Investigating a Derecho in a Future Warmer Climate

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ABSTRACT: Derechos are extensive swaths of damaging winds produced by some long-lived, widespread mesoscale convective systems. Little research has been conducted concerning how derecho mechanisms might change in a future, warmer climate. In this study, the pseudo–global warming method is utilized to evaluate how the 10 August 2020 midwestern U.S. derecho, the costliest thunderstorm event in U.S. history to date, might differ if it instead occurred in a warmer climate at the end of this century. The 10 August derecho event is first simulated in its observed environment, and then resimulated in environments altered according to projections from different climate models using a high-emissions climate change scenario. Results suggest that near the end of this century, a similar derecho event may not necessarily have more intense winds but could possibly impact a geographical area 50% to 100% larger. The physical chain of events leading to this greater geographical impact result from the derecho winds beginning earlier in the storm lifetime, due to increased precipitation combined with decreased relative humidity right above the ground, and derecho winds extending northward due to a strengthening of the parent storm from increased instability there. All these factors enhance the area of evaporative cooling and thus the cold pool, which in turn extends the area covered by the rear-inflow jet within the storm, the likely main mechanism for most of the damaging winds at the ground in the historical event. More study of other cases is required to evaluate the generality of this result.

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The 10 August 2020 derecho that occurred in parts of the midwestern United States resulted in four deaths, hundreds of injuries, and was the costliest thunderstorm event in U.S. history to date (estimates at $12.3 billion in damage; NCEI 2022). There were over 500 reports of severe winds (Fig. 1a), some even exceeding 104 kt (1 kt ≈ 0.51 m s⁻¹) (120 mph); there were also 24 reports of tornadoes on this day, but all were weak (EF1 or less) and were responsible for only a very small fraction (∼0.003%) of the total damage (NCEI 2022). The derecho traversed a distance more than 1,000 km and had a duration of nearly 12 h. Although a consensus about the formal definition of a derecho continues to evolve in the meteorological community [e.g., original definition proposed by Johns and Hirt (1987), that given by the Glossary of the AMS since 2019, and further refinements suggested by Corfidi et al. (2016)], the 10 August 2020 event had the essential characteristics of these definitions that are based upon wind strength/damage, their continuity in time and spatial extent, and their parent storm type. The storm's appearance on radar (Fig. 1b) was generally that of a mesoscale convective system (MCS) in which two or more convective cells combine to develop into a single, organized convective system with extensive, spatially continuous precipitation and severe weather (e.g., Zipser 1977; Houze 2018, and references therein). Through much of its lifetime and extent, the MCS manifested specifically as a quasi-linear convective system (QLCS) (e.g., Weisman and Trapp 2003) but having a protruding middle section, thus appearing on radar as a bow echo (Fujita 1978; Przybylinski 1995; Weisman 2001).

The presence of a bow echo like that shown in Fig. 1b is suggestive of a convection-induced rear-inflow jet (RIJ; Smull and Houze 1987; Weisman 1992), a jet of strong winds originating at the rear of the MCS directed toward its leading edge. Downdrafts behind the storm leading edge can transport this jet of strong winds down toward the ground, causing significant damage there, and potentially contributing to derecho production. The descent of the RIJ usually culminates in a localized advancement of the storm, creating a bow echo in the radar reflectivity pattern. The RIJ is inextricably linked to the presence of a cold pool (e.g., Weisman 1992, 1993), an outward-spreading region of cold air at and above the ground resulting from the evaporation of precipitation in the storm downdrafts. The RIJ can be considered a response of the wind field to horizontal vorticity that is baroclinically generated (i.e., dependent upon a temperature gradient) at the back edge of the cold pool and MCS (e.g., Weisman 1992, 1993). In this regard, a more expansive cold pool begets more expansive RIJ forcing. Baroclinically generated horizontal vorticity within the leading edge of the cold pool also plays a role in RIJ forcing, through its contribution to the formation of counter-rotating midlevel mesovortices acting near the opposite ends of the MCS (also referred to as “bookend vortices”), which in turn focus the RIJ (Weisman 1992).

Other mechanisms that can be responsible for a derecho include downbursts (e.g., Fujita 1978), intense, negatively buoyant downdrafts that are deflected at the ground to produce strong horizontal winds, and low-level mesovortices, convectively generated vertical vortices with several-kilometer horizontal scales that can produce intense winds near the ground (e.g., Weisman and Trapp 2003; Trapp and Weisman 2003). Given their relatively small scales, downbursts and mesovortices are sometimes not easily discerned in data from operational weather radars. Any of these three mechanisms may be the primary contributor to the derecho or may work in tandem with any of the others.

Significant events such as the 10 August derecho raise questions about how severe convective weather may change due to anthropogenic climate change, but derecho-producing
MCSs have received little attention in this regard. Because most global climate models do not resolve MCSs, one approach to address such questions involves analyses of convective environments in climate model predictions (e.g., Del Genio et al. 2007; Trapp et al. 2007, 2009; Diffenbaugh et al. 2013; Gensini et al. 2014; Seeley and Romps 2015; Hoogewind et al. 2017; Lepore et al. 2021, and others). This is more problematic for derechos, because the bulk environmental characteristics evaluated from global climate model simulations do not readily distinguish between those environments supportive of a severe MCS versus other types of convective storms (e.g., Thompson et al. 2012).

