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Short Communication

Future convective environments using NARCCAP

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ABSTRACT: This study examines trends in atmospheric environments conducive to the development of severe convection in the United States, as simulated by a regional model forced with output from a global climate model. Meteorological variables necessary for severe convection from current (1981–1995) and future (2041–2065) epochs were compared. Results indicate a statistically significant increase in the number of significant severe weather environments in the Northeast United States, Great Lakes, and Southeast Canada regions. Regional severe weather environment increases can be attributed to both an increase in convective available potential energy (CAPE) and the number of times deep-layer wind shear and CAPE juxtaposition. Given the current distribution of severe convective weather, these changes would alter the current physical risk of severe convective storms across a large population.

KEY WORDS convection; climate; NARCCAP

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1. Introduction

Severe convective weather events have a significant impact on local, state, and national economies, as well as the livelihoods of those in the path of the storms. During the 32-year period 1980–2011, there were 110 weather-related disasters in the United States causing damages totalling over one billion dollars (NCDC, 2011). Of these 96 weather disasters, about 30% (32 disasters) were the result of severe thunderstorms. While billion-dollar severe thunderstorm events only occur once per year on average, they can have lasting societal and physical impacts on the local landscape. For example, outbreaks of severe thunderstorms across the Southeast United States in April of 2011 were responsible $17.3 billion in damages and over 350 fatalities across 20 states. The increasing trend of losses from severe thunderstorms (Changnon *et al*., 2001) and tornadoes (Brooks and Doswell, 2001; Changnon, 2009) can be attributed to interannual societal and economic changes rather than an increase in event frequency. However, recent research has indicated that the potential for severe thunderstorm environments may increase under future anthropogenic-induced climate change scenarios (Trapp *et al*., 2007; Van Klooster and Roebber, 2009). The combination of increasing societal vulnerability (Cutter *et al*., 2003) and severe thunderstorm environment frequency may lead to greater severe thunderstorm hazards in the future.

With the advances in computing power, it has become possible to examine the effects of different emissions scenarios on mesoscale weather phenomena by dynamically downscaling (Hewitson, 1996) global climate model (GCM) output. Due to the societal impact of convective weather events, it is of interest to examine the potential for the change in frequency and magnitude of these events in future climate change scenarios. Therefore, this study examines the differences between current and future potentially severe convective environments for a region in the Southeast United States.

2. Background

Determining a potentially convective environment uses a best discriminator approach from proximity reanalysis soundings based upon research conducted by Brooks *et al*. (2003b; hereafter B03). In particular, B03 show that when the product of 100 hPa mixed-layer convective available potential energy (CAPE) and 0–6 km wind difference is greater than 20 000, the environment is favoured to accommodate significant severe weather events, if events indeed occur.

Using a high-resolution Regional Climate Models (RCM) (RegCM3), Trapp *et al*. (2007) found that average 0–6 km wind shear values decrease in the late 21st Century under the A2 emissions scenario. However, a dramatic increase in CAPE was found. When evaluating the product of CAPE and wind shear, it was found that the increase in CAPE more than compensated for the decrease in wind shear. Therefore, the resulting environment was considered more favourable for severe

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thunderstorm formation. Similarly, Van Klooster and Roebber (2009) showed that potential for severe convection is found to increase east of the Rocky Mountains mainly due to warm season surface warming and moistening. This study differs from Trapp *et al*. (2007) and Van Klooster and Roebber (2009) by examining both future and present convective environments as simulated by a dynamically downscaled GCM. Thus, this study will be able to compare and contrast environments from present and future climates in order to make hypotheses about the trends in severe convective weather in the future. In addition, of particular interest, is the ability to use high-resolution dynamical downscaling to resolve severe convective storms. Recently, this has been explored by Trapp *et al*. (2010), and is an area of ongoing research. However, the change in frequency and magnitude of current severe environments is important from a climatological perspective. For example, it has been shown that atmospheric environments favourable for the development of significant severe weather [hail at least 5 cm ($\sim$2 in.) in diameter, convective wind gusts $\geq$120 km h^{-1} (65 kts), or a tornado of at least EF2/F2 damage] have changed little in the past 30-years (Gensini and Ashley, 2011).

