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Key Points:

- The effects of climate change on tornado intensity have been unclear
- A novel, multi-modeling approach is used to address such effects
- The intensity of cool-season tornadoes would appear to be most susceptible

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

R. J. Trapp,
jtrapp@illinois.edu

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Author Contributions:

Conceptualization: Matthew J. Woods, Robert J. Trapp
Formal analysis: Matthew J. Woods, Robert J. Trapp, Holly M. Mallinson
Methodology: Matthew J. Woods, Robert J. Trapp
Software: Matthew J. Woods, Robert J. Trapp, Holly M. Mallinson
Supervision: Matthew J. Woods, Robert J. Trapp
Writing – original draft: Matthew J. Woods, Robert J. Trapp

The Impact of Human-Induced Climate Change on Future Tornado Intensity as Revealed Through Multi-Scale Modeling

Matthew J. Woods[1,2], Robert J. Trapp[1], and Holly M. Mallinson[1]

[1]Department of Atmospheric Sciences, University of Illinois, Urbana, IL, USA, [2]Now at National Weather Service, Las Vegas, NV, USA

Abstract A novel, multi-scale climate modeling approach is used to show the potential for increases in future tornado intensity due to anthropogenic climate change. Historical warm- and cool-season (WARM and COOL) tornado events are virtually placed in a globally warmed future via the "pseudo-global warming" method. As hypothesized based on meteorological arguments, the tornadic-storm and associated vortex of the COOL event experiences consistent and robust increases in intensity in an ensemble of imposed climate-change experiments. The tornadic-storm and associated vortex of the WARM event experiences increases in intensity in some of the experiments, but the response is neither consistent nor robust, and is overall weaker than in the COOL event. An examination of environmental parameters provides further support of the disproportionately stronger response in the cool-season event. These results have implications on future tornadoes forming outside of climatologically favored seasons.

Plain Language Summary A novel climate-modeling approach is used to show evidence of potential increases in tornado intensity due to human-induced climate change.

1. Introduction

Hazardous convective weather (HCW) in the form of damaging winds, hail, and tornadoes poses a serious threat to life and property, and tends to be one of the largest contributors to "billion-dollar" (inflation-adjusted) disasters annually in the United States (NOAA, 2022). The occurrence of HCW depends on the 3D characteristics of environmental temperature, humidity, and wind, which appear to have changed over the last few decades (Gensini & Brooks, 2018; Tang et al., 2019; Taszarek et al., 2021) and are projected to change further by the late 21st century due to anthropogenic climate change (ACC). For example, as shown by Trapp et al. (2007), warming and humidification of lower-tropospheric air yields increases in convective available potential energy (CAPE), which leads to increases in the potential intensity of convective-storm updrafts. Conversely, relatively more warming at high latitudes weakens the meridional temperature gradient and thus weakens the vertical shear of the horizontal wind (hereinafter, VWS) per the thermal wind relation (e.g., Trapp et al., 2007); this alone would reduce the tendency for convective updrafts to develop significant, long-lived rotational cores. General circulation model (GCM) and regional climate model simulations reveal decreases in VWS that are disproportionately smaller than increases in CAPE, indicating an increase in frequency and/or intensity of future HCW events under ACC in the United States (e.g., Del Genio et al., 2007; Diffenbaugh et al., 2013; Gensini et al., 2014; Hoogewind et al., 2017; Seeley & Romps, 2015; Trapp et al., 2007; Trapp et al., 2009). Of relevance herein is the seasonal non-uniformity to this increase: Boreal winter tends to exhibit the largest relative increase in the CAPE–VWS covariate (Diffenbaugh et al., 2013). This is consistent with historical trends of environmental parameters computed using reanalysis data (Gensini & Brooks, 2018).

Precisely how these conclusions relate to *tornado intensity*, and thus address the very basic question of whether the environmental conditions due to 21st century ACC will contribute to more intense tornadoes, is unclear. This is partly because relationships between observed tornado intensity and environmental parameters such as CAPE and VWS are ambiguous. For example, although nonzero CAPE is considered a necessary condition for, and thus critically relevant to tornadic-storm formation, CAPE alone does not correlate well with observed tornado intensity (Thompson et al., 2012). As supported by our analyses in Section 3.3, a possible link could be made using multivariate environmental parameters such as the significant tornado parameter (STP), which appears to better discriminate environments of significant tornadoes from those of nonsignificant tornadoes (Thompson et al., 2012), although still not perfectly. However, an environment-only argument has a critical limitation, namely, that realization of a significant tornado is conditional on tornadic-storm initiation, which STP does not unambiguously predict. Indeed, the mean frequency of storms that initiate given a supportive environment is non-uniform in time and space, and even appears to change under late 21st century ACC (Hoogewind et al., 2017).

