overall conclusion is that under the high emissions scenario of SSP585, outbreaks are projected to increase in the future, especially during the spring and winter seasons, over a broad area generally south of 40°N latitude, and east of 100°W longitude. Accompanying this conclusion is an uncertainty for outbreaks that is relatively higher than that for tornado occurrence alone.

The spatial metrics of the tornado proxies are presented in Table 1. Compared to the historical period, the mean proxy outbreak area as well as the mean outbreak area fraction (proxy outbreak area normalized by the land area within each simulation domain) are projected to increase in the future under SSP585, at the 0.05 significance level. When magnified to the scale of tornado proxy swaths, a future increase in the area of tornado proxy swaths and a decrease in the density of tornado proxy swaths are observed during outbreak events, but they are not statistically significant. This suggests that tornado outbreaks in the future may be spatially larger but not necessarily composed of more spatially connected tornado swaths. For all events, only the maximum swath length is observed to significantly increase in the future while the maximum swath area and mean swath length and area remain at the same levels. The distribution of the swath metrics are identical in two periods (Table S1).

Table 1

Ensemble mean metrics on the spatial distribution of tornado proxies over the historical and future (SSP585) period, with the p-value of paired two-sample t-test.

	Metric (Ensemble Mean)	Historical	SSP585	P-value
Tornado Proxy Outbreak Areas	Outbreak Area (km ²)	143,897.73	153,560.04	0.0440
	Outbreak Area Fraction	0.1223	0.1321	0.0089
	Proxy Swath Area (km ²)	3,041.36	3,183.36	0.3309
	Outbreak Swath Density	0.0446	0.0398	0.3486
Tornado Proxy Swath Characteristics	Mean Swath length (km)	20.13	20.02	0.8435
	Mean Swath Area (km ²)	130.89	131.81	0.8477
	Maximum Swath length (km)	386.45	510.55	0.0397
	Maximum Swath Area (km ²)	8,454.38	10,037.25	0.5870

Discussion

Our CPDD-based projection of future tornadic activity under a high emissions scenario highlights an increase in tornado proxy occurrence and outbreaks over a broad geographical area centered on approximately 35°N, 90°W, which is inclusive of the southeast U.S. and parts of the Midwest. Although applicable specifically for a midcentury (2040–2059) time period under SSP585, this conclusion is consistent with historical trends in reported tornadoes^{3,5,37}. It is also consistent with trends in observed environmental conditions supportive of tornadoes^{5,38,39}. In this regard, the past does indeed reveal clues about the future, at least for tornadoes.

For insight beyond midcentury, we can again return to environmental conditions evaluated using GCM data. As a function of bi-decade periods, exceedances of the multivariate parameter STP clearly indicate a progressive increase, under SSP585, in the mean annual frequency of days of tornado-supportive environments to the end of the 21st Century (Fig. 5); for reference, the annual frequency of such days is approximately 60% less during the period 2040–2059 for SSP245 relative to SSP585 (cf. Figure 5b and Figure S10), thus emphasizing that our use of a high emissions scenario yields a high end projection. Although we have already argued that such environment-based information lacks the details generated by CPDD, especially related to where and when tornadic storms are realized²⁴, it nonetheless adds to the evidence indicating a regional increase in U.S. tornadic activity during boreal spring. Indeed, an ECONUS-wide increase is likewise indicated in annual counts of STP exceedances over 2015–2099 (Fig. 5e). This outer bound estimate of an approximately 18% increase in annual days with tornado-favorable environments under SSP585 contrasts with the long-term negative trend of annual tornado days based on reports over 1990–2025 (Figure S1b). The projected increase is consistent, however, with the positive trend and associated 15% increase in tornado days over the last decade (2015–2025) of the report database (Figure S1b). Trend confirmation awaits additional years of data as well as the next generation of GCM simulations⁴⁰.