3. Data/methods

Data for this project was supplied by the North American Regional Climate Change Assessment Program (NARCCAP) project. NARCCAP is an ongoing international effort to produce downscaled, high-resolution data simulations to address a myriad of climate change questions. The regional scale projections of future climates can help generate climate projections for use in various future impact assessments. NARCCAP researchers are running several Regional Climate Models (RCM) forced by a variety of atmosphere–ocean general circulation models (AOGCM). The current domain for the completed data covers all of the United States and parts of Canada. All RCMs are run at a spatial resolution of 50 km. It is important to note that all AOGCMs have been forced with the Special Report on Emission Scenarios (SRES) A2 emissions scenario for future century time slice encompassing the years 2041–2065. The A2 scenario is an aggressive SRES emission scenario, but not the most pessimistic. This was selected with the assumption that if a society can adapt to the changes in the A2 scenario, they could adapt to a future climate that has a less dramatic increase.

For the purposes of our study, we use the Weather Research and Forecasting Model (WRF-G) RCM forced with the Community Climate System Model (CCSM3) version 3.0. The CCSM3 was created through a joint initiative between the National Center for Atmospheric Research (NCAR), National Science Foundation (NSF), Department of Energy (DOE), National Aeronautical and Space Administration (NASA), and the National Ocean and Atmospheric Administration (NOAA). The CCSM3 has 26 vertical levels with 4 levels below 850 hPa, the model top is at 2.2 hPa. The WRF RCM was created through a multi agency effort between NCAR and several agencies within NOAA. WRF is a non-hydrostatic mesoscale model with 35 vertical layers and was chosen for this study because due to its vertical layer specification (i.e. it was configured with the most vertical layers; desirable for a study examining convective environments). For more information about the WRF RCM specifics, please visit http://www.narccap.ucar.edu/data/rcm-characteristics.html.

A variety of three-dimensional variables from NARCCAP are available at every 25 hPa from 1050 hPa to 700 hPa, and every 50 hPa from 650 hPa to 50 hPa in NetCDF format. For this study, NARCCAP CCSM3-WRF dynamically downscaled data were downloaded for three fields (10 m wind, 500 hPa wind, and CAPE) at 0000 UTC for a 15-year ‘current’ (1981–1995) and ‘future’ (2041–2065) period. NARCCAP fields used for this study include the instantaneous zonal (*ua*) and meridional (*va*) wind velocity components at 10 m AGL, and at 500-hPa. These *ua* and *va* fields will be used to calculate the bulk vertical wind difference, a proxy for 0–6 km shear. Convective forecasters typically calculate bulk wind shear over the 0–6 km layer (Rasmussen and Blanchard, 1998). While 500-hPa is typically near 5.5 km AGL for regions near sea level (COESA, 1976), a substantial difference can exist between the two heights AGL, especially on high terrain. Thus, high-elevation areas in the domain should be viewed conservatively, as deep-layer wind shear is likely underrepresented.

The other field used for this study was CAPE, which is not currently available to the public through NARCCAP. Measured in J kg^{-1}, CAPE is essentially the amount of energy available to a positively buoyant parcel of air, which, in theory, is directly related to updraft velocity. Calculations of CAPE entail dividing the lowest 180-hPa of the atmosphere into six 30-hPa deep layers. Average physical properties then are computed for each 30-hPa layer. Using properties of the 30-hPa layer with the largest θ_e, CAPE is calculated. Theoretical parcel calculations in the WRF RCM do not use the virtual temperature correction (M. Bukovsky, personal communication). Calculating CAPE using the virtual temperature correction can result in larger and more realistic values of CAPE (Doswell and Rasmussen, 1994). Given the CAPE constraints, it is likely that the results will be conservative in depicting favourable convective environment regimes.

NARCCAP netCDF files were queried for the desired variables and times using custom written Python routines. One important intermediate step was to calculate the magnitude of the horizontal winds using:

$$|\overline{U_x}| = \sqrt{U_x^2 + U_y^2} \qquad (1)$$

where U_x corresponds to the *ua* winds and U_y corresponds to the *va* winds from previously specified NARCCAP levels. For this project, four combinations of the output data were examined: frequency of CAPE exceeding 2000 J kg^{-1}, frequency of deep-layer shear exceeding

$18\,\mathrm{m\,s^{-1}}$ in the presence of CAPE exceeding $100\,\mathrm{J\,kg^{-1}}$, frequency of CAPE × shear exceeding 10000, and frequency of CAPE × shear exceeding 20000. The 10000 and 20,000 values were chosen to represent severe and significant severe environments, respectively, following results from B03 and Trapp *et al*. (2007).