An alternative approach is to employ high-resolution dynamical downscaling of climate model output (summarized by Kotamarthi et al. 2021), whereby regional-scale, convection-allowing models are initialized and constrained by environments predicted by climate models. This approach can therefore be used to determine explicitly whether severe...
MCSs would occur in the environments predicted by climate models. The downscaling models are run, for example, over large regional domains and multidecadal time periods, and can be successful in determining how the frequency of a particular kind of severe weather event might change in a future warmer climate over a particular geographical region of the globe (e.g., Hoogewind et al. 2017; Ashley et al. 2023). However, due to the computational expense associated with these large domains and time scales, the downscaling simulations are usually limited to the use of a single global climate model (GCM) prediction, or a single composite of many GCM predictions, and to a model resolution that is too coarse to examine the underlying mechanisms responsible for the severe weather.

Yet another approach that can provide more detail and depth of understanding is called the event-level “pseudo–global warming” (PGW) method (see Trapp et al. 2021). Here, a past severe weather event is modeled in its original environment, and then modeled again in a representation of that environment altered by anthropogenic climate change as predicted by a GCM. The simulations are run over shorter duration (only over the severe weather event itself), at high resolution, and typically with a variety of GCM predictions to assess variability in future convective environments.

We thus use the PGW method to investigate the question, “How might the 10 August 2020 derecho event differ if it instead occurred in an end-of-the-century, warmer climate, and why?” Specifically, we seek to understand how the underlying physical mechanisms of the derecho might be influenced by climate change. We delve more deeply into this question than a recent study by Li et al. (2023), who examined the 29 June 2012 North American derecho under a single pseudo–global warming scenario computed from the average of multiple GCMs. Because in both that study and ours, only a single derecho event is examined, they cannot provide information on how the frequency of derechos might change in the future, a question better addressed with dynamical downscaling of climate model output. Both types of knowledge are useful, but the focus here is upon gaining an improved understanding of how the underlying physical mechanisms of derechos could change, given changes in the larger-scale meteorology suggested by climate model projections.

Methodology
The PGW method was effectively introduced by Schär et al. (1996) and has been used in numerous studies of individual hazardous weather events (e.g., Lackmann 2013, 2015; Trapp and Hoogewind 2016; Carroll-Smith et al. 2019). In general, the PGW method consists of first simulating the event in its true, 4D environment (the “historical” simulation; hereinafter HIST), and then resimulating the event as if it had occurred in a future environment affected by climate change (hereinafter the PGW simulations). The “pseudo” moniker of this method is an acknowledgment that this exact environment used for the simulation of the future event is unlikely ever to occur, but it is used as an approximation to storm environments that might be possible at the end of the century. The observed environment typically used for the HIST simulation is from a gridded reanalysis dataset, in this case the High-Resolution Rapid Refresh (HRRR) analysis dataset (Blaylock et al. 2017). For the PGW simulations, that environment is somewhat altered by adding climate change perturbations based upon historical simulations and end-of-century future projections from GCMs. The perturbations are not so extreme as to change the synoptic-scale environment, but typically alter heat and moisture and wind speeds. Finally, the HIST and PGW simulations are compared, to assess how and (more importantly) why the characteristics of a derecho simulated in a warmer climate may differ from that simulated in the present day.

Historical simulations and end-of-century future projections from five different GCMs within the Coupled Model Intercomparison Project phase 5 (CMIP5) suite were used to create five separate sets of climate change perturbations, or “deltas”: GFDL-CM3, MIROC5,
NCAR-CCSM4, IPSL-CM5A-LR, and NorESM-1M. The future projections assume the RCP8.5 scenario, which represents the worst-case scenario (i.e., the most future warming due to no reduction in greenhouse gas emissions) and thus helps determine potential extremes for a future derecho event. These five separate sets of deltas were added onto the HRRR data for the 10 August derecho event to produce different environments for five PGW simulations of that event. Understanding differences among the particular GCM projections and their deltas, resulting from differences in the GCMs themselves, is not relevant to the goals of this study and thus is not addressed.