The driver of this increase is CAPE, as can be deduced from a separation of the environmental contributions to STP. Perhaps unsurprisingly given the narrative introduced in early studies^{12,15}, the generally negative contributions from CIN and the wind shear parameters are more than offset by the positive contributions from CAPE (Figure S11). Also consistent with the narrative in early studies^{16,21} is that the increase in the frequency of tornado-supportive CAPE is

primarily a response to increases in temperature and water vapor within the atmospheric boundary layer (Figure S11). The specific regional increase in the tornado proxy occurrences as well as tornado-supportive environments revealed in this study appears to be driven by changes in the synoptic-scale processes that condition the atmosphere for deep convection. Future minus historical differences in mean sea level pressure, 500-hPa geopotential height, and 850-hPa meridional wind on days selected for CPDD suggest an eastward shift and/or intensification of the extratropical storm track, particularly in boreal spring (Figure S12). In particular, the corresponding shift/intensification of low-level moisture flux originating from the Gulf of Mexico (Figure S12 ad–ed) would enhance CAPE especially from the Gulf coast northward through the Midwest (Figure S12 ae–ee). This corroborates previous findings on the importance of heat and humidity sourced from the Gulf of Mexico for convective storms in North America ^{41,42}.

These environmental as well as downscaled changes extend from the multi-GCM ensemble, which thus provides more confidence in the results by balancing the biases and internal variability of different members. Because CMIP6 simulations are freely evolving rather than initialized to reproduce the observed climate state, internally generated variability is generally not synchronized in phase across different GCMs ^{43–45}. The contribution of randomly phased internal climate variability, therefore, is reduced by averaging across the ensemble. The tornado proxy occurrences from simulations with different GCM drivers do have offsets in phase (Figure S13). The extent to which internal variability affects the interpretations is difficult to quantify, which is still a limitation of this work. Nevertheless, as compared to downscaling studies using single drivers, our multi-GCM methodology provides a more balanced perspective.

An important caveat is that the projection herein does not differentiate occurrences by intensity. By invoking theoretical reasoning applied to environmental parameters ⁴⁶, stronger tornadoes would be expected under future conditions. In fact, a tendency for cool-season tornadoes to be disproportionately strengthened in the future relative to warm-season tornadoes has been shown ⁴⁷. Further research involving the use of climate modeling approaches at much higher resolution, e.g., from ~ 100 m to ~ 10 m mesh lengths, will be needed to more fully address the physical drivers of future intensity.

Indeed, grid resolution is an ever-present limitation that must be balanced with other methodological choices, including computational domain size, temporal period of consideration, numbers of experiments, etc. ³¹. Our choice of 3-km mesh lengths allowed for an explicit representation of thunderstorms and their attributes such as updraft core rotation, which were used to diagnose likely tornado occurrence. Support for this approach, including a theoretical analysis, is provided by ref ⁴⁷. We do acknowledge, in the vernacular of forecast verification, the possibility both of “false alarms” and “misses” with our proxies. The geospatial and seasonal correspondences between our proxy occurrences and observed tornadoes during the historical period (Figure S3a–c) argue that our modelled proxies provide both an acceptable reference state and a basis for an assessment of future changes relative to it.

Methods

Kilometer-scale simulation ensemble via the EICPDD approach

This study employed the ensemble of kilometer-scale simulations generated by ref. ³¹ via the environment-informed convection permitted dynamical downscaling (EICPDD) approach. In essence, EICPDD is targeted downscaling, wherein all potential “targets” – in this case, days – were identified in each GCM using an environmental-parameter

threshold. More specifically, daily maximum supercell composite parameter (SCP) values at each grid point of each GCM were used to calculate the 75th percentile for each month and then the anomaly with respect to it. Hard thresholds of daily-maximum SCP greater than 0.5 and daily-maximum CAPE greater than 100 J kg^{-1} were applied. After Gaussian smoothing, grid-point signals less than a monthly mean plus standard deviation of daily-maximum SCP were masked out. If the associated geographical area of the remaining signal was sufficiently large, and was located within the ECONUS, the event was effectively included as a candidate case for downscaling.