Explicit climate modeling of tornadoes is an alternative to the use of environmental parameters and removes the storm-initiation limitation. Although such an approach has been computationally prohibitive because of the small-scale of tornadoes (∼100 m–1 km), multi-scale modeling now offers a tractable solution. Herein we follow Trapp and Hoogewind (2016) and employ the pseudo global warming (PGW) method (Frei et al., 1998; Kimura & Kitoh, 2007; Sato et al., 2007; Schär et al., 1996) using a novel, multi-scale, multi-model approach. Briefly, the PGW method involves a comparison of simulations of events under their true 4D environment (the control; CTRL) with those under a 4D environment modified by a climate-change perturbation representative of *mean atmospheric conditions* over future (here, late 21st century) and historical (here, late 20th century) time slices. Thus, this method allows for an isolation of the response of an event to an imposed environment of the future. Because *event-level* PGW applications (see Trapp et al., 2021) involve relatively short time integrations, they also allow for the use of higher resolution and multiple realizations.

Two archetypal yet regionally and seasonally contrasting events are considered. The first is the 10 February 2013 (hereinafter, COOL) event that includes the EF-4 tornado in Hattiesburg, Mississippi, and the second is the 20 May 2013 (hereinafter, WARM) event that includes the EF-5 tornado in Moore, Oklahoma. Together, these tornadoes were responsible for 24 fatalities, more than 300 injuries, and approximately $2 billion in damage (NOAA, 2013). Our working hypothesis is that the WARM event will exhibit relatively less intensity changes under PGW than the COOL event.

Analyses of these event simulations provide the initial means to address this hypothesis. However, the spatio-temporal representations of the tornadic storms, and even the total numbers of storms, are different between the PGW and CTRL simulations (see Figure 1). This implied lack of a clear CTRL–to–PGW comparison of *specific* tornadic storms means that a quantitative evaluation of the climate change effect on the intensity of *specific* tornadoes is tenuous. Accordingly, we introduce an additional step wherein an idealized numerical model is integrated using initial and boundary conditions (ic/bc) drawn from the regional-model simulations. The relatively reduced complexity and higher spatial resolutions afforded by this idealized-modeling implementation of the PGW methodology helps further isolate the climate change response on a single storm, and allows for explicit diagnoses of tornado intensity.

2. Materials and Methods

2.1. PGW

The PGW method involves simulations of some event wherein its actual, present-day forcing is modified through the addition of a climate-change perturbation or "delta," which is the difference between mean conditions over future and historical time slices during a relevant month. Separate sets of deltas are constructed using historical and Representative Concentration Pathway 8.5 simulations from each of five GCMs (GFDL-CM3, MIROC5, NCAR-CCSM4, IPSL-CM5A-LR, and NorESM-1M). The GCM data originate from the Coupled Model Intercomparison Project Phase 5 (Taylor et al., 2012), and provide a range of convective-storm environments over historical and future time periods (e.g., see Diffenbaugh et al., 2013; Seeley & Romps, 2015).

Three different formulations of the climate-change deltas (see Trapp et al., 2021), computed using five different GCMs, provide an ensemble of 15 simulations plus an additional composite-delta simulation to assess the PGW response of each event. Because these 16 different deltas explicitly represent a range in the climate-change signal, we argue that their use toward generation of an ensemble is more relevant than other approaches. Specifically, and importantly, we are interested in the model response to the imposed future climate change and associated ic/bc rather than in the model response to variations in parameterization schemes, etc.

2.2. Regional Model Configuration

The CTRL and PGW simulations of the WARM and COOL events are performed using version 4.0 of the Weather Research and Forecasting model (WRF) (Skamarock et al., 2008). The parent computational domains have horizontal grid spacings of 3 km. Subdomains of 1-km grid spacing are nested within the parent domains over central