Epoch spatial differences were examined and tested for statistical significance at the 95% confidence level using a student's t-test for each set of output data. Thus, one is able to visually interpret locations where historical and future convective environments differ significantly. A shift in the magnitude or spatial location of severe convective environments could provide insight concerning locations where the greatest potential exists for changes in severe convective weather. This study assumes that the statistical relationship exploited by B03 will remain similar in the future. This may or may not be true; however, given the ingredients necessary for severe thunderstorms (i.e. CAPE, moisture, wind shear, lift) the variables examined will remain important in some physical capacity. In addition, while not examined in this study, it is important to note that the annual temporal cycle of convective environments may change in a future climate as indicated by Van Klooster and Roebber (2009).

4. Results

An increase was found in the NARCCAP domain-averaged frequency of CAPE × shear environments that exceeded significant severe criterion (i.e. $\geq$20 000; Figure 1). The increase in domain-average significant severe convective environments appears to involve both an increase in deep-layer shear in the presence of $\mathrm{CAPE} \geq 100\,\mathrm{J\,kg^{-1}}$ (to assure the environment can be characterized as convective) and an increase in the number of times that CAPE and deep-layer shear are juxtaposed. In addition, domain averaged CAPE is found not to significantly differ from current to future periods. This suggests that any regional increases in CAPE are balanced by losses in CAPE in other portions of the study domain.

While these domain averages serve a purpose for detecting large regional change, local variability in severe convective environments is not properly being represented by such scale. Therefore, spatial epoch variability maps of change were constructed to analyse local grid point variability. The number of 'High CAPE' ($\mathrm{CAPE} \geq 2000\,\mathrm{J\,kg^{-1}}$) days is shown to increase across a large portion of the Great Lakes, Northeast United States, and Southeast Canada (Figure 2). Results indicate that these regions could expect to see anywhere from four to ten extra days per year with High CAPE. Significant decreases in High CAPE days were found in the South Central Great Plains and the Southern Mississippi River Valley, while other locations did not exhibit a significant change. Since the entire annual convective cycle could not be examined due to time constraints, it is hypothesized that an increase in High CAPE days can be attributed to warmer surface temperatures throughout the annual cycle, while a decrease in High CAPE days across the aforementioned areas could be attributed to warmer vertical temperature profiles (e.g. surface through 700-hPa). These changes would contribute to lower near-surface lapse rates and thus CAPE values. In addition, a lower frequency of High CAPE days could be attributed to a decrease in surface moisture values in these locations; however, the former appears more likely, as surface moisture has been shown to be increasing recently in the Central and Eastern United States (Gaffen and Ross, 1999; Dai, 2006).

Analysis of deep-layer wind shear indicates that the Great Lakes, Northeast United States, and Southeast Canada will also see significant increases in wind shear profiles supportive of severe convection (Figure 3). A contributing factor to such increases in these areas is due to the CAPE threshold used when analysing deep-layer shear environments. That is, deep-layer wind shear environments ($\geq 18\,\mathrm{m\,s^{-1}}$; roughly the median United States deep-layer shear value) were only examined in the presence of $\mathrm{CAPE} \geq 100\,\mathrm{J\,kg^{-1}}$ to make sure non-convective environments were excluded from the analysis. Thus, an increase in the number of deep-layer shear values supportive of severe convection may be a result of the increase in the number of days per year that acquire at least $100\,\mathrm{J\,kg^{-1}}$ of CAPE. Altogether, these results suggest that polar jet stream movement may play a role in future distributions of convective environments. Further research may be needed to examine when these additional days are accumulating during the annual convective cycle as this would be important to the annual temporal distribution of severe weather (Van Klooster and Roebber, 2009).

Given the significant increase in High CAPE and deep-layer wind shear over the Northeast United States, Great Lakes, and Southeast Canada, it is not surprising that severe environments (i.e. product of CAPE and deep-layer shear exceeding 10 000; similar to NDSEV in Trapp *et al*. (2007); not shown) and significant severe environments (i.e. product of CAPE and shear exceeding 20 000; similar to C-composite parameter in B03) both show future increases across these regions (Figure 4). Like High CAPE and deep-layer shear, results indicate that these regions may see an extra 5–10 $\mathrm{d\,year^{-1}}$ with environments that would be potentially favourable for significant severe weather. The remainder of the domain depicts small, mostly non-significant, decreases in such environments. This increase in significant severe weather environments could shift risk (and thus vulnerability) northward from the region depicted by Ashley (2007). In addition, the large spatial variability found indicates that the examination scale interaction is indeed important, as these trends were not obvious from domain-averaged data.

