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Elevated Risk of Compound Extreme Precipitation Preceded by Extreme Heat Events in the Upper Midwestern United States

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Abstract: Compound extreme events can potentially cause deadlier socio-economic consequences. Although several studies focused on individual extreme climate events, the occurrence of compound extreme events is still not well studied in the upper Midwestern United States. In this study, compound extreme precipitation preceded by extreme hot day events was investigated. Results showed a strong linkage between extreme precipitation events and extreme hot days. A significant increasing trend was noticed mainly in Iowa (10.1%), northern parts of Illinois (5.04%), and Michigan (5.04%). Results also showed a higher intensity of extreme precipitation events preceded by an extremely hot day compared to the intensity of extreme precipitation events not preceded by an extremely hot day, mostly in the central and lower parts of Minnesota, western and upper parts of Iowa, lower and upper parts of Illinois, parts of Ohio, Michigan, and Wisconsin for 1950–2010. In other words, extreme heat contributed to more extreme precipitation events. Our findings would provide important insights related to flood management under future climate change scenarios in the region.

Keywords: compound extreme events; extreme precipitation; extreme heat; trend

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1. Introduction

The upper Midwestern United States is known as the “corn belt” and is a major region for growing corn and soybeans. Therefore, the agricultural productivity in this region contributes greatly to the national output of the United States of America [1]. This region is also considered the ‘brightest ‘spot on Earth during the growing season due to high photosynthetic activity and gross productivity [2,3]. However, the region is susceptible to devastating floods primarily caused by extreme precipitation events [4–9]. Floods have significantly affected agricultural productivity, resulting in substantial financial losses as well as loss of human lives in this region [10,11]. Extreme precipitation, especially during the summer, could be attributed to mesoscale convective systems, atmospheric rivers, tropical cyclones, and frontal systems, as pointed out in the previous literature [12–15]. Previous studies also demonstrated an increase in both frequency and intensity of extreme precipitation, thus increasing the likelihood of flooding in the Midwest [16–20].

Besides extreme precipitation events, extremely hot days, including heat waves, are responsible for the loss of human lives and heat-related illnesses such as heat exhaustion and heat stroke, especially during summer [21,22]. Previous literature highlighted a delayed correlation between extreme hot days (including heat waves and heat stress) and extreme precipitation events (including flooding events), which could be attributed to the interplay and interdependence of temperature and precipitation [23,24]. High temperatures will lead to a proportional rise in the atmosphere’s capacity to hold water [25], which could create ideal conditions for heavy rainfall [26]. Prolonged extremely high temperatures could potentially lead to atmospheric instability, resulting in heavy precipitation events at a regional scale [27,28].

Compound extremes refer to the simultaneous or sequential occurrence of more than one extreme event [29,30]. The compound extreme event of extreme precipitation preceded by extremely hot days, such as heat waves, can cause more socioeconomic damage compared to individual extreme events [31,32]. Although compound flooding and heat stress were studied previously [24], there has not been any study to investigate the compound extreme precipitation preceded by extreme hot days (CEPEH) in the context of the upper Midwestern United States (UMUS) to our knowledge. In the present study, the CEPEH events were analyzed to understand the lagged correlation between extreme precipitation and extremely hot days in the UMUS. The objectives of the study are the following:

1. To determine the trend of CEPEH applying the modified Mann–Kendall test in the UMUS;
2. To investigate if the intensity of extreme precipitation events preceded by extreme hot days (ICEP) is higher compared to the intensity of extreme precipitation events not preceded by extreme hot days (INCEP) on the annual scale;
3. To find out if the frequency of CEPEH increased/intensified in the recent decades, especially since 1980 from 1980–2010.

2. Materials and Methods

2.1. Study Area and Data

A total of 441 stations are analyzed located in nine different upper Midwestern states (Illinois (IL), Missouri (MO), Kentucky (KY), Indiana (IN), Ohio (OH), Iowa (IA), Minnesota (MN), Wisconsin (WI), and Michigan (MI)) in the United States which has a humid continental climate (Figure 1). For this study, daily precipitation and temperature data from 441 weather stations were collected for 61 years (1950–2010) for nine Midwestern States, i.e., Illinois (IL), Missouri (MO), Kentucky (KY), Indiana (IN), Ohio (OH), Iowa (IA), Minnesota (MN), Wisconsin (WI), and Michigan (MI). Stations with at least 90% complete data were chosen for the analysis. Data for the majority of the 781 stations were from the United States Department of Agriculture-Agriculture Research Service (USDA-ARS) database, including the Cooperative Observer Network (COOP) and Weather-Bureau-Army-Navy (WBAN) weather stations. The rest of the data was collected from the Midwestern Regional Climate Center (MRCC).