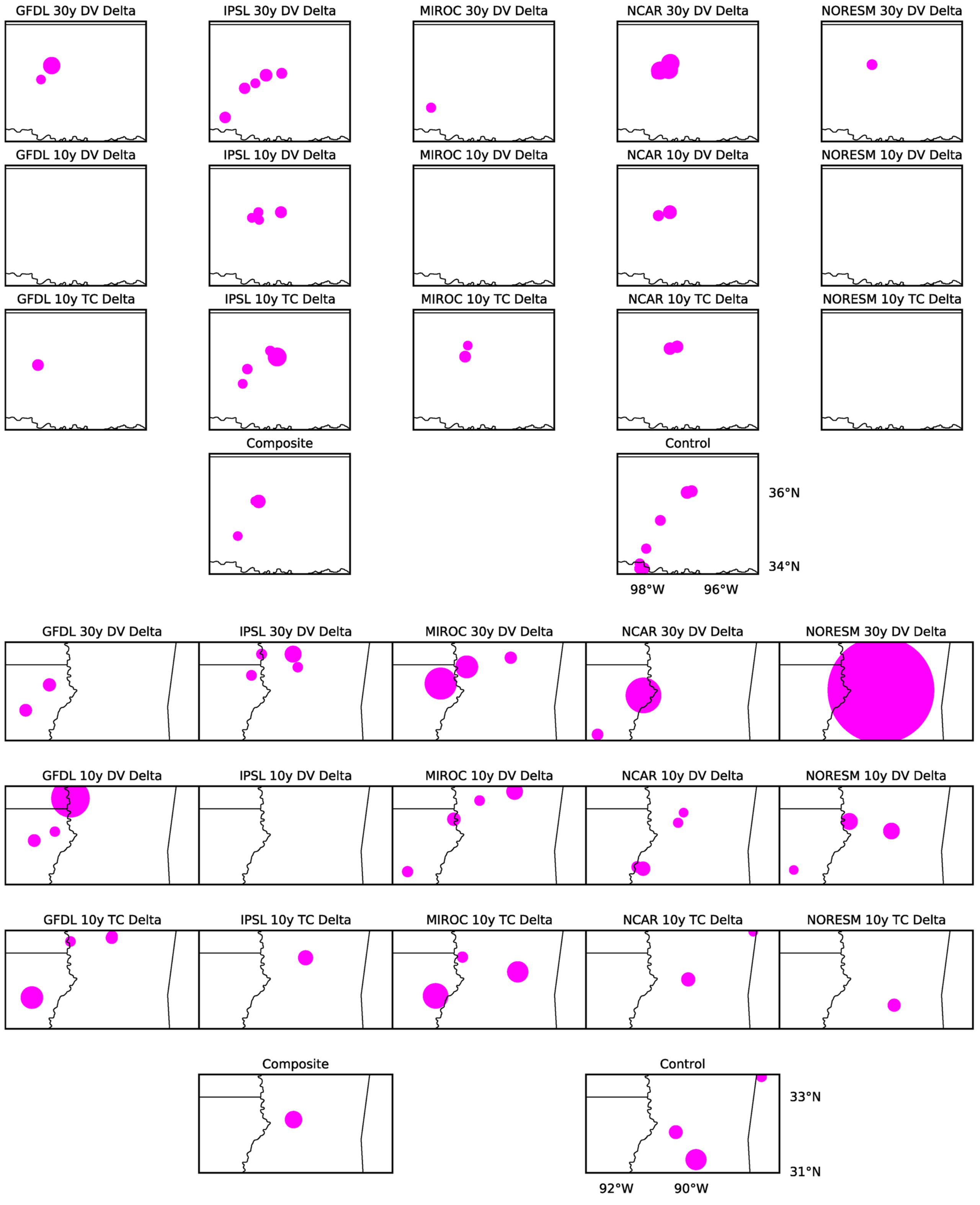

Figure 1. Locations of tornado proxies (magenta dots) for the regional-modeling simulations of the WARM event during the hour ending 21:00 UTC (upper panels), and COOL event during the hour ending 22:30 UTC (lower panels). The size of the dots correspond nonlinearly to the VV associated with the proxy. The subpanels indicate the individual experiments composing the ensemble.

Oklahoma and central Mississippi, respectively (Figure S1 in Supporting Information S1). The results reported in Section 3.1 are based on analyses over the nested domains.

The simulations are initialized at 12 UTC for both events. This allows for more than six hours of "spin-up" time prior to the observed EF-5 Moore (∼20:00 UTC) and EF-4 Hattiesburg (∼23:00 UTC) tornadoes, which is typical for weather-event simulations with WRF (Skamarock, 2004). Initial and boundary conditions are derived from the North American Mesoscale Forecast System analysis. Additional details regarding the WRF configuration can be found in Trapp et al. (2021). Decisions on the configuration and on the ultimate veracity of the CTRL simulations were established by comparing model output from configuration-sensitivity experiments to observed radar characteristics and tornado reports, as described in Woods (2021).