To roughly estimate bias, results from the current period reconstruction were compared to results from Gensini and Ashley (2011). The current period (1981–1995) compares very well with distributions from

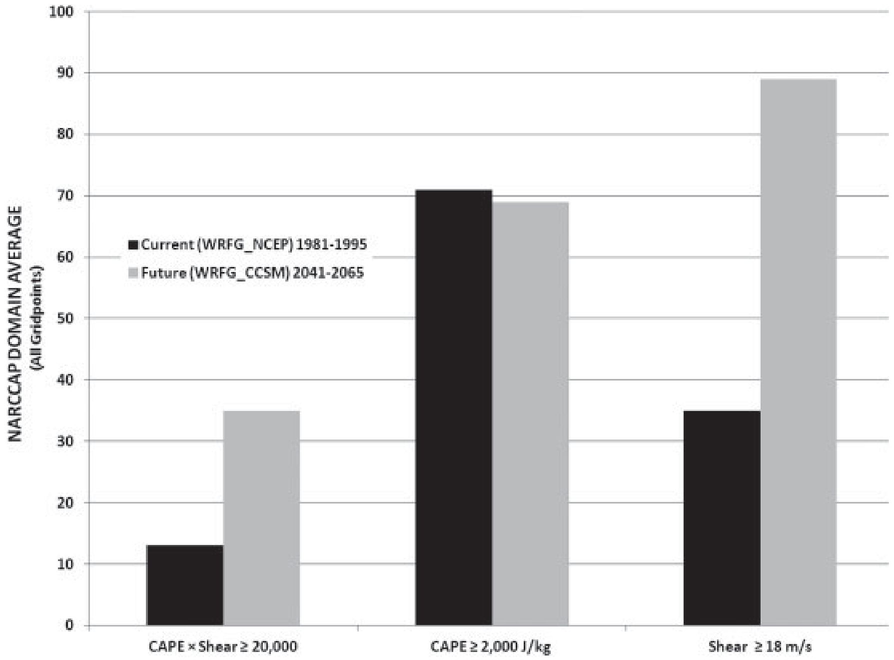

Figure 1. NARCCAP domain averaged comparisons CAPE × Shear ≥ 20 000, CAPE ≥ 2,000 J kg^{-1}, and Shear ≥ 18 m s^{-1} for the current (1981–1995; black) and future (2041–2065; grey) periods.

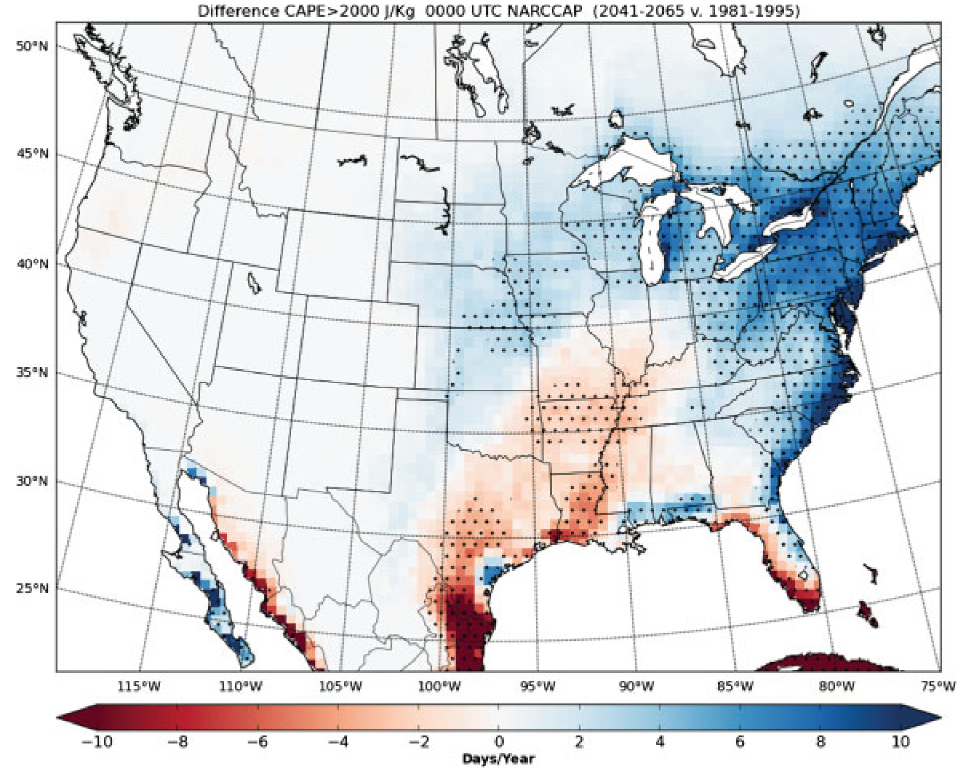

Figure 2. Difference of 2041–2065 and 1981–1995 annually averaged 0000 UTC CAPE exceeding 2000 J kg^{-1}. Speckles indicate statistical significance at the 95% confidence level.

