# Variability and Transitions in Precipitation Extremes in the Midwest United States

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ABSTRACT: Monthly to seasonal precipitation extremes, both flood and drought, are important components of regional climates worldwide, and are the subjects of numerous investigations. However, variability in and transition between precipitation extremes, and associated impacts are the subject of far fewer studies. Recent such events in the Midwest region of the United States, such as the 2011–12 flood to drought transition in the upper Mississippi River basin and the flood to drought transition experienced in parts of Kentucky, Ohio, Indiana, and Illinois in 2019, have sparked concerns of increased variability and rapid transitions between precipitation extremes and compounded economic and environmental impacts. In response to these concerns, this study focuses on characterizing variability and change in Midwest precipitation extremes and transitions between extremes over the last 70 years. Overall we find that the Midwest as a region has gotten wetter over the last seven decades, and that in general the annual maximum and median wetness, defined using the standardized precipitation index (SPI), have increased at a larger magnitude than the annual minimum. We find large areas of the southern Midwest have experienced a significant increase in the annual SPI range and associated magnitude of transition between annual maximum and minimum SPI. We additionally find wet to dry transitions between extremes have largely increased in speed (i.e., less time between extremes), while long-term changes in transition frequency are more regional within the Midwest.

SIGNIFICANCE STATEMENT: The U.S. Midwest has experienced several rapid transitions in precipitation extremes over the past decade. These events, such as the 2012–13 drought to flood transition, have sparked concerns of more frequent, rapid swings in precipitation extremes. We use a 69-yr daily precipitation record to document transitions in precipitation extremes across the Midwest. We find that since the 1950s the Midwest has gotten wetter, but annual wet extremes have increased at a much larger rate than annual dry extremes. Furthermore, we find the area from eastern Missouri to western Ohio has experienced more frequent, more rapid flood to drought transitions in recent decades. This provides evidence of increased precipitation variability in this region, and associated rapid transitions between extremes.

KEYWORDS: Extreme events; Precipitation; Climate variability

## 1. Introduction

Monthly to seasonal precipitation extremes, both flood and drought, are important components of regional climates worldwide. However, these extremes and their corresponding impacts are typically studied and communicated independently, without consideration of additional or magnified impacts due to a rapid transition from one extreme to another. For example, economic impacts from 2011 flooding along the Mississippi River in the United States were estimated between \$2 and \$4 billion (NOAA/NCEI 2011), while impacts from the subsequent 2012 drought in the same region were estimated at \$30 billion (NOAA/NCEI 2012). The well-documented economic (e.g., Changnon and Easterling 1989; Mallya et al. 2013), environmental (e.g., Lowery et al. 2009), and individual mental health impacts from extreme, variable weather (e.g., Yazd et al. 2019) mandate improved understanding of transitions between extreme precipitation events.

The 2011–12 flood to drought transition is an example of what was described by Cohen (2016) as "weather whiplash," the evolution from one climate extreme to one of the opposite sign in a relatively short time period. Previous studies have documented transitions in precipitation extremes, herein referred to as simply transitions, in many regions globally using a wide variety of statistical and modeling techniques (e.g., Ji et al. 2018; Swain et al. 2018; Chen et al. 2019). Christian et al. (2015) found that annual precipitation extremes in the U.S. Great Plains followed annual extremes of the opposite sign at a rate significantly higher than what would be expected by chance.

Recent events in the Midwest region of the United States, such as the aforementioned 2011–12 transition and the flood to drought transition experienced in parts of Kentucky, Ohio, Indiana, and Illinois in 2019 (Di Liberto 2019; Voiland 2019) have sparked concerns of the risk of rapid transitions between precipitation extremes and risks posed to the Midwest thereof. Loecke et al. (2017) found rapid drought to flood transition in the Midwest between 2012 and 2013 resulted in considerable environmental impacts due to nutrient runoff from agricultural fields. In this study, the Midwest is broadly defined as including

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the entirety of Ohio, Michigan, Indiana, Kentucky, Illinois, Missouri, Iowa, and Minnesota, as well as parts of surrounding states (Fig. S1 in the online supplemental material).