Tornadoes are not resolved on model grids with 1-km spacings. However, as demonstrated in the Supplement, their signatures and potential intensity can be inferred using vertical vorticity (VV) computed at 80 m AGL, which is approximately the height of the first level above the lower boundary of the model. A VV value locally exceeding 7.5×10^{-3} s^{-1}, which is the 99th percentile of gridpoint values in the CTRL simulation, serves as a tornado proxy occurrence. A VV value exceeding 1.25×10^{-2} s^{-1}, which is the 99.9th percentile, serves as a significant tornado proxy occurrence. Coexistence of local updraft velocities exceeding 5 m s^{-1} is also required, to ensure that the VV is associated with a convective updraft. Differentiating tornado intensity based on VV is justified in the Supplement through an analyses of a vortex model, and also follows from Doppler radar-based studies by Toth et al. (2012) and others.

2.3. Idealized Model Configuration

The idealized simulations are performed using Cloud Model 1 (CM1) (Bryan & Fritsch, 2002). Grid stretching is employed such that the horizontal grid spacing is 64 m over the inner 80 × 80 km of the 180 × 180 × 18.5 km model domain, and then increased to 2.5 km at the domain edges. Vertical grid spacing varies from 20 m in the lowest model levels to 250 m in the upper levels. Additional details regarding the CM1 model configuration can be found in Woods (2021). Note that the actual tornadoes that occurred on 20 May 2013 and 10 February 2013 had damage widths of 1,600 and 1,200 m, respectively. Even if the core diameters of maximum winds of these tornadoes were 50% of these widths, the cores would still be represented by ∼10 grid points. So, although our simulations do not have grid spacings appropriate to resolve fine-scale structures of the tornadoes, the simulations are certainly sufficient to represent core widths and windspeeds, which is one goal of these simulations.

The initial and boundary conditions are drawn from the WRF output of the CTRL and PGW simulations. Specifically, 60 × 60 km horizontal averages centered about the WRF grid point nearest to Moore, Oklahoma and Hattiesburg, Mississippi are used to obtain vertical profiles at 20 UTC 20 May 2013 and 23 UTC 10 February, respectively, which represent the pre-tornadic conditions during these two events. A single deep convective storm is initiated within these environments via updraft nudging (Naylor & Gilmore, 2012) that persisted for 20 min. Our analysis of the subsequent tornadic circulations begins at 30 min, that is, 10 min after the cessation of the nudging.

Tornadic-like vortices (TLVs) are identified by examining near-surface fields of windspeed, VV, and the Obuko-Weiss (OW) parameter. Adapting the approaches of Sherburn and Parker (2019), Gray and Frame (2021), and others, TLV identification requires VV, windspeed, and OW to exceed 0.1, 30 m, and 0.03 s^{-2}, respectively, and be collocated with low-level updraft speeds exceeding 5 m s^{-1}. Upon locating the strongest TLV, maximum and minimum of x-direction and y-direction wind components are found within 500 m of the vortex center. The locations of these maxima and minima are used to determine an average radius (r) of maximum winds (V).

3. Results

3.1. Regional-Modeling Perspective

An ensemble of 16 simulations is used to assess the PGW response of each event. The ensemble members represent a range of possible future realizations of the event. Herein, if 75% of the ensemble members exhibit the same sign in the percentage change (PGW relative to CTRL) in a given metric, we consider the PGW response for that metric to be *consistent*. If we equate the signal in the metric to the mean value across the ensemble, and the noise to the standard deviation, the response in this metric is considered to be *robust* (*highly robust*) if the PGW signal-to-noise ratio in a given metric exceeds one (two) (e.g., Diffenbaugh et al., 2013).