For each GCM, on average 1,500 candidates (out of 20-year periods) were identified for the historical and future periods respectively. A large (300) sample of days per GCM, per period, was randomly selected (with restrictions on temporal and spatial spacing), and then simulated using the Weather Research and Forecasting (WRF) model version 4.4.1⁴⁸. The choice of the sample size is supported by ref.³¹ and Figure S14. Of note is the use of 3-km horizontal grid point spacings over regional computational domains with dimensions 1,500 km (east-west) by 900 km (north-south). Additional information about the WRF model configuration and implementation can be found in ref.³¹.

The following eight GCMs were downscaled using this approach, as applied over two bi-decade epochs, 1995–2014 (historical) and 2040–2059 (SSP585): BCC-CSM2-MR^{49,50}, CanESM5^{51,52}, CESM2^{53,54}, CNRM-ESM2^{55,56}, MIROC6^{57,58}, MPI-ESM1-2-HR^{59,60}, MRI-ESM2-0^{61,62}, and NorESM2-MM^{63,64}. This midcentury future epoch was chosen to satisfy a desire to gain information that could be actionable by stakeholders and practitioners. The historical epoch was constrained by the CMIP6 historical simulation period, which ended on the year 2014.

Proxies of tornado occurrence and outbreaks

Herein we adopted the concept of a “proxy” from paleoclimatology, and represented tornado occurrence based on attributes of the explicitly resolved thunderstorms in the downscaled simulations. This also follows the well-established practice of using thresholds of quantified thunderstorm-scale attributes to approximate the occurrence of attendant hazardous convective weather^{24,27–29,47,65}. The specific justification for a tornado proxy is provided in ref.⁴⁷, which includes a theoretical analysis in their Supporting Information. Of particular relevance to tornado occurrence are quantifications of rotating updraft cores over near-ground and mid-altitude layers (0–2 km and 2–5 km updraft helicity, respectively)⁶⁶, as well as evidence of a precipitating convective storm (simulated radar reflectivity).

The exceedance thresholds were determined using NOAA Storm Prediction Center tornado reports and corresponding data from EICPDD simulations forced by ERA5³¹. For each of 300 simulation days during the historical period of 1995–2014, model grid points with a simulated radar reflectivity greater than or equal to 30 dBZ were considered matched to a report if they occurred within a search radius of approximately 30 km (about 300 nearest grid points) centered at each report’s location (Figure S15). About 95% of the reports on the 300 simulation days were successfully matched to at least one model grid point. The maximum values of the updraft helicity in 0–2 and 2–5 km layers within the search region for each matched report were catalogued and then averaged across all matched reports. It is noteworthy that these averaged values ($25.76 \text{ m}^2 \text{ s}^{-2}$ for 0–2 km updraft helicity, $115.13 \text{ m}^2 \text{ s}^{-2}$ for 2–5 km updraft helicity), which are thus the exceedance thresholds, are consistent with those used in CP model-based weather forecasting of tornadoes⁶⁶, as are the thresholds of column-maximum radar reflectivity ($\geq 30 \text{ dBZ}$). Accordingly, the exceedance of updraft helicity and radar reflectivity thresholds at a grid point in the WRF simulations were regarded as a tornado proxy occurrence.

Here we clarify that because simulated thunderstorms meeting our criteria are typically composed of multiple grid points, the expectation is that our tornado proxy occurrences are some multiplicative factor of tornado reports. In this light, we consider an outbreak of tornado proxies to have occurred when the number of proxies within a simulation day exceeds the 50th percentile value of the daily proxy distribution among all historical EICPDD simulations (Figure S9c), which is comparable to six tornado reports per day (Figure S9d), thus aligning with some past studies of outbreaks⁶⁷. A test of the sensitivity of proxy outbreak trends to this threshold shows that the trends are similar for thresholds based on a 30–70th percentile range (Figure S9a&b). We also consider a tornado proxy day to be one on which the number of proxies exceeds the 10th percentile value (as shown in Figure S9c).