the North American Regional Reanalysis data used in Gensini and Ashley (2011). Furthermore, the month of May was analysed between Gensini and Ashley (2011), current, and future periods to see if the RCM was accurately representing the peak of convective activity in the United States (Brooks *et al*. 2003a). This analysis indicated that the GCM/RCM combination chosen from the NARCCAP project was accurately representing the annual convective cycle in both space and time, except on the High Plains, where a consistent underestimation

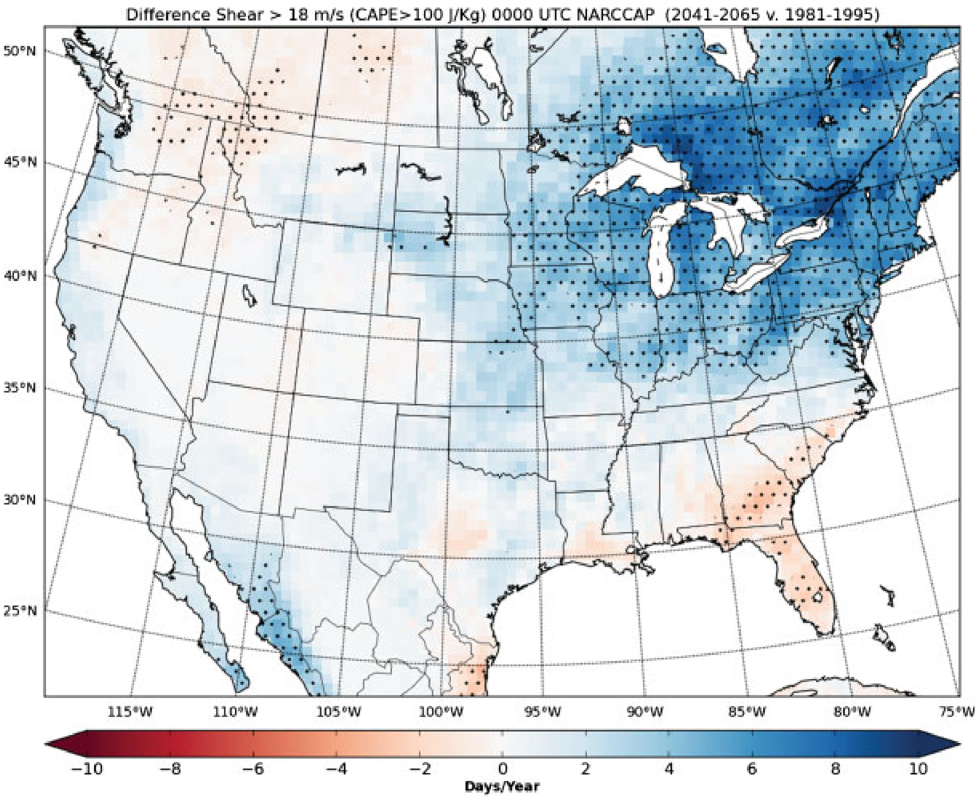

Figure 3. Difference of 2041–2065 and 1981–1995 annually averaged 0000 UTC deep-layer shear exceeding 18 m s^{-1}. Speckles indicate statistical significance at the 95% confidence level.

of severe convective environments was noted. As previously stated, this is an expected outcome, given the calculation used for deep-layer shear in this study. Thus, it does not appear that a large positive or negative bias exists in the calculation of convective environments from NCEP-driven current period runs.

It should be noted that the methodology used herein would likely do a poor job at capturing convective regimes in the Southeast United States cool-season, as these events are climatologically characterized by a low-CAPE and high-shear environment (Brooks *et al*., 2007) that may not exceed the severe convective environment threshold. However, they may still produce severe weather regimes due to strong synoptic-scale forcing (Galway and Pearson, 1981). Finally, these results are characterized by one particular GCM/RCM combination and should not be considered the only potential change for future convective environments. While comparable studies (Trapp *et al*. 2007) depict results similar to those presented here, an ensemble framework for studying such convective environments should be desirable for future work.