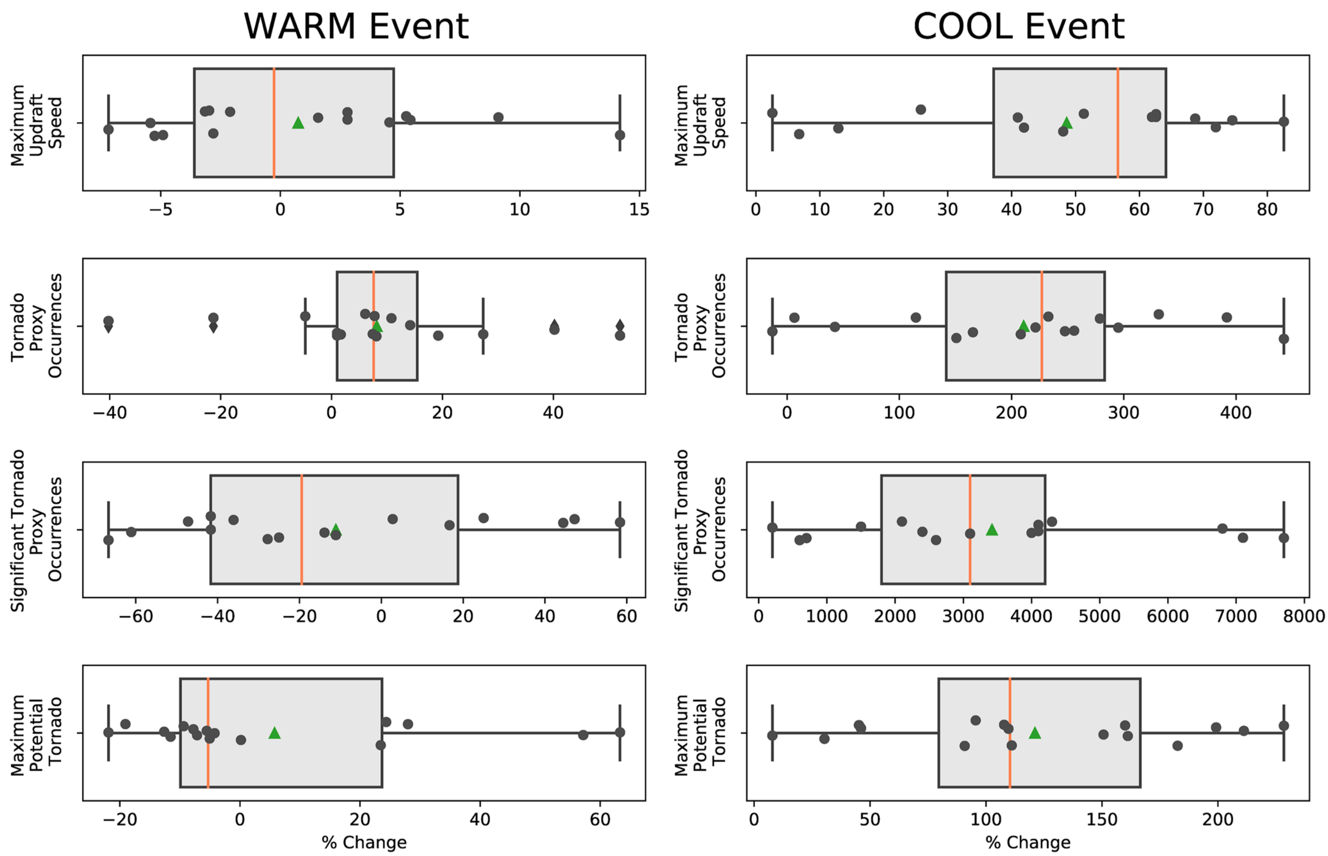

Figure 2. Box-and-whisker plots of tornadic-storm intensity metrics, as evaluated from the regional modeling simulations of the WARM event (left) and COOL event (right). Values of these metrics are given as percentage changes in the PGW simulations relative to the CTRL simulation. The median is the orange line, mean is the green triangle, and individual data points are the black circles.

We begin with two metrics that provide information on overall storm intensity. The first is the cumulative gridpoint exceedance of 55 dBZ simulated radar reflectivity (Figures S2 and S3 in Supporting Information S1). This metric quantifies the total area of intense convective storms over a given simulation. A consistent, robust response is shown in this metric, as represented by a mean percentage increase of +110% (PGW exceedances relative to those in the CTRL) (Figure S3 in Supporting Information S1). Thus, the PGW-modified conditions resulted in relatively more extensive and intense convective storms in association with the WARM event.

Cumulative gridpoint exceedances of simulated updraft speed confirm this increase in the extent of intense convective storms under PGW (Figures S3 and S4 in Supporting Information S1); a consistent, robust response is represented by a mean percentage increase of +40%. The *peak* updraft speeds are comparatively stronger in only half of the PGW simulations, with a mean percentage increase of +1% (Figure 2). These results indicate that intense convective updrafts in a late 21st century realization of the WARM event would be more numerous or larger, but not always stronger.

The PGW response in occurrences of our tornado proxy is consistent albeit not robust, with a mean percentage increase of 8% (Figure 2). The occurrences of our significant tornado proxy is neither consistent nor robust, with a mean percentage decrease of −11% (Figure 2). Finally, the peak VV per PGW simulation, which provides some information about the *potential* tornado intensity, is also neither consistent nor robust, with a mean percentage increase of 5% (and median percentage decrease of −5%) (Figure 2). Thus, the regional modeling suggests relatively more but not necessarily stronger tornadic circulations in a late 21st century realization the WARM event, albeit with large uncertainty (see also Figure 1).