This study uses diurnally varying deltas averaged over the month of August. Using temperature as an example, the deltas contribute to the PGW environment as

\[ T(x,y,z,t) = T_0(x,y,z,t) + \Delta T_{month}(x,y,z,t), \]

where \( T \) is the future temperature at the spatial location \((x, y, z)\) and time \(t\), \( T_0 \) is the temperature at that same location and time from the HRRR analysis, and \( \Delta T_{month} \) is the diurnally varying “delta.” The diurnally varying temperature delta is found, for example, by calculating differences between the monthly averaged 3D values of temperature from a GCM projection over the decade 2090–99, and the similarly averaged 3D values of temperature from a GCM historical simulation over the decade 1990–99, at 6-h intervals (0000, 0600, 1200, and 1800 UTC). Given that the event studied here occurred in 2020, it would have been preferable to compute historical deltas over the decade 2010–19 rather than 1990–99, but the CMIP5 historical simulations ended at 2005. Our deltas may thus overestimate the magnitude of the change in climate, although Taszarek et al. (2021) show little observed change in mean surface temperature in the U.S. Midwest from 2000 to 2020, so perhaps not. The averages calculated over 6-h intervals are then linearly interpolated to 3-h values, to coincide with the times that the PGW simulations are updated with HRRR data. In addition to temperature, deltas are also computed for surface pressure, specific humidity, soil temperature, soil moisture, and zonal and meridional winds. Further discussion of PGW deltas can be found in Trapp et al. (2021).

The HIST and PGW simulations of the event were all conducted using version 4.2 of the Advanced Research core of the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008). The parent domain had 3 km horizontal grid spacing and 40 vertical levels. A higher-resolution nested domain having 1 km horizontal grid spacing was located over the central Midwest (Fig. 2), centered upon the location of storm intensification and the primary wind swath of the 10 August 2020 derecho. Two-way feedback was permitted between the two domains. All simulations were initialized at 0900 UTC 10 August 2020 with 3-hourly ingests of the HRRR reanalysis dataset and ended at 0600 UTC 11 August 2020; PGW simulations had their respective deltas added to the HRRR data at these 3-hourly intervals. Other details of the WRF Model setup, including the particular cloud microphysics scheme, land-use scheme, radiation scheme, and atmospheric boundary layer and surface layer schemes are provided in Table 1. Output from the nested domain was saved at 15-min intervals and then analyzed.

Various quantities computed from the simulation results characterize the storm environment. The convective available potential energy (CAPE) indicates a theoretical upper limit for how fast air within a thunderstorm updraft may ascend, with larger values favoring stronger updrafts (and thus stronger storms). The convective inhibition (CIN) is another theoretical estimate of how much negative buoyancy air must overcome before it can ascend freely within a storm updraft; larger magnitudes can discourage thunderstorms from forming at all. The values of CAPE and CIN presented in this study are all for the most unstable parcel; in the simulation output, they are calculated using the cape_2d function of wrf-python (Ladwig 2017).
The storm organization also depends on the environmental vertical wind shear, here evaluated as the magnitude of the difference in the vector winds either over the lower troposphere (between the 1,000 and 700 hPa pressure levels), or over the low to midtroposphere (between the 1,000 and 500 hPa pressure levels). The precipitable water (PW) is a measure of the total water vapor integrated through the depth of the troposphere in the storm environment. Because water vapor mass generally decreases with altitude in the atmosphere, large differences in the PW will largely indicate differences in the bottom half of the atmospheric column, i.e., in the air potentially ingested by the storm that could be converted to precipitation. However, for derechos, which can be enhanced by increased evaporation of rain near the ground, the relative humidity (RH), simply the ratio of water vapor mass to the theoretical upper limit at a given temperature, dictates the amount of evaporation and is thus also pertinent.

Other quantities computed from the simulation results help to diagnose possible source mechanisms of the derechos. The RIJ is defined here as locations where winds exceed 25 m s\(^{-1}\) (~50 kt) at the 950 hPa level within a simulated radar echo exceeding 20 dBZ. The RIJ will be compared to the area of the cold pool, defined here as a potential temperature perturbation of −5 K or colder compared to the time-averaged, domain-averaged potential temperature at the lowest model level. Possible downbursts are analyzed from model output at 15-min intervals as locations where downdrafts stronger than 5 m s\(^{-1}\) occur at the 925 hPa level. Possible mesovortices are diagnosed using the Okubo–Weiss (OW) parameter

![Fig. 2. Domain configuration for all simulations, showing the parent domain (outer box, 3 km grid spacing) and the inner (nested) domain (white outlined box, 1 km grid spacing).](image)

Table 1. WRF Model parameterizations used in all simulations.

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<tr>
<th>Type</th>
<th>Name</th>
<th>Description/reference</th>
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<tbody>
<tr>
<td>Microphysics</td>
<td>NSSL double-moment</td>
<td>Mansell et al. (2010), Mansell and Ziegler (2013)</td>
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<tr>
<td>BL PBL physics</td>
<td>YSU</td>
<td>Hu et al. (2013)</td>
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<td>Land surface</td>
<td>RUC land model</td>
<td>Smirnova et al. (2016)</td>
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<td>Radiation</td>
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<td>Mielikainen et al. (2012)</td>
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<td>Surface layer</td>
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<td>Nishizawa and Kitamura (2018)</td>
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(Okubo 1970; Weiss 1991), a measure of the wind deformation and vertical vorticity, calculated using the 10 m winds output at 15-min intervals, with a value less than $-10^{-4}$ s$^{-2}$ designated as a possible mesovortex center.