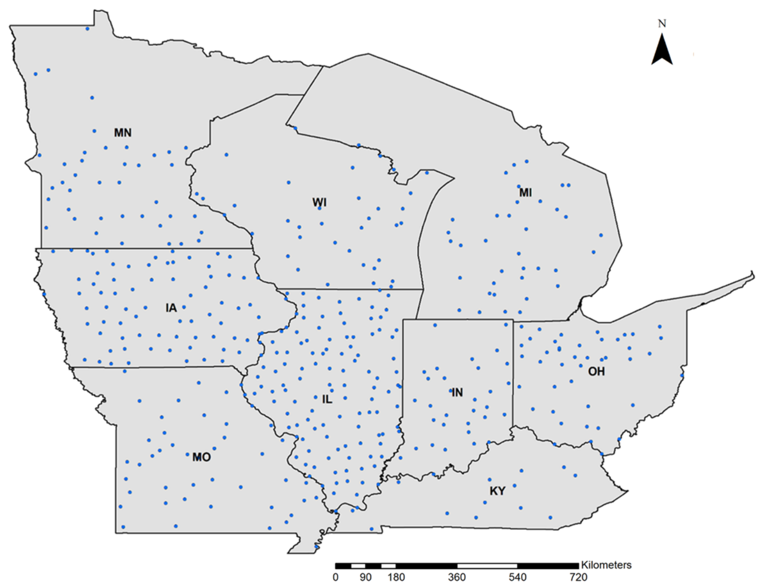

Figure 1. Locations of 441 gage stations (blue circles) used in the study which are located in Illinois (IL), Missouri (MO), Kentucky (KY), Indiana (IN), Ohio (OH), Iowa (IA), Minnesota (MN), Wisconsin (WI), and Michigan (MI).

2.2. Compound Extreme Precipitation Preceded by Extreme Hot Day (CEPEH)

An extreme precipitation (R95) event is defined as the day when the amount of precipitation exceeds or equals the 95% quantile of the daily precipitation time series from 1950–2010. Similarly, an extreme hot day (TMAX90) event is defined as the day when the daily maximum temperature exceeds or equals the 90% quantile of the daily maximum temperature time series from 1950–2010. The CEPEH event is defined as a preconditioned compound event when an R95 event is preceded by at least one extremely hot day (TMAX90) in the last 3 days before the precipitation event [24,32]. The frequency of CEPEH is calculated as a fraction of total extreme precipitation events. The frequency of CEPEH is calculated as a fraction of total extreme precipitation events as defined below:

$$Fraction\ of\ annual\ CEPEH = \frac{Number\ of\ annual\ CEPEH\ events}{Number\ of\ total\ annual\ R95\ events} \quad (1)$$

The intensity of extreme precipitation events preceded by an extreme hot day (ICEP) is calculated as follows:

$$ICEP = \frac{Total\ amount\ of\ precipitation\ during\ R95\ events\ preceded\ by\ hot\ day}{Number\ of\ R95\ events\ preceded\ by\ hot\ day} \quad (2)$$

The intensity of the extreme precipitation events not preceded by extreme hot days (INCEP) is determined as follows:

$$INCEP = \frac{Total\ amount\ of\ precipitation\ during\ R95\ events\ not\ preceded\ by\ hot\ day}{Number\ of\ R95\ events\ not\ preceded\ by\ hot\ day} \quad (3)$$

2.3. Modified Mann–Kendall Test

The null hypothesis for the Mann–Kendall test (Mann, 1945; Kendall, 1948) is that there is no trend in the data, assuming the data are independent and randomly ordered. The significance of trend is determined at 95% significance level. The Mann–Kendall test statistic S can be calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right) \quad (4)$$

where, n = the number of data points in the observation series, x_i and x_j = values of the data at time i and j respectively $(j > i)$, and $sgn\left(x_j - x_i\ \right)$ is the sign function given by:

$$sgn(x_j - x_i) = \begin{cases} -1 & for\ \left(x_j - x_i\right) < 0 \\ 0 & for\ \left(x_j - x_i\right) = 0 \\ +1 & for\ \left(x_j - x_i\right) > 0 \end{cases} \quad (5)$$

More details on the Modified Mann–Kendall test have been provided in The Supplementary Material.