Like the WARM event, the COOL event under PGW also tends to be characterized by more intense convective storms. Specifically, cumulative gridpoint exceedances of simulated reflectivity of 55 dBZ are greater in all but one of the PGW simulations, thus contributing to an average percentage increase of +125%, and a consistent and robust response in this metric (Figures S2 and S3 in Supporting Information S1). The other metric for overall storm intensity, cumulative gridpoint exceedances of updraft speed of 25 m s^{-1}, is consistent but not robust; notably, the average percentage increase in such strong updraft occurrence in the COOL event is +712%, as compared to the +40% increase associated with the WARM event (see Figures S2 and S3 in Supporting Information S1). *All* PGW simulations had peak updraft speeds exceeding the 31 m s^{-1} peak of the CTRL (Figure 2), thus implying a consistent and robust response. Moreover, half of the PGW simulations had peak updrafts exceeding 50 m s^{-1}, which historically are speeds more readily supportive in warm-season, Great Plains environments than in cool-season, southeast U.S. environments. These results indicate that intense convective updrafts in a late 21st century realization of the COOL event would be more numerous *and* stronger.

Occurrences of the tornado proxy are substantially greater under PGW in many of the simulations, leading to a mean percentage increase relative to CTRL of +211% (Figure 2). Occurrences of the significant tornado proxy are also substantially greater, with a mean percentage increase of +3,244%, in this consistent and robust response (Figure 2). Finally, a consistent and robust response is indicated in the peak VV per PGW simulation, and thus potential tornado intensity, with an average percentage increase of +121% (Figure 2).

Collectively, these results suggest that tornadic circulations in a late 21st century realization of the COOL event would be more numerous and stronger. In agreement with our hypothesis, the magnitude of the response of this archetypal cool-season event to PGW is much larger than that of the archetypal warm-season event; this finding is also in agreement with Bercos-Hickey et al. (2021). There is still ambiguity, however, in precisely how the analyzed response relates to tornado intensity, given both the model grid resolution and the nature of the tornado proxy. Thus, we now use the TLV–resolving idealized PGW simulations to compute explicit measures of tornado intensity, and thus help clarify the regional-model results.

3.2. Idealized Modeling Perspective

The idealized PGW simulations have steady, horizontally homogeneous initial and boundary conditions that were drawn from the regional-model simulations of the WARM and COOL events (Figures S5 and S6 in Supporting Information S1). The much finer grid spacings (64 m) allow for explicit quantifications of TLVs that form within the simulated storms. For this we use *tornado power*, which accounts for the tornadic wind speed as well as the width and length of the tornado track. As adapted from Fricker et al. (2014), instantaneous tornado power can be calculated as

$$P = \pi r^2 \rho V^3 \tag{1}$$

where r represents the average radius of maximum winds, ρ is the air density (assumed to be 1 kg m^{-3}), and V is the average maximum surface wind speed at radius r. Total tornado power here is the summation of log(P) over the lifetime of the tornado-like vortex,

$$P_t = \sum \log(P) \tag{2}$$

In simulations of the WARM event, the PGW response in total power is neither consistent nor robust. However, the 16-member ensemble contributed to a mean percentage increase in P_t of +124% (Figure 3). This percentage increase is due to a few experiments with relatively stronger vortex windspeeds; none of the experiments exhibited wider vortices (Figure 3). Thus, as in the coarser-resolution regional modeling simulations, there are indications of intensity increases in this violent, Great Plains, warm-season tornado given an imposed climate change, but with large uncertainty.

For the COOL event, the PGW response in total power is both consistent and robust, with an average percentage increase of +109% (Figure 3). The increases in P_t are driven by consistent and robust increases in tornadic-vortex strength and width (Figure 3). The relatively longer duration of the tornadic vortices (+81%) also contribute to the larger P_t under PGW. These high-resolution simulations are in agreement with the regional modeling simulations, and clearly demonstrate an increased intensity and duration for this archetypal cool-season tornado given an imposed climate change. The collective simulations also confirm our hypothesis regarding a relatively larger response of this cool-season event.