Transitions between precipitation extremes are superimposed on multidecadal trends of increasing spring and decreasing late summer Midwest precipitation (Dai et al. 2016). The seasonal variability and potential transition from wet to dry extremes are projected to increase in this region with continued climate change (Loecke et al. 2017). These findings agree with the broader climate change literature indicating projected increases in both spring flooding and summer drought in the Midwest under a warmer climate (Kunkel et al. 1999; Hatfield et al. 2013). Frequent, widespread transitions from wet to dry extremes, particularly timed immediately prior to or during the growing season, can cause significant impacts to Midwest agriculture (Dixon and Segerson 1999; Liu and Basso 2020). Given the region's strong agriculture economy, increased frequency and/or severity of transitions in precipitation extremes could increase the risk of agricultural impacts with future climate change.

Despite the importance of the seminal studies on weather whiplash or transitions in extremes, our current understanding of these phenomena, including their climatological precedent and recent and long-term changes in characteristics such as frequency and severity is lacking. This is particularly in the case for humid continental climates such as the Midwest. This study focuses on characterizing 1) precipitation variability, 2) trends in precipitation extremes, and 3) transitions between precipitation extremes across the Midwest. This includes the development of a transition climatology and documentation of the changes in transition frequency, periodicity, and severity. The overall goal of the study is to improve our understanding of variability of and transitions in precipitation extremes in the Midwest, and therefore contribute to knowledge of the risks that these events pose to the region.

## 2. Data and methods

### a. Precipitation extremes

The study uses daily precipitation from NOAA's climate divisional dataset (nClimDiv, Vose et al. 2014), which is based on the gridded Global Historical Climatology Network–Daily dataset (GHCN-D; Menne et al. 2012). The nClimDiv dataset has been operational since 2014 and provides monthly updated 5-km grids of temperature and precipitation across the contiguous United States, with a historical record currently spanning 1951 to the present. The daily grids are the result of climatologically aided interpolation, incorporating more stations and updated quality-control techniques than the previous daily divisional dataset. More information for the climatologically aided interpolation method used for nClimDiv can be found in Vose et al. (2014) and Willmott and Robeson (1995).

Precipitation extremes are characterized by computing the standardized precipitation index (SPI; McKee et al. 1993) using daily precipitation from nClimDiv grids. The SPI algorithm standardizes $n$-day precipitation accumulation by fitting a gamma distribution to the historical series of $n$-day precipitation accumulation at a specific location. SPI is widely used for drought research and monitoring and is a key indicator of conditions in the U.S. Drought Monitor (Svoboda et al. 2002). Although its primary use is a meteorological drought indicator, SPI can characterize extreme dry and extreme wet conditions at monthly to interannual time intervals (e.g., Hayes et al. 1999; Ford and Labosier 2014; Katsanos et al. 2018), making it an ideal metric for assessing transitions between precipitation extremes.

We apply the SPI algorithm to 30-, 90-, and 180-day precipitation accumulation totals that move 1 day at a time. SPI is computed incrementally using an $n$-day moving window that ends on the calendar day being analyzed. Therefore, the 30-day SPI on any given day $x$ represents the standardized value of precipitation that accumulated between day $x - 29$ and day $x$. This is done separately at each nClimDiv 5-km grid cell.

Most previous studies examine transitions and variability using monthly, seasonal, or annual resolution climate data (e.g., Christian et al. 2015; Swain et al. 2018; Ji et al. 2018). Chen et al. (2019) identify a transition as adjacent months with opposite water balance extremes (i.e., wet to dry, dry to wet). When characterizing climate extremes and transitions between extremes, the data temporal resolution can affect the magnitude and frequency of the extreme. This is important when dry or wet extremes begin near the middle of a calendar month, season, or year and persist to the next month, season, or year. In this case a 1-, 3-, or 12-month SPI time series will likely underestimate the overall magnitude of the extreme. The moving window approach used in this study overcomes this challenge, but it does come with other limitations, which should be noted. These include the fact that the moving window 30-, 90-, and 180-day SPI time series do not contain independent samples, and therefore caution must be taken in analysis of the time series, particularly when assessing statistical significance.

Finally, although SPI can reasonably represent moisture conditions over periods ranging from 2 weeks to 2 years, we use 30-, 90-, and 180-day SPI to capture transitions in monthly to seasonal precipitation extremes. The methods implemented in this study could easily be adopted to characterize transitions between longer-term extremes, such as changes in multiyear or multidecade regimes of anomalously wet or dry conditions.

### b. Transition identification

Multiple methods have been developed by previous studies attempting to characterize precipitation extremes and the transition between them (e.g., Christian et al. 2015; Francis et al. 2018; Casson et al. 2019). In this study we focus on two different aspects of precipitation extremes: intra-annual variability and transitions. The first, intra-annual variability, is used to characterize precipitation variability within a calendar year. Intra-annual variability is defined as the difference between the annual maximum and annual minimum SPI within each calendar year.