5. Conclusions

Although GCM downscaling to the mesoscale is a relatively new approach for severe convective storm climatology, some work has already been completed to help answer critical questions about climate change and convective storms. Trapp *et al*. (2007) provide insight to potential results, although, this study used a different RCM/GCM combination and examines a future period that occurs closer to the middle of the century rather than the later period (2078–2098) analysed by Trapp *et al*. (2007). Even with these methodological differences, regional increases in severe storm environments have been found, similar to previous results shown by Trapp *et al*. (2007).

High CAPE days, deep-layer wind shear, and severe/significant severe convective environments were all shown to increase across portions of the Great Lakes, Northeast United States, and Southeast Canada during the period 2041–2065. Results indicate that these regions could see an increase of 5–10 d year^{-1} with atmospheric environments favourable for severe weather. Decreases or no change in days per year with favourable convective regimes were found across southern portions of the United States. For all periods of all variables, it was important to examine the raw distribution of these variables to get a true sense of how they may or may not change in the future, opposed to using domain averages.

Future studies should continue to perform analysis on other GCM/RCM combinations to gain an ensemble estimation of how severe convective environments could potentially be altered in the future. Extension of work done by Trapp *et al*. (2010) will also continue to be important, as computing power increases and RCMs are

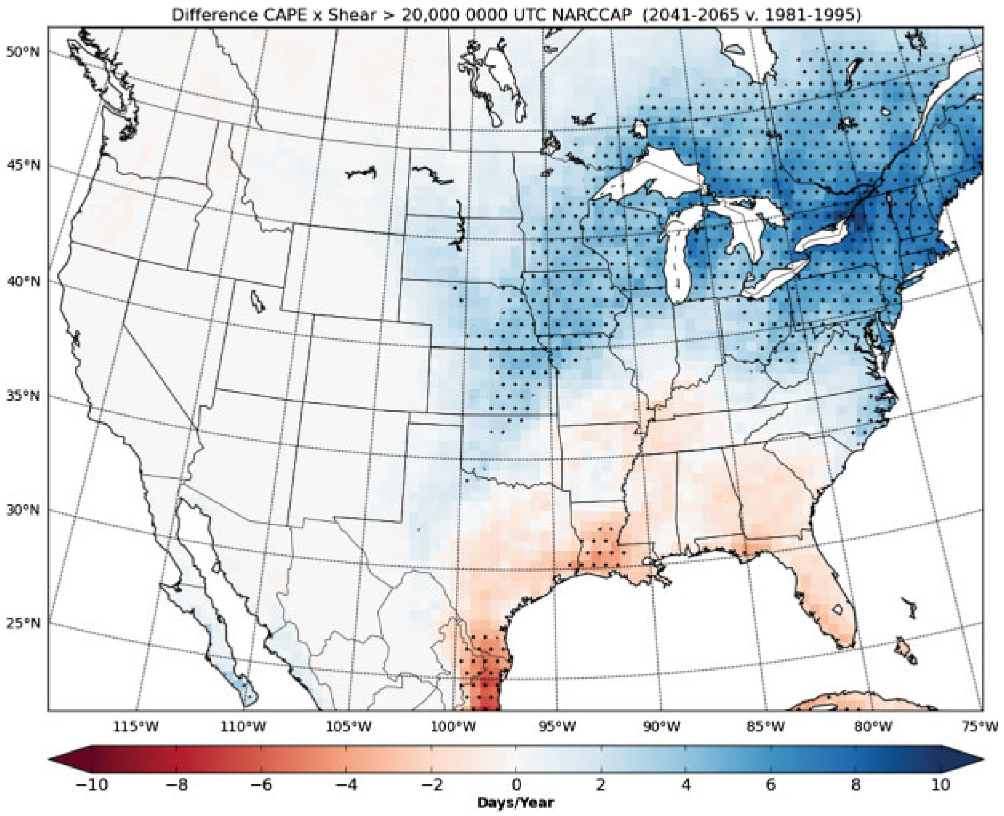

Figure 4. Difference of 2041–2065 and 1981–1995 annually averaged 0000 UTC product of CAPE and deep-layer shear exceeding 20 000. Speckles indicate statistical significance at the 95% confidence level.

explicitly able to resolve convection. Further analysis of the annual variability in severe convective environments would also be useful, exposing any potential changes in the timing and onset of the annual convective cycle.

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