3. Results

3.1. Spatial Distribution of Compound Extreme Events

The fraction of total extreme precipitation events (R95) that were preceded by at least one extremely hot day in the last 3 days of occurrence was observed to be mostly spatially heterogeneous in the UMUS (Figure 2). The fractional contribution ranges from 21% to 35% per year from 1950–2010. The fractional contributions were found to be 28.3%, 30.5%, 27.6%, 28.4%, 29.4%, 26.1%, 28.1%, 30.9%, 29.1% for Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin. The smaller fractional contribution was mainly noticed in the southern part of Illinois and Ohio and in the southeastern part of Iowa. In comparison, the larger fractions were found mostly in the central and upper parts of Illinois, Indiana, Idaho, and lower parts of Wisconsin and Michigan.

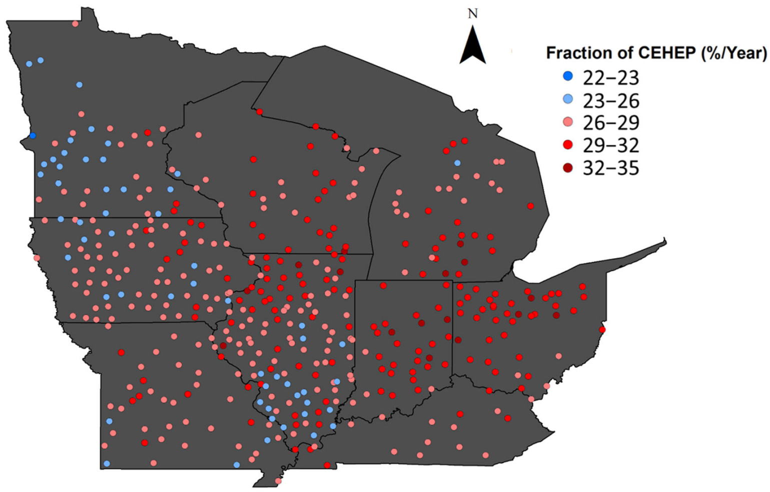

Figure 2. Spatial distribution of compound extreme precipitation events preceded by extreme hot days expressed as fraction of total extreme precipitation events from 1950–2010 in the upper Midwestern United States.

3.2. Trends of Compound Extreme Events

Mostly, a significant decreasing trend (the significance of the trend was determined at a 95% significance level) in the fraction of compound extreme heat extreme precipitation (CEPEH) was found in Illinois (25.2%), Ohio (10.9%), and Indiana (7.6%) from 1950–2010 (Figure 3a). On the other hand, a significant increasing trend was noticed mainly in Iowa (10.1%), northern parts of Illinois (5.04%), and Michigan (5.04%). When CEPEH was analyzed since the 1960s, the most significant increasing (10.1%) and decreasing (10.1%) trends were identified in Illinois (Figure 3b). Mostly, a significant increasing trend was observed in Illinois (10.9%), Michigan (7.6%), Ohio (4.2%), and Wisconsin (4.2%) when the trend analysis was performed in the 1970s (Figure 3c). A significant increase in the magnitude of the increasing trend of CEPEH has been noticed since 1980, especially in Michigan (12.6%) and Illinois (10.1%) (Figure 3d).