Because precipitation extremes often span multiple calendar years, we also define transitions adopting the methods of DeGaetano and Lim (2020, hereinafter DL20). The method was developed and applied by DL20 to study transitions or ''tail swings'' in daily mean air temperature, averaged over 7-, 30-, and 90-day time periods across the contiguous United States. In the current study, a transition occurs when the 30-, 90-, or 180-day SPI moves from at or above +1.6 to at or below −1.6, or vice versa. These thresholds approximate the 95th and 5th percentile of historical SPI distributions, in line with the probability thresholds used by DL20. We also completed the analysis using the 95th and 5th percentiles of SPI for each individual nClimDiv grid cell, and the results were not sensitive to this change in methodology.

The example in Fig. 1 shows a transition identified from the 90-day SPI record at the nClimDiv grid cell corresponding with Peoria, Illinois. Following the DL20 method, a transition begins when the 90-day SPI crosses a threshold, either −1.6 (dry) or +1.6 (wet). The transition ends when the 90-day SPI subsequently crosses the opposite threshold. Using the example in Fig. 1, the wet to dry transition begins on the last day in which the 90-day SPI is at or above the +1.6 threshold, and ends on the first day in which the 90-day SPI is at or below the −1.6 threshold. Each transition's occurrence is assigned to the date on which the change to the opposite extreme threshold first occurred; in the case of Fig. 1 the transition is documented on 3 April. Both wet to dry and dry to wet transitions are identified at each nClimDiv grid cell between 1951 and 2019.

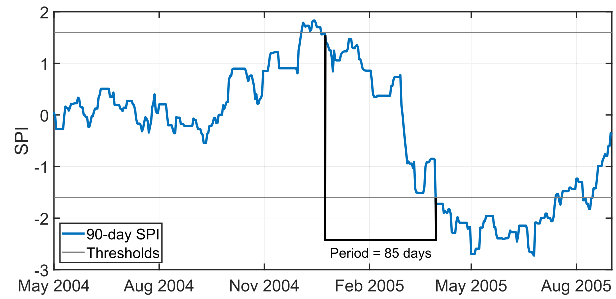


FIG. 1. Example of interannual transition in precipitation extremes. Blue line shows 90-day SPI between May 2004 and August 2005 in Peoria, Illinois (40.69°N, 89.59°W). The black lines indicate the transition start and end, with an overall duration of 85 days.

### c. Statistical analysis

We define two primary features of Midwest precipitation intra-annual variability: magnitude and duration. Variability magnitude is defined as the difference between the annual maximum and minimum SPI, while duration is defined as the time period (in days) that elapses between these intra-annual extremes. Likewise, we define two primary features of transitions in the Midwest: the frequency and the duration. Frequency is defined as the total number of transitions in the historical record at each nClimDiv grid cell. Duration is defined as the number of days that elapse between the SPI extremes marking the beginning and end of each transition. In the case of the transition in Fig. 1, 85 days elapse between the last occurrence of a wet extreme and the first occurrence of a dry extreme.

We assess long-term change in transition frequency, magnitude, and duration over the 69-yr study period, based on trend analysis using median of pairwise slopes regression (Lanzante 1996). Although the individual transitions are independent from one another, the underlying SPI values are not. This is because the moving window approach for calculating SPI results in a single day informing SPI for multiple calendar days. Therefore, we use a bootstrap resampling approach to robustly assess the statistical significance of trends in SPI, transition magnitude, and transition duration. The 30-, 90-, and 180-day SPI time series are shuffled, transitions are identified in the shuffled time series, and trends are computed. This process is repeated 10 000 times. The real SPI and transition trends are compared to the 95th and 5th percentile of the trend distributions derived from the resampling method. A trend is considered statistically significant if it either exceeds the 95th percentile or is less than the 5th percentile.

Trends in annual minimum and annual maximum 30-, 90-, and 180-day SPI are also evaluated using a median of pairwise slopes regression with a Mann–Kendall tau test for statistical significance. Statistically significant trends are herein denoted as significant.