Results

**Evolution of the observed MCS and its representation in the HIST simulation.** Radar data on 10 August 2020 indicated that convection initiation occurred over the elevated regions of the Black Hills in southwestern South Dakota between 0500 and 0600 UTC. Soundings at 0000 UTC 10 August 2020 showed most unstable CAPE values exceeding 3,000 J kg$^{-1}$ throughout South Dakota, Nebraska, Iowa, and Illinois. Orographic lifting over the Black Hills likely forced air parcels up to their level of free convection, allowing them to access the elevated CAPE values there. The initial convective cells merged as they moved southeastward through South Dakota and northeastern Nebraska. The 1200 UTC environment of those cells consisted of most unstable CAPE values from 2,000 to 3,000 J kg$^{-1}$, which were in advance of a weakening cold front at that time. CAPE values continued to increase in Iowa and Illinois throughout the day, with most unstable CAPE values exceeding 3,000 J kg$^{-1}$, while CIN gradually eroded across the warm sector. The 1200 UTC 10 August 0–6 km vertical wind shear vector across the High Plains was westerly with magnitudes exceeding 20 m s$^{-1}$. Such deep-layer shear weakened toward the south and east, however, with magnitudes less than 10 m s$^{-1}$ at Omaha, Nebraska (OAX), at 1200 UTC. In contrast, the 0–3 km vertical wind shear at OAX was nearly 13 m s$^{-1}$ at 1200 UTC, which is more favorable for MCS formation. Relatively stronger low-level shear was also found at Davenport, Iowa (DVN), and Lincoln, Illinois (ILX).

The evolution of the storm can be seen in the hourly composite reflectivity plotted as a time chronology (Fig. 1b). The convection intensified in northeastern Nebraska and began to form into an organized MCS as it moved into Iowa by 1400 UTC, and well into the warm sector ahead of the front. In eastern Nebraska, the MCS began to produce severe surface winds that resulted in wind reports starting at 1200 UTC. The MCS progressed across Iowa and continued to intensify as it moved into areas of higher CAPE. A bow echo, usually indicating a RIJ descending right behind the leading edge of the storm, appeared on radar reflectivity between 1500 and 1600 UTC in central Iowa. In addition, near Cedar Rapids, Iowa, and Clinton, Iowa, radar-indicated mesovortices likely contributed to some of the severe straight-line wind damage at those locations (NWS Quad Cities 2020). The severe surface winds intensified and became more extensive as the MCS elongated into a QLCS and moved through Iowa and northern Illinois by 2200 UTC (Figs. 1a,b). Some other MCS activity occurred in Missouri, and produced wind reports (Figs. 1a,b) but did not produce a derecho and thus is not analyzed.

Differences between the true storm environment, and that provided by the HRRR reanalysis dataset that was used to initialize the WRF Model, made it difficult to simulate all details of the actual event. Despite extensive experimentation aimed at matching the observed storm, the simulated convection initiated a few hours later, and in a location eastward, of that observed (Fig. 3a); such timing and location differences have been found in simulations of other MCS events (e.g., Squitieri and Gallus 2016). The 10 August MCS has been especially difficult for various groups to model, with the candidate reason being that the initial conditions provided by any of the (re)analysis datasets or other model drivers failed to capture remnants from convective storms on the previous evening that appear to have been important. Other studies have noted the relatively large impact of initial and boundary conditions over other model configuration choices on derecho-event simulations (e.g., Toll et al. 2015).

The MCS in the HIST simulation is later and therefore eastward compared to the true event, but its general morphology, including the bow echo and its strength as indicated by the simulated radar reflectivity, is represented well when compared to the observations. The brief intensification of the maximum radar echoes right before the bow echo appears in
the observations at 1500 UTC just west of central Iowa is also captured in the HIST simulation, only displaced in time and space to 1900 UTC and eastern Iowa. The observed north–south extension of the MCS while the observed maximum radar echoes become smaller in spatial extent at 1900 UTC near the Iowa–Illinois border is also represented in the HIST simulation at 2100 UTC in central Illinois. The overall speed of the MCS across central Iowa and Illinois is also similar, requiring about 6 h to traverse that distance in both observations and the HIST simulation.

The HIST simulation does produce a large swath of strong near-surface winds (Fig. 3b). Because of the delay in the initiation of the simulated MCS, these strong winds begin in central Iowa rather than western Iowa. The maximum near-surface wind speed within any 1 km² grid box in the simulated derecho was 47 m s⁻¹ (over 90 kt; 105 mph), while storm reports indicate the occurrence of isolated wind gusts exceeding 55 m s⁻¹ (107 kt; 123 mph). The 1 km model resolution used here would not be expected capable of replicating the strongest winds observed at a single geographical point, however.