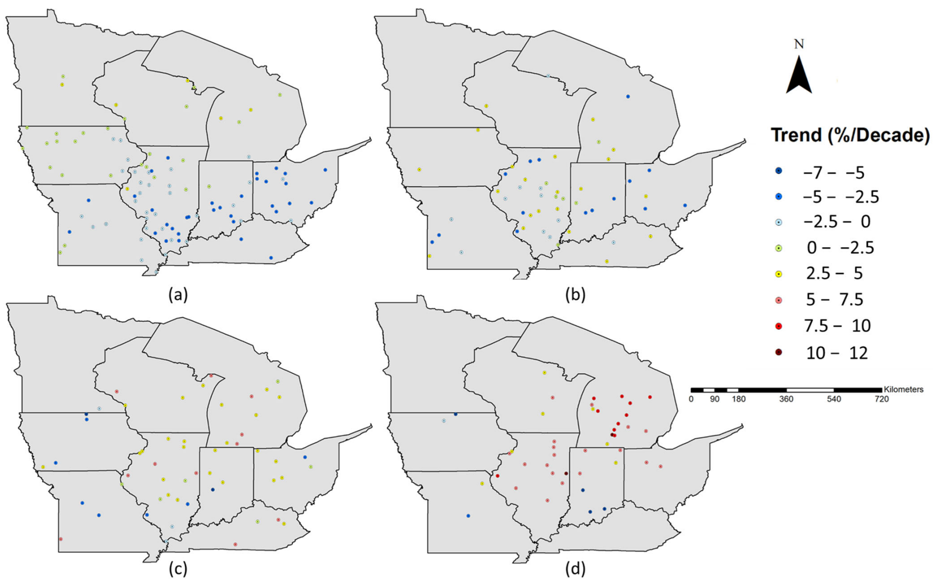

Figure 3. Trend of compound extreme precipitation events preceded by extreme hot day expressed as fraction of total extreme precipitation events from (**a**) 1950–2010; (**b**) 1960–2010; (**c**) 1970–2010; (**d**) 1980–2010 in the upper Midwestern United States. The significance of trend is determined at 95% significance level.

3.3. *Comparison of Rainfall Intensity between Extreme Rainfall Preceded and Not Preceded by Extreme Hot Day*

The intensity of extreme precipitations events preceded by extreme hot day (ICEP) and the intensity of extreme precipitation events not preceded by extreme hot day (INCEP) were calculated for each decade (i.e., 1950–1960 (Figure 4a), 1961–1970 (Figure 4b), 1971–1980 (Figure 4c), 1981–1990 (Figure 4d), 1991–2000 (Figure 4e), 2001–2010 (Figure 4f)) and for the entire time span (i.e., 1950–2010 (Figure 4g)). Results showed higher ICEP compared to INCEP mostly in the central and lower parts of Minnesota, western and upper parts of Iowa, lower and upper parts of Illinois, parts of Ohio, Michigan, and Wisconsin for 1950–2010 (Figure 4g). On the other hand, INCEP was found to be higher compared to ICEP, primarily in parts of Illinois, Missouri, and Iowa. The decadal comparison of intensities mostly showed a similar pattern. The difference between ICEP and INCEP was found to be statistically significant between 1950–2010, especially in Minnesota, Illinois, and a few stations in Iowa, Missouri, Indiana, and Ohio (Figure 4g).