## 3. Results

### a. Midwest precipitation

Average (1951–2019) annual maximum and minimum 30-, 90-, and 180-day SPI show considerable variability across the Midwest (Fig. 2). The eastern half of the region exhibits an overall larger annual 30-day SPI range, while the northwestern quadrant of the Midwest exhibits larger annual 90-day and 180-day SPI ranges. This suggests that shorter-term precipitation variability is higher in the eastern and southeastern Midwest, while longer-term precipitation variability is higher in the western and northwestern Midwest. The actual magnitudes of annual extremes are similar at all locations, with annual maximum SPI roughly ranging from 1.5 to 2.5, and annual minimum ranging from −1.5 to −2.5.The 30-day SPI extremes are of larger magnitude than the 90- and 180-day extremes. This is indicative of the higher variability of 30-day SPI due to sensitivity to both individual heavy rainfall events and short-term dry spells.

Trend analysis indicates large areas of statistically significant increases in annual maximum, annual median, and annual minimum SPI across the Midwest (Fig. 3). Significant SPI increases range from 0.08 to 0.20 decade$^{-1}$, with the overall highest magnitude trends in the eastern half of the region. The only significant decreasing trends are for 180-day SPI in the extreme southeast corner of the region. The dominance of positive SPI trends is consistent with widely observed increases in total seasonal and annual precipitation across the Midwest over the last few decades (Angel et al. 2018).

Overall, significant increases in annual maximum SPI are more spatially extensive and of higher magnitude than those for annual minimum SPI, particularly at 90- and 180-day intervals. The Great Lakes and eastern Midwest exhibit