The HIST simulation allows an examination of possible mechanisms for producing the derecho. The appearance of a descending RIJ close behind the storm’s leading edge is very clear.
in vertical cross sections of horizontal and vertical winds taken before the bow echo appears and is coincident with the onset of the stronger wind maxima shown in Fig. 3b. At 1700 UTC (Figs. 4a,b), the RIJ angles downward from near 5 km altitude to the surface, right behind the leading edge of the storm and coincident with a strong downdraft there. The maximum winds near the ground are only 60–75 kt at that location and time. One hour later (Figs. 4c,d), at a segment of the MCS that is starting to push forward (to produce a bow echo), the RIJ has strengthened considerably, bringing winds of 90–105 kt near the ground. The areal extent of the RIJ over the duration of the HIST simulation (Fig. 4e) shows that it was present along much of the path of the MCS. When potential downburst locations (Fig. 5a) are overlayed upon the plotted maximum 10 m wind swath (Fig. 5b), only 11% of the strong near-surface winds shown in Fig. 5b overlap with the diagnosed downbursts, even when assuming a 4 km radius around these points. When potential mesovortex locations (Fig. 5c) are overlayed upon the 10 m wind swath (Fig. 5d), they often lie upon the strongest wind maxima. The mesovortices are near the leading

Fig. 4. Low-level HIST simulation radar reflectivity over Iowa for (a) 1700 and (c) 1800 UTC, with corresponding locations of vertical cross sections denoted by blue lines. Corresponding vertical cross sections at (b) 1700 and (d) 1800 UTC show wind speed (kt; color fill) and downward vertical velocity (black dashed contours; interval: 0.5 m s⁻¹). (e) Time history and areal extent of maximum 950 hPa horizontal wind speeds over the duration of the simulation.
edge of the MCS, and a majority are located north of the apex of the bow echo, corresponding with expectations from the idealized modeling of Trapp and Weisman (2003). However, their coverage is again sparse; only 0.15% of the strong near-surface winds overlap with the diagnosed mesovortices, even when assuming a generous 20 km radius around each mesovortex center. As such, the descending RIJ was the primary contributing mechanism to severe near-surface winds in the HIST simulation, with minor contributions made by downbursts and mesovortices. The geographical extent and persistence of the observed bow echo on radar lends credence to the fidelity of the simulation in identifying the RIJ as the most important contributor to the derecho.

In the following sections, how the 10 August 2020 event could be altered by anthropogenic climate change at the end of the century is addressed. First, changes in the environments of the HIST and the PGW simulations are described. Thereafter, the simulated HIST and PGW MCSs, their swaths of severe winds, and the possible mechanisms causing these winds, are then compared to understand possible modifications due to end-of-the-century climate change projections.

**Differences in the PGW environments compared to HIST.** Relative to the HIST environment, the PGW environments have 7%–74% more area-averaged CAPE at 1200 UTC (Fig. 6a; spatial maps of the inner domains of the PGW simulations indicate little variability among the increases in CAPE and thus are not shown). The increased CAPE suggests that some future storms could be substantially stronger, and perhaps also more widespread, in regions in the HIST environment that lack sufficient CAPE to fuel storms. The CAPE values increase by 1800 UTC as would be expected with increased surface heating during the day. However, the PGW environments also possess 87%–162% more area-averaged CIN at 1200 UTC (Fig. 6a), with the magnitudes of the increases in CIN again having little variability across the inner model domain. The much higher CIN values in the PGW environments imply that storm initiation could be substantially suppressed, potentially reducing the total storm area, but the greatest CIN values tend to occur in
regions having modest increases in CAPE. The CIN values decrease substantially by 1800 UTC. This dichotomy in the thermodynamical effects of climate change on convective storm potential has been discussed by Trapp and Hoogewind (2016), Hoogewind et al. (2017), and others. It also shows a limitation of arguments based only on environmental parameters that lack explicit consideration of the mechanisms of convection initiation: one cannot know for certain whether potentially stronger and more widespread convection would actually initiate. This is a major reason why numerical modeling of the storms themselves in the projected future environments is necessary.

All the environments examined here have modest values of (spatially averaged) vertical wind shear (Fig. 6b), which are consistent with those in the environment of the warm-season derecho event documented by Coniglio et al. (2012). Relative to the HIST environment, the PGW environments on average have only slightly weaker vertical wind shear over both layers, suggesting that at least in this regard, the PGW environments would still be supportive of intense, long-lived MCSs.

The 16%–47% increases in area-averaged PW in the PGW environments (Fig. 6c) indicate the possibility for more precipitation in those storms due to their ingestion of air containing more water vapor. An evaluation of the “deltas” for water vapor mass near the ground shows that the PGW environments within the nested domain have mixing ratios ranging from 2 to 6 g kg$^{-1}$ greater than the HIST environment, with the deltas decreasing with height to values ranging from 0.5 to 1.1 g kg$^{-1}$ by the 500 hPa level, and less than 1 g kg$^{-1}$ above 500 hPa.