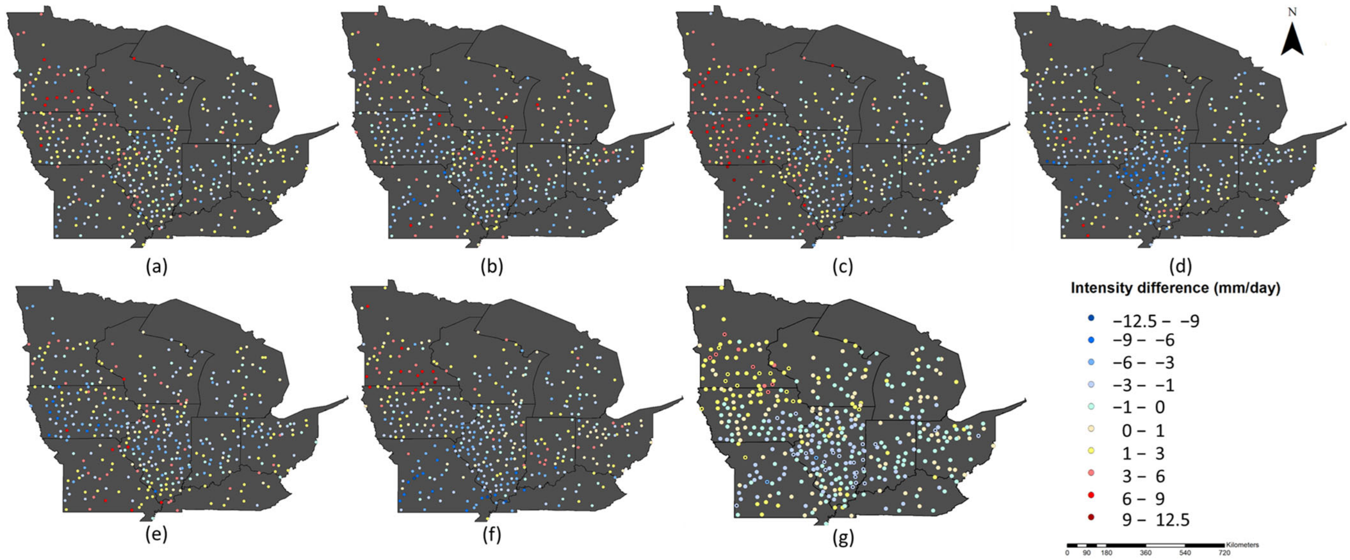

Figure 4. Difference between intensity of extreme precipitation events preceded by extremely hot day (ICEP) and the intensity of extreme precipitation events not preceded by extreme lyhot day (INCEP) from (**a**) 1950–1960; (**b**) 1961–1970; (**c**) 1971–1980; (**d**) 1981–1990; (**e**) 1991–2000 (**f**) 2001–2010; (**g**) 1950–2010 in the upper Midwestern United States. In (**g**), the circles with a dot in the center indicate the stations at which the difference between intensity of ICEP and INCEP is statistically significant from 1950–2010. The significance is determined at 95% significance level.

4. Discussion

Results showed a significant increase in CEPEH, mainly in Iowa, northern parts of Illinois, and Michigan since 1950. As compound extreme events can potentially cause more socio-economic damage compared to individual extreme events [31,32], planning and management of resources should be done accordingly, especially in Iowa, Michigan, and Illinois. An increasing trend in compound flood events preceded by heat stress in Iowa and Illinois is also reported by a previous study [24]. High temperature accompanied by high humidity generates favorable conditions for water vapor convergence. Further, both high temperature and humidity can be linked to convective available potential energy (CAPE) as they can cause instability in the atmosphere by acting as the provider of atmospheric moisture as well as dynamical forcing, leading to the development of convection and stormy weather in the Midwestern United States [24,33]. For example, [24] showed a strong correlation between CAPE and compound flooding and heat stress. Apart from CAPE, large-scale factors such as convective inhibition (CIN) and vertically integrated moisture divergence (VIMD) also play a crucial role in such compound events [34]. Favorable conditions for stormy weather may arise due to a combination of high CAPE and low CIN, potentially leading to extreme rainfall following the conclusion of heat waves. On the contrary, such compound events are unlikely to take place under both high CAPE and CIN [34]. Further, a significant increase in the magnitude of an increasing trend of CEPEH was also evidenced since 1980, especially in Michigan and Illinois. Analysis of CIN (Figure 5) showed lower values of CIN in the case of compound extreme precipitation preceded by extremely hot days compared to the compound event of extreme precipitation not preceded by extremely hot days from 1980–2010, especially in Michigan, Wisconsin, and the upper parts of Illinois. This suggests that CIN may be partly attributed to the trends of CEPEH. This can also be partly attributed to the warming of near-surface air temperature under global warming. As warmer air has the capacity to contain more water vapor, it can lead to an increase in more frequent extreme precipitation [35]. Global warming can intensify heat waves and result in a greater synchronization of extreme precipitation and heat waves. This synchronization can lead to a substantial rise in the proportion of combined extreme heat-precipitation occurrences [23].