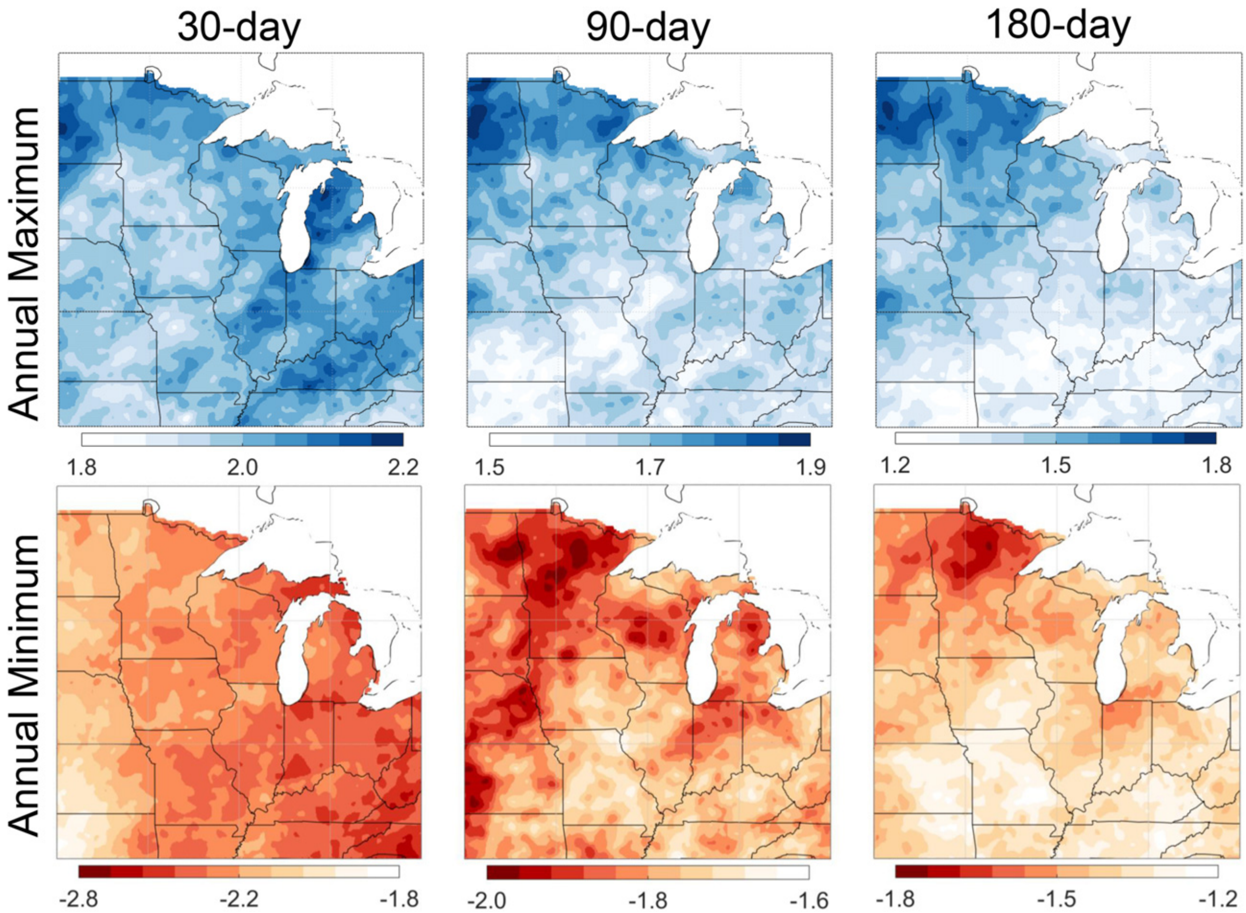


FIG. 2. Maps show the climatological (1951–2019) average annual (top) maximum and (bottom) minimum SPI across the Midwest. From left to right columns show 30-, 90-, and 180-day SPI, and color map ranges differ between the SPI durations.

significant positive trends of similar magnitude in both maximum and minimum SPI, suggesting the entire distribution of 90- and 180-day precipitation accumulation has shifted to more frequent wet conditions. In contrast, areas of Illinois, Missouri, and Iowa show significant increases in annual maximum SPI without corresponding increases in the annual minimum. This suggests 90- and 180-day precipitation accumulation has become more variable in this part of the central and southern Midwest, with higher magnitude wet extremes and continued occurrence of high magnitude dry extremes.

*b. Intra-annual variability*

Intra-annual variability is characterized in two ways. The first is the magnitude, which is the difference between the annual maximum and minimum SPI for each year (1951–2019). The second is the duration, which is the time period (in days) that elapses between the annual maximum and minimum SPI for each year. The maps in Fig. 4 show the spatial distribution of intra-annual variability magnitude and duration, averaged over all 69 years. In general, the magnitude follows the pattern of climatological average annual maximum and minimum SPI in Fig. 2. Variability is largest at 30 days in the eastern and southeastern parts of the Midwest, between 2.0 and 2.5, while 90- and 180-day SPI variability is largest in the northern and western areas of the region, between 1.5 and 2.0. Duration shows more consistency between the three SPI intervals, with the shortest duration (i.e., shortest time between annual extremes) in the northwest part of the Midwest, and generally longer duration transitions in the east and southeast. The bottom row of maps in Fig. 4 show the interannual standard deviation of duration, in days, calculated over the 69-yr study period, which represents the variability in the seasonal timing of annual precipitation extremes. The variability maps loosely follow the spatial patterns of magnitude (top row Fig. 4), with higher overall variability at 30-day SPI than 90 or 180 day. The southern half of the Midwest generally exhibits higher variability at 30- and 90-day SPI, but the northern and western parts of the Midwest have a higher variability 180 days. This indicates less year-to-year consistency in the timing of precipitation extremes at shorter time scales, particularly in the southern Midwest, relative to the longer time scales.

Neither intra-annual variability magnitude nor duration shows widespread significant trends over the 69-yr study period (Fig. 5). The area spanning northeast Missouri to