These column-integrated quantities used to characterize the convective environment do obscure some important details in the projected climate environments that may be important for derechos, however. All the PGW deltas show the greatest warming of air near the ground (e.g., at 1200 UTC ranging from 6° to 11°C), then decrease by a couple of degrees or less and remain

![Fig. 6. Meteorological parameters characterizing the changes in potential convective environments averaged over the nested domain of the simulations, evaluated at 1200 UTC over any column having less than a simulated 20 dBZ echo: (a) most unstable CAPE and CIN; (b) lower-tropospheric and low-to-midtropospheric vertical wind shear; (c) precipitable water. Percentages represent changes in PGW relative to HIST.](image-url)
relatively constant with height until becoming much smaller near the 200 hPa level. The greatest temperature deltas at the lower levels support larger CAPE and CIN values. As shown in Fig. 7, the average surface-to-900-hPa RH for all PGW environments at 1200 UTC is actually lower than that of the HIST environment. Although there is more water vapor mass present at those altitudes, due to the higher temperatures there as well, the air is actually farther from saturation (lower relative humidity). Thus, evaporation of rain should be enhanced in the PGW environments, potentially strengthening all three of the aforementioned mechanisms that can produce a derecho.

Fig. 7. (a)–(e) Maps of differences in percent of the average surface-to-900-hPa relative humidity in the PGW environments relative to HIST, at 1200 UTC. White/green areas in the plots, including in northwestern Iowa and several areas in the eastern third of the domain, are not valid due to convection being present at those locations at 1200 UTC. (f) Average difference in percent of the surface-to-900-hPa relative humidity from the HIST environment, over the inner domain at 1200 UTC. Labels correspond to same quantities but evaluated over the 900–700 hPa layer or 700–500 hPa layer.
In addition, the lower relative humidity in the PGW environments also persists at higher altitudes (Fig. 7f), and might enhance the effects of entrainment, the introduction of dry air from outside a developing cloud or storm into its interior, due to the overturning motions at its edges. Entrainment decreases liquid or frozen hydrometeor mass by introducing dry air that induces evaporation of water or sublimation of ice inside the cloud. The lower the RH of the entrained air, the more evaporation/sublimation that can occur. The latent cooling resulting from this evaporation/sublimation, in addition to the lower temperature of the entrained environmental air, decreases the cloud/storm buoyancy from what would be expected from calculations of CAPE. Relative to the HIST environment, the PGW environments all have lower relative humidity from the surface up to 700 hPa, and all but one have lower relative humidity up to 500 hPa (labeled in Fig. 7f). Thus, entrainment could prevent (or delay) convection initiation in the PGW environments or limit the maximum storm updraft speeds attained. Numerical simulations are required to see if this is indeed the case.

**The MCS and derecho in the PGW simulations, and possible derecho mechanisms.** Four of the five PGW simulations produced a long-lived MCS with a bow echo similar to that in the HIST simulation (Fig. 8). The four long-lived MCSs had radar reflectivity exceeding 60 dBZ
and thus generally similar maximum intensities as the MCS in the HIST simulation. The maximum updraft speeds in the PGW simulations were a little less than in the HIST simulation (except for the MIROC simulation), possibly due to the effects of entraining air with lower RH. The tracks of the strongest echoes within the PGW MCSs extended farther northward relative to that of the HIST MCS, as can be discerned by comparing the underlying state outlines in Fig. 8. Their extension northward likely results from increased CAPE north of the latitude of the Indiana border, where the HIST environment had CAPE values less than 3,000 J kg⁻¹, but the PGW environments had values of nearly 4,000 J kg⁻¹ or more by 1800 UTC when the storms were near that region. No differences in CIN, RH, nor vertical wind shear were apparent in that region at that time. Another line of convection occurred to the south of the MCS in some PGW simulations, similar to the HIST simulation, but did not create substantial winds near the ground. Henceforth, all subsequent spatial averages presented here are conducted upon the northern MCS representative of that producing the derecho (north of 40°N, i.e., just below the Iowa/Missouri border). The GFDL PGW simulation failed to create a MCS until near the end of the simulation. Its initial convection moved onto the South Dakota–Nebraska border (like the other PGW simulations) but encountered much higher CIN there than in the other PGW simulations, and thus decayed. This outlier behavior demonstrates the utility in using more than one climate model projection for a PGW study.

The PGW storms initiate about an hour later and cover less total area (14%–90% decreases) than the HIST storm (Fig. 9a). This would be consistent not only with the relatively larger CIN in the PGW environments, but also with more difficult convection initiation from enhanced entrainment effects due to the lower RH in the PGW environments. In most PGW storms, the maximum area of more intense convection (Fig. 9b) at some time during the simulation surpasses that of the HIST storm (especially between 1500 and 1800 UTC), but averages over the duration of the simulations exhibit decreases in intense storm area relative to HIST as well.