We can use the ic/bc of the idealized experiments to explore the meteorological arguments on which this hypothesis is based. The mean, PGW-enhanced CAPE of 4484 and 1037 J kg^{-1} for the WARM and COOL events,

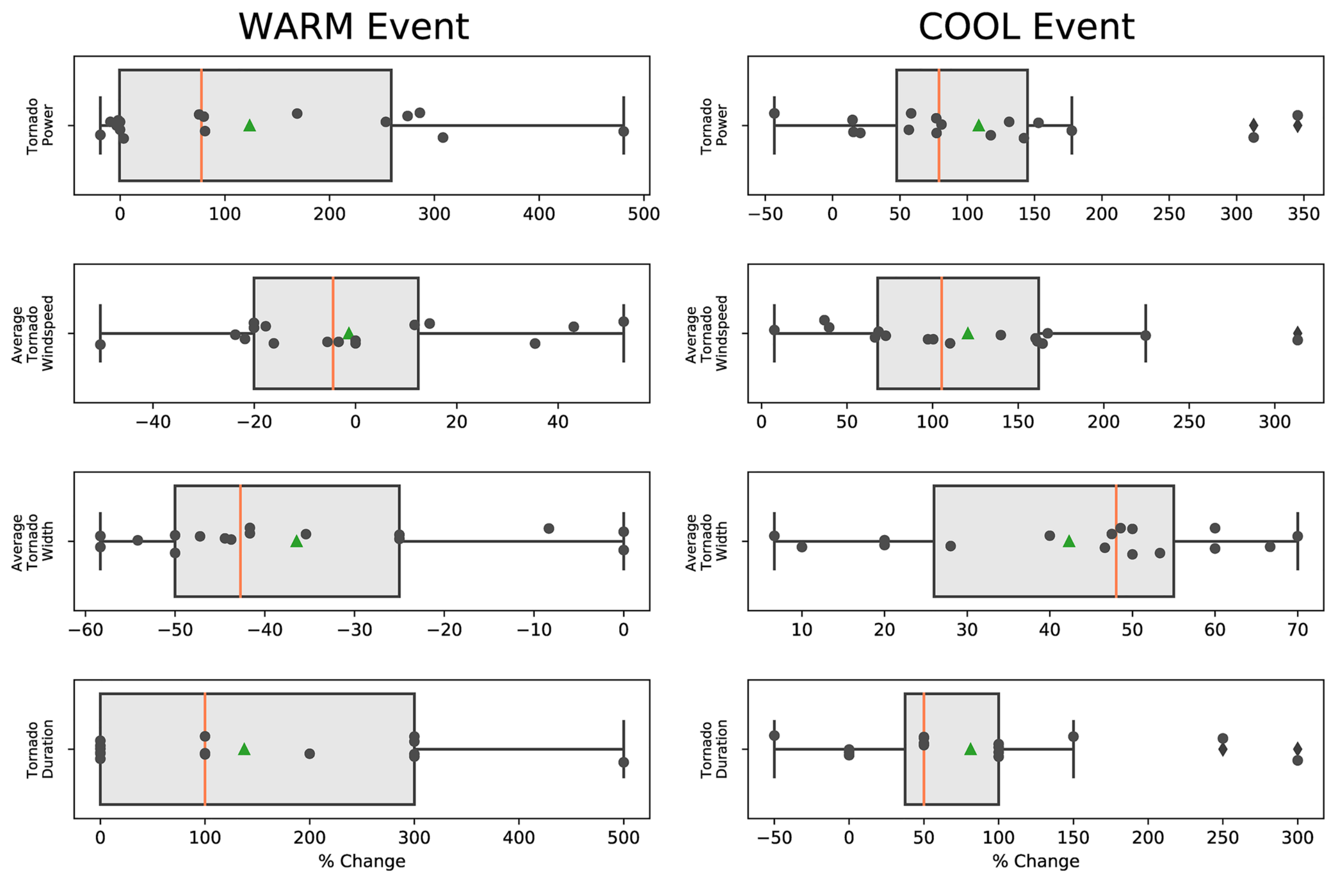

Figure 3. As in Figure 2, except for tornado intensity metrics (see text).

respectively, represent consistent and robust increases of +56% and +162% relative to the corresponding CTRL environments (Table 1). The mean, PGW-diminished VWS of 24 and 36 m s^{-1} for the WARM and COOL events, respectively, represent consistent and robust decreases of −14% and −4% relative to the corresponding CTRL environments (Table 1); disproportionate decreases of storm-relative helicity, another measure of VWS, are also revealed for the WARM versus COOL events (−53% and −23%, respectively; Table 1). When these and other environmental parameters are combined through the multivariate parameter STP, the environment of the WARM event is found to be relatively *less* supportive of a significant tornado under PGW (mean percentage decrease of −72%), while the environment of the COOL event is relatively *more* supportive under PGW (mean percentage increase of +100%) (Table 1).