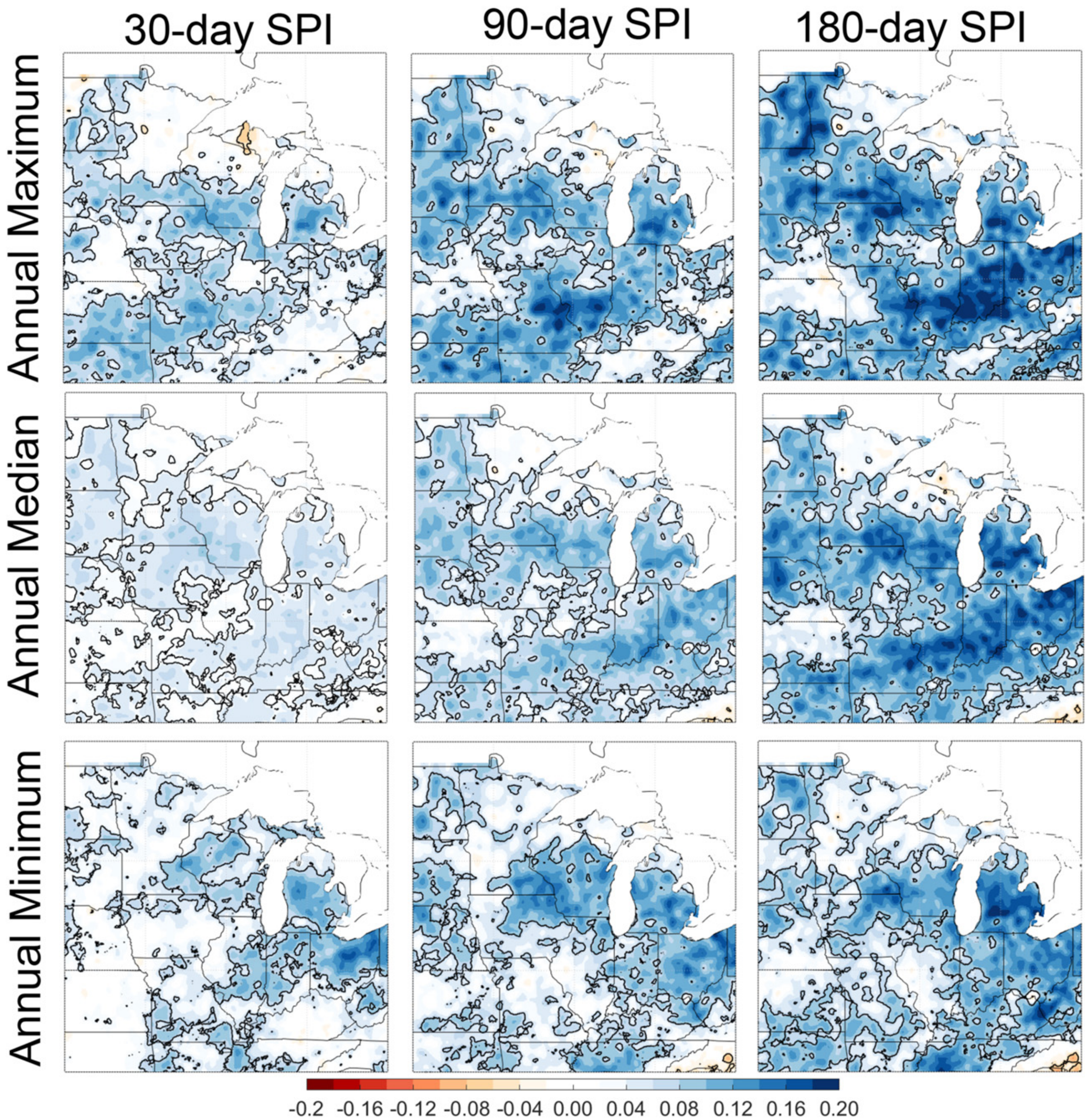


FIG. 3. Maps show (left) 30-, (center) 90-, and (right) 180-day SPI trends (change per decade) across the Midwest, calculated from 1951 to 2019. Trends are shown for (top) annual maximum, (middle) annual median, and (bottom) annual minimum SPI. Black contours indicate areas with trends that are statistically significant.

southwest Indiana, does exhibit a strong, significant increase in variability for 90- and 180-day SPI. The average trends in this area are 0.10 and 0.12 decade$^{-1}$ for 90- and 180-day SPI, respectively. This region of the southern Midwest was also noteworthy because of a significant increase in annual maximum SPI without a corresponding change in annual minimum (Fig. 3). These findings match well and together provide strong evidence that the annual range of moisture conditions and overall precipitation variability at 90- and 180-day intervals are increasing in this part of the Midwest. These changes are illustrated in more detail in Fig. 6, which shows plots of annual maximum and annual minimum 90-day SPI in St. Louis, Missouri. The annual maximum 90-day SPI trends are approximately 3.5 times larger than the annual minimum trends, resulting in an increase in annual SPI range and variability.

Trends in intra-annual variability duration are much less spatially coherent than magnitude (Fig. 5). Most areas of the