The swaths of strong near-surface winds in the simulations do not follow the trends in the total storm areas, however (Figs. 10 and 11a). Despite the later start to the storms in the PGW simulations (Fig. 9a), their strong surface winds (exceeding 20 m s⁻¹, or 39 kt, or

![Fig. 9. Time series of hourly (a) simulated total storm area (area over which column-maximum reflectivity exceeded 20 dBZ), and (b) intense storm area (area over which column-maximum reflectivity exceeded 50 dBZ), north of 40°N. HIST simulation shown as black line; PGW simulations shown in other colors. Percentages are time averages relative to HIST, color-coded according to the PGW simulation. All times are in UTC.](attachment:fig9.png)
45 mph) begin earlier in the storm lifetime and last longer (Fig. 11b). Therefore, the PGW wind swaths actually begin west of central Iowa as compared to the HIST simulation and cover more area in Indiana (Fig. 10). In addition, the swaths extend farther north in the PGW simulations compared to that in the HIST simulation, including southern Wisconsin and Michigan. When averaged over the entire simulated derecho event, the area encompassed by the strong wind swath in the PGW simulations are 45%–106% larger relative to that in the HIST simulation (Fig. 11a). In fact, if the area of these potentially damaging derechos is normalized by the total storm area for each simulation, the wind swaths in the PGW simulations occupy half of the total storm area, whereas the wind swath in the HIST simulation occupies roughly one-quarter of the total storm area (Fig. 11b). Statistical tests (not shown) revealed that the maximum winds within the PGW derechos were not significantly stronger than in the HIST simulation. Nonetheless, PGW simulations suggest that the 10 August 2020 derecho could have covered twice the area if it had occurred at the end of the century, based on worst-case-scenario GCM projections.

As in the HIST simulation, the RIJ was the primary contributor to the damaging near-surface winds in the PGW simulations. However, in the PGW simulations, the areal coverage of the RIJ was more than 50% larger (Fig. 12) than that in the HIST simulation. The RIJ in the PGW simulations was only minimally stronger (though the 3–6 m s⁻¹ greater average wind speed

Fig. 10. As in Fig. 8, but for corresponding wind swaths of maximum winds 10 m above the ground and 20 m s⁻¹ and greater, output by the model at 15-min intervals over the duration of the simulations.
The increase was statistically significant at the 90% confidence level in three of the PGW simulations. The RIJ extended farther northward, in accord with the northward extension of the strongest echoes in the PGW storms (Fig. 8). The RIJ also formed earlier in the PGW simulations relative to the age of the convection (Fig. 12), beginning at the western Iowa border or shortly thereafter, in accord with the earlier start to the derecho in those four PGW simulations (Figs. 10 and 11b).

The larger RIJ area in the four PGW simulations producing a derecho can be explained by their larger cold pools (Fig. 13) which increased by 19%–65% in area compared to the HIST simulation. The mean thermal perturbations of the PGW cold pools were not significantly colder compared to that of the HIST simulation, but some areas within the PGW cold pools did contain air that was 2–4 K colder than the coldest air in the HIST cold pool. The strongest precipitation echoes within these four PGW MCSs extended farther north, thus also extending their respective cold pools northward. As also evident in Fig. 13, the cold pools in turn appear to have been initiated sooner (i.e., farther to the west). This earlier initiation of the cold pool can be attributed to the lower relative humidity in the lowest kilometer of the PGW environments east of central Iowa (Fig. 7), and to more precipitation falling from those storms into this lower-humidity air. The existence of lower-humidity air in the PGW simulations is consistent with multidecadal negative trends in lower-tropospheric RH shown in reanalysis data (Taszarek et al. 2021). Rainfall accumulations (not shown) in the four PGW simulations producing a derecho exceeded one inch in western Iowa, in contrast to HIST where 1 in. (∼2.54 cm) accumulations did not begin until central Iowa, likely due to the enhanced low-level moisture in the PGW environments. The PGW RIJs and cold pools, when normalized by the total storm area, occupied near 75% and 85% of the overall total storm area, respectively,

Fig. 11. (a) Total wind swath area, with percentage change relative to HIST simulation shown by the corresponding colors; (b) hourly time series (UTC) of ratio of total area of maximum near-surface wind speeds exceeding 20 m s⁻¹ to the total storm area from Fig. 9a, with line colors corresponding to legend in (a). All quantities calculated north of 40°N.
while that for HIST only occupied about 50% (Figs. 14a,b). The low-level average RH in the PGW environments (Fig. 14c) was 11%–26% lower than in the HIST environment, and the average precipitation mass in the storm downdrafts (Fig. 14d) was 44%–182% larger. Thus, earlier rainfall from the PGW storms, falling into air with much lower relative humidity, initiated cold pools earlier, and thus strengthened the RIJ earlier, which when descending to the ground behind the leading edge of the storms, initiated their respective derechos earlier (to the west) compared to the storms in the HIST simulation.