3.3. Generality of the Conclusions

Although the intensity changes described herein apply to the specific WARM and COOL events simulated, all potential tornadic-storm events realized during the warm- and cool-season months of consideration would be

Table 1
Mean Values, and Percentage Changes Relative to the CTRL Experiment, of Environmental Parameters Computed From the Initial/Boundary Conditions of the Idealized-Modeling PGW Experiments

Event	CAPE (J/kg)		CIN (J/kg)		LCL (m)		SRH3 (m^2/s^2)		SRH1 (m^2/s^2)		S06 (m/s)		STP	
WARM	4,484	+56	0	+100	1,774	+23	86	−58	34	−53	24	−14	0.2	−72
COOL	1,037	+162	−24	−61	243	+33	427	−21	327	−23	36	−4	2.2	+100

CIN is convective inhibition; LCL is lifting condensation level; SRH3 is storm-relative environmental helicity, evaluated over the 0–3 km layer; SRH1 is storm-relative environmental helicity, evaluated over the 0–1 km layer; S06 is the bulk wind shear, evaluated over the 0–6 km layer.

subject to the same range of climate-change perturbations. To help quantify how these perturbations alone might contribute to environments of significant tornadoes, STP is calculated at all points within the regional-model domain for the CTRL and PGW simulations of both events (Figures S7 in Supporting Information S1). The PGW–CTRL difference for each PGW ensemble member represents the contribution of the monthly climate change perturbation for that member (see Section 2.1) to the STP change. Upon spatially averaging the PGW–CTRL differences, we find that the ensemble mean STP perturbation is −0.30 for the month of May, and +0.70 for the month of February. The implication is that ACC would contribute, *on average*, to environments that are relatively *less* supportive of a significant tornado during May across the central Great Plains U.S., and relatively *more* supportive of a significant tornado during February across the southeast U.S. Such environmental changes have been noted in studies by Gensini and Brooks (2018), Bercos-Hickey et al. (2021), and Lepore et al. (2021).

4. Summary and Conclusions

Evidence for the potential of ACC to impact future tornado intensity is provided through a novel climate modeling study of two contemporary, archetypal, warm- and cool-season tornado events. The tornadic-storm and associated vortex of the cool-season event experiences a consistent and robust increase in intensity when virtually placed in a globally warmed future via the PGW method. The tornadic-storm and associated vortex of the warm-season event experiences increases in intensity in some of the virtual experiments, but the response is neither consistent nor robust, and is overall weaker than in the cool-season event. Consideration of other data lends support to such a disproportionate response based on season of the year.

The preceding statement should not be interpreted to mean that *all* tornadoes will be stronger in the future. The atmospheric heterogeneity arising from naturally variable large-scale atmospheric circulations, high-frequency weather systems, convective storms and their residual effects, and land-surface variations (e.g., see Trapp, 2013) will continue to create diverse environmental conditions both supportive and non-supportive of thunderstorm formation. Significant tornadogenesis within such thunderstorms will also continue to require a delicate balance between VWS and CAPE, among other environmental parameters. Yet because cool-season environments in the current climate tend to be characterized by very large VWS and small CAPE, future increases in CAPE (decreases in VWS) due to ACC appear to be relatively more conductive to (less impactful on) this balance and thus on cool-season tornado potential.

These findings have implications on the possible impacts of future tornadoes forming outside of climatologically favored seasons, in the United States and elsewhere around the world. Indeed, situational awareness of tornado risk tends to be reduced during seasons such as boreal winter, which offers one explanation for high fatalities from tornadic events during these times (e.g., Ashley, 2007). It follows that more intense future tornadoes would have the potential to result in more fatalities and damage.

Data Availability Statement

The following GCM data sets used in this study are available through the CMIP5 repository (https://esgf-node.llnl.gov/projects/cmip5/), using these criteria: Models: GFDL-CM3, MIROC5, NCAR-CCSM4, IPSL-CM5A-LR, and NorESM-1M; Experiments: historical and RCP8.5; Ensemble: r1i1p1; Realm: atmos; and Time Frequency: 3 hr or 6 hr. The WRF model is available at https://www2.mmm.ucar.edu/wrf/users/, and the CM1 model is available at https://www2.mmm.ucar.edu/people/bryan/cm1/. Relevant simulation data are available through the Illinois Data Bank at https://databank.illinois.edu/datasets/IDB-4479773.

Acknowledgments

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