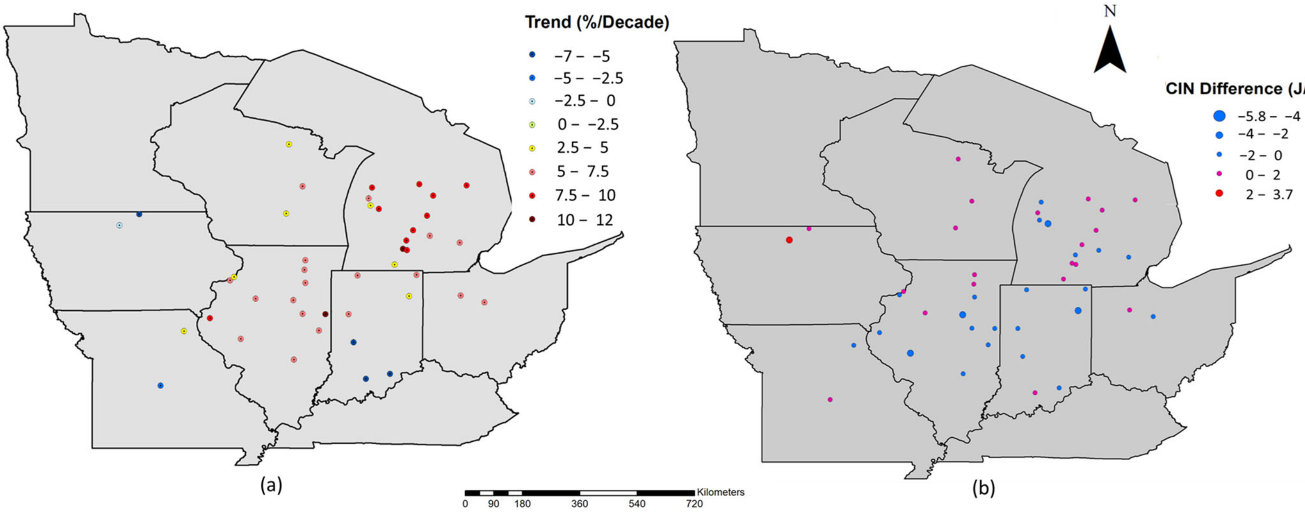

Figure 5. (**a**) Trend of compound extreme precipitation events preceded by extreme hot day expressed as fraction of total extreme precipitation events from 1980–2010 and (**b**) difference of convective inhibition (CIN) between compound events preceded by extreme hot day and not preceded by extremely hot day.

The upper Midwest of the United States is one of the key producers of corn and soybeans in the world, and the variability in corn and soybean production has been linked to the climate in the Midwest [36]. Extreme precipitation can increase the soil moisture significantly, leading to a loss in crop yield, especially in poorly drained soil conditions, whereas extreme temperature can intensify water stress for crops, leading to crop yield loss. However, the impact of such compound events can vary spatially depending on the soil and tile drainage conditions. Moreover, the timing of such events in different stages of crop growth also plays an important role in crop production. The crop yield loss-related risk is also expected to increase under future climate scenarios in the region [36]. Management strategies such as early plantation of existing cultivars or planting new cultivars with better yield potential and resilience to extreme climate conditions can help offset the negative impact of extreme events. Heat stress can also negatively impact health, especially for people with pre-existing health conditions and rural residents without air conditioning. Further, prolonged high temperatures can lead to a rise in cooling-related electricity demand, causing unusually high and prolonged peak loads on power grids. As both extreme precipitation and heat waves are expected to increase under future climate change scenarios, understanding the trends and patterns of such events is crucial for better climate adaptation and mitigation policies on a regional scale. By revealing these insights, we can better understand the scientific implications for addressing the potential societal and economic hazards resulting from these compound extreme climate events.

5. Conclusions

The compound extreme precipitation preceded by extreme hot day events was studied in the upper Midwestern United States from 1950–2010. Results showed a strong linkage between extreme precipitation events and extreme hot days. A significant increasing trend was noticed mainly in Iowa (10.1%), northern parts of Illinois (5.04%), and Michigan (5.04%). This implies that the social infrastructure of these regions is more susceptible to such compound hazards. Results also showed a higher intensity of extreme precipitation events preceded by an extremely hot day compared to the intensity of extreme precipitation events not preceded by an extremely hot day, mostly in the central and lower parts of Minnesota, western and upper parts of Iowa, lower and upper parts of Illinois, parts of Ohio, Michigan, and Wisconsin for 1950–2010. This suggests that extreme heat contributed to more intense precipitation events in those regions. Due to the indications from climate projections that the occurrence of extremely hot days is likely to become more frequent in the future, it is reasonable to anticipate a greater frequency of such compounding extreme events throughout the upper Midwestern United States. This, in turn, is likely to result in more significant societal and economic impacts.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14091440/s1.

Author Contributions: M.K.: conceptualization; data curation; formal analysis; investigation; methodology; software; visualization; writing—original draft. R.B.: conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review and editing. L.C.: formal analysis; investigation; methodology; writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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