As in the HIST simulation, downbursts and mesovortices made only minor contributions to the PGW simulated wind swaths. The areas containing potential downbursts were a tenth of a percent of the areas containing the RIJ (not shown), and thus were only capable of explaining a tiny fraction of the simulated damaging wind swaths. No clear trend was found among these four PGW simulations in downburst area with respect to climate change: two had increases in the area covered by potential downbursts (12%–38% relative to the HIST simulation), while the other two showed decreases in the potential downburst area (−42% to −81% relative to the HIST simulation). In the four PGW simulations having a derecho, mesovortices were also only capable of explaining a tiny fraction of the simulated damaging wind swaths. In fact, three of the four PGW derecho simulations exhibited decreases in possible mesovortex area (ranging from −28% to −58% less than the HIST simulation), with only

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**Fig. 12.** Time history and areal extent of the 950 hPa horizontal wind exceeding 25 m s⁻¹, used here to represent the RIJ, output every 15 min for the duration of all simulations.
one simulation showing an increase of 50%. Further study with higher-resolution modeling would be required to understand if such a trend is robust, and if so, why.

Summary and discussion
The 10 August 2020 midwestern derecho was simulated using the PGW method and five different end-of-the century climate model projections under the worst-case scenario, that is, assuming humankind does nothing to alter its greenhouse gas emissions. The goal of this study was to investigate how this derecho event might differ if it instead occurred in a warmer climate, and why. Using convection-permitting simulations within possible future environments, four of the five PGW simulations initiated a long-lived MCS that produced damaging winds near the ground. This result would not have been readily anticipated using environmental parameters alone, thus illustrating the value of the PGW method.

Four of those PGW simulations yielded derechos with 50%–100% larger swaths of potentially damaging winds near the ground than for the simulation of the actual event (HIST). The wind intensity near the ground in the PGW simulations was not greater than that in the HIST simulation, but the intense winds did start earlier and lasted longer. These results appear to conflict with those published recently by Li et al. (2023), who found that the June 2012 derecho event they simulated with a different PGW method covered less area and prematurely

Fig. 13. As in Fig. 12, but showing areal extent of cold pools over the duration of each simulation, as defined in the text.
decayed relative to the actual event. However, their PGW simulations appeared to be largely affected by the occurrence of some additional convection ahead of the derecho that formed in the PGW environments. Li et al. did not delve into the derecho-generating mechanisms as done here, so the disagreement in their study and the current study may result more from differences in convective forcing for the storms. More studies are needed to help reconcile these differences.

Upon analyzing the detailed numerical simulations for the possible derecho-generating mechanisms, it was found that a larger RIJ area contributed to the larger swath of potentially damaging surface winds in the PGW simulations based on projected climate change. The larger area of the RIJ was then traced to two sources: (i) a larger cold pool area originating from the enhancement of evaporating rainfall by storms that made more precipitation earlier which fell into lower-relative-humidity air and (ii) an extension of the strongest precipitation echoes of the storms northward due to the higher CAPE there in the PGW environments.

These results should not be interpreted as a high-probability prediction. A single case study is insufficient to show all plausible climate change outcomes of severe weather events and cannot establish a general result. Projections of the magnitude of climate change continue to be refined, especially regionally, and the climate scenario used here was at the extreme end, that in which humankind makes no alteration to anthropogenic greenhouse gas emissions. Thus, the results found here should be considered as another early step in the progression of studies required to evaluate, with confidence, changes in derechos with anthropogenic climate change. It should also be noted that the response found here may be larger than what will be realized by the end of the century.

Nonetheless, the usefulness of the PGW method is showing what is physically plausible, given current projections of the storm environment, by allowing for an investigation of changes to the underlying physical chain of events that could lead to more, less, stronger, or weaker
severe weather. As a result of this study, for the first time, some evidence exists of how the underlying physical mechanisms of derechos may change due to climate change, which can be monitored as future derecho events occur. Such monitoring may help give early warning if derechos indeed start to become more extensive in their areal impact.

Current work is also investigating the utility of the PGW method in performing actual attribution studies, that is, simulating a current-day severe weather event, and then using GCM historical back-projections to approximate the storm environment as if it had occurred in the previous century, to help judge if it may indeed have been altered due to climate change. The goal would be to study the underlying physical mechanisms and how they were altered by climate change, as discussed here. It is not yet clear how useful the PGW method will be in that regard.

Finally, through publishing this PGW study in the Bulletin of the American Meteorological Society, we hope that its utility in conveying climate change impacts in a less technical manner to the nonscientist, including policy-makers and the general public (Hazeleger et al. 2015; Shepherd 2016) is demonstrated. The PGW method is a robust method of scientific inquiry but is also more intuitive than many other kinds of climate change analyses presented through high-level statistical methods with which the general public is unfamiliar. The PGW method can instead more easily communicate a fact-based, physically plausible chain of events, showing the influence of potential environmental changes brought about by climate change upon severe weather events that greatly impact society. Such communication is essential for promoting a ubiquitous shared value to addressing climate change.

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Data availability statement. GCM data were obtained from the Earth System Grid Federation, available at https://esgf-node.llnl.gov/projects/cmip5/. The HRRR data for this event are available at https://home.chpc.utah.edu/~u0553130/Brian_Blaylock/cgi-bin/hrrr_download.cgi. The WRF Model is open-source and can be downloaded at www2.mmm.ucar.edu/wrf/users/download/get_source.html.