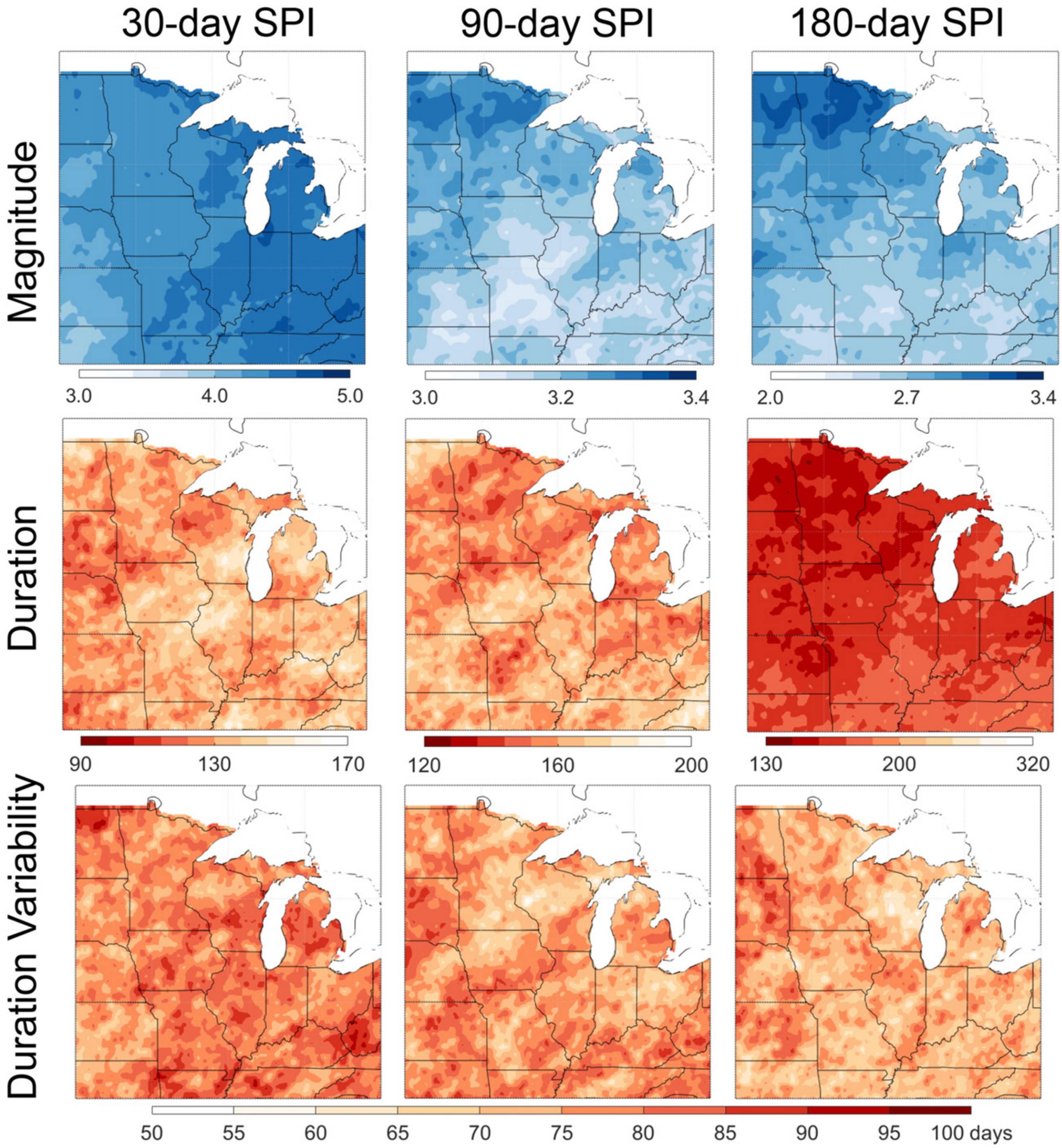


FIG. 4. Maps show climatological average intra-annual variability (top) magnitude, (middle) duration, and (bottom) duration variability. Magnitude is shown in SPI units, and duration is in units of days. Averages are computed over the period 1951–2019.

Midwest have not undergone significant changes in duration. An exception is the area around the southern bend of Lake Michigan, which has exhibited significant decreases in 30-, 90-, and 180-day SPI duration. The magnitude of the decrease in this area ranges from 10 to 15 days decade$^{-1}$, meaning that the time elapsed between the annual maximum and minimum SPI has decreased by approximately 70–90 days over the study period (Fig. 5). Unlike variability magnitude, the changes in duration do not necessarily reflect trends in precipitation variability but could instead illustrate changes in the seasonality of those extremes. For example, Fig. 7a shows the months in which the annual maximum and minimum 30-day SPI values occurred in Chicago, Illinois between 1951 and 2019. The lines indicate the time elapsed between the annual extremes, and the endpoints are colored based on the extreme (blue = maximum, red = minimum). It should be noted that there are