Result compilations

The proxy occurrences are summed within 1°×1° grid cells over eastern contiguous United States (110°W–60°W, 20°N–55°N, ECONUS) for each GCM and period. Trends, annual cycles, and seasonal and regional analyses, including tests of robustness and statistical significance, are based on these 1°×1° grid cell compilations with additional Gaussian smoothing. The interpretations and principal conclusions are therefore based on coherent regional patterns rather than isolated significant grid points.

Since only selected candidate cases informed by the convective environment are dynamically downscaled, we “inflated” the number of occurrences by multiplying the ratio of the number of candidate cases to the simulated cases (300), for each GCM and period. Tornado proxy outbreak values are also inflated with the same factors. This inflation procedure introduces changes mainly to magnitude with little effect on spatial patterns. Ensemble means are normalized by the ensemble size. Seasonal (and annual) means are the number of occurrences normalized by the number of years in the period. Annual occurrences in trend analysis are the number of occurrences in ECONUS of each year.

Spatial metrics

Proxy outbreak area is characterized by the minimum convex hull polygon of all grid points with proxy occurrences during each outbreak case. Proxy outbreak area fraction is the ratio of outbreak area to the land area in the corresponding WRF domain. Proxy occurrence area is the total area of grid boxes with one or more proxy occurrence during each outbreak case. Outbreak density is characterized by the fraction of proxy occurrence area to the outbreak area.

Proxy tracks are two-dimensional objects consisting of continuous grid points with tornado proxy occurrences during the whole simulation. Grid points must be adjacent to each other to be categorized into the same track.

Significant tornado parameter

The significant tornado parameter (STP) is an environmental parameter used to gain insight into tornado activity beyond midcentury under SSP585 as well as under the SSP245 scenario. The surface-based (SB) formulation of STP is defined as a variation of the original formula¹¹:

$$STP = \begin{cases} \left(\frac{SBCAPE}{1500 \text{ J kg}^{-1}} \right) \left(\frac{2000m-SBLCL}{1000m} \right) \left(\frac{0-1 \text{ km SRH}}{150 \text{ m}^2 \text{ s}^{-2}} \right) \left(\frac{S06}{20 \text{ m s}^{-1}} \right), & SBCIN \leq 125 \text{ J kg}^{-1} \\ 0, & SBCIN > 125 \text{ J kg}^{-1} \end{cases} \quad (1)$$

where SBCIN is expressed with positive values. The LCL term is set to 0 when LCL is higher than 2000 m and 1 when LCL is lower than 1000 m; and the S06 term is set to 0 when S06 is smaller than 12.5 m/s and 1.5 when S06 exceeds 30 m/s.

Declarations

Competing Interests

Dr. Robinson reports personal fees from Aon Ltd during the conduct of the study; personal fees from Aon Ltd outside the submitted work; and Aon Ltd is engaged in the business of insurance broking, which may or may not, at times, consider the implications of climate change and its impacts in the context of advising clients about financial risk. This may involve representing the client in negotiations with third parties where differing views on climate impacts may have meaningful implications for business transactions. The other authors declare no competing financial interests. All authors declare no competing non-financial interests.

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Data Availability

All CMIP6 model outputs can be obtained from Earth System Grid Federation (ESGF, <https://esgf-node.llnl.gov/projects/cmip6/>). ERA5 data can be obtained from ECMWF Climate Data Store (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-complete>).

Code Availability

The source code of WRF model can be accessed at https://www2.mmm.ucar.edu/wrf/users/download/get_source.html. Other information including namelist files for WRF simulations, case lists, and the modification to WRF to calculate 0–2 km updraft helicity can be accessed through <https://github.com/Songningw99/EICPDD-info> ⁶⁸.

Author Contribution

R.T., S.W., J.A., and E.R. designed the research; S.W. conducted the WRF model simulations and developed the analysis code; D.G. and J.A. contributed the GCM-based environmental parameter calculations and WRF initiation and boundary conditions; J.A. and E.R. provided valuable insights on the interpretation of the results; S.W. drafted the first version manuscript and subsequently all co-authors contributed edits and comments to improve the manuscript.

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