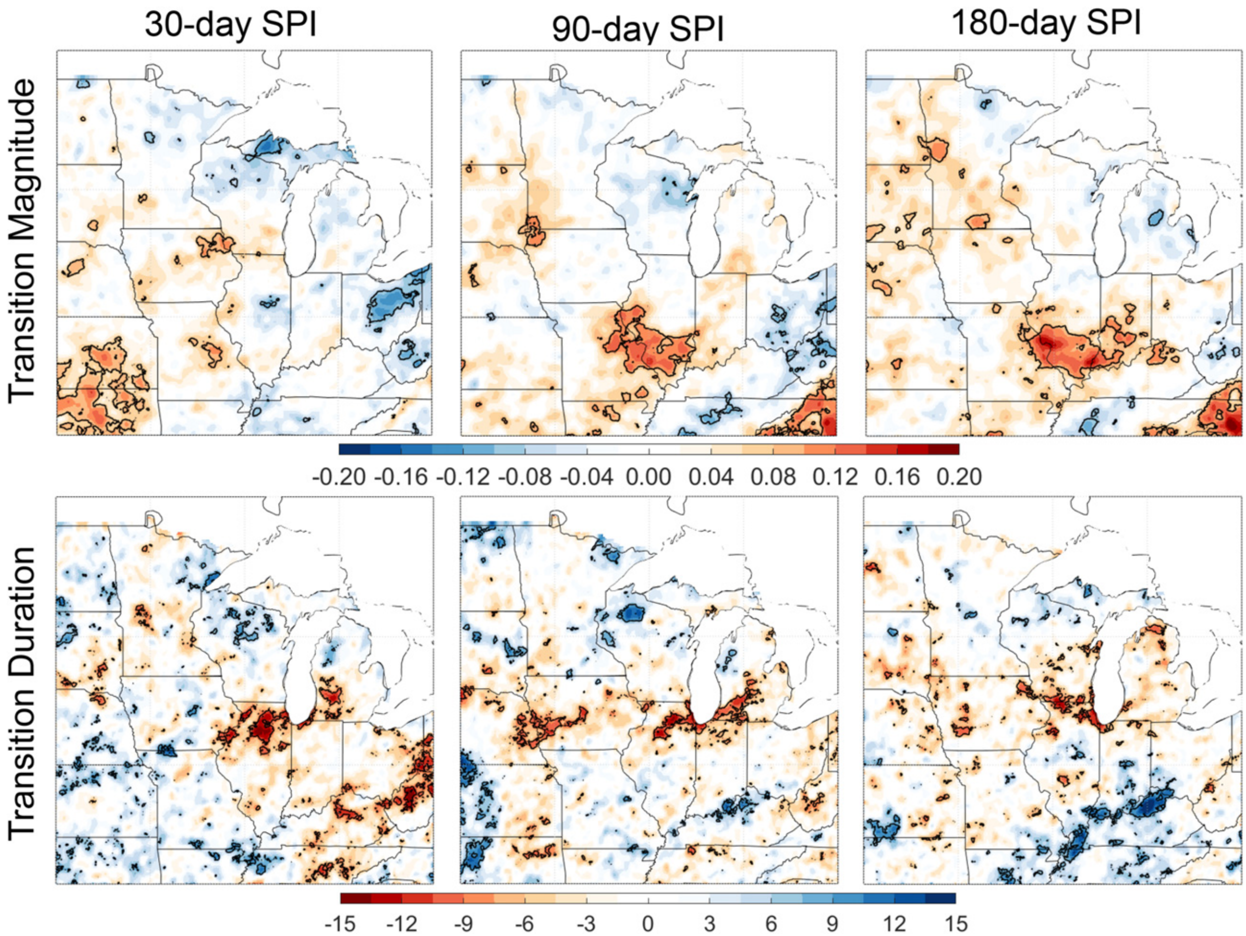


FIG. 5. Maps show trends in (top) intra-annual variability magnitude and (bottom) transition duration. Magnitude units are in change in SPI per decade, and duration trends are shown as days per decade. Black contours highlight areas with statistically significant trends.

two occurrences of the annual maximum and annual minimum SPI values occurring in the same month in Chicago, in 1981 and 2013. This phenomenon is caused by a very intense precipitation event following a prolonged dry period, and they are denoted in Fig. 7a as a lone red point. The frequency of very short durations has increased in recent years (Fig. 7a). The 10-yr average intra-annual variability duration is lowest in the most recent 2010–19 time period, at just over 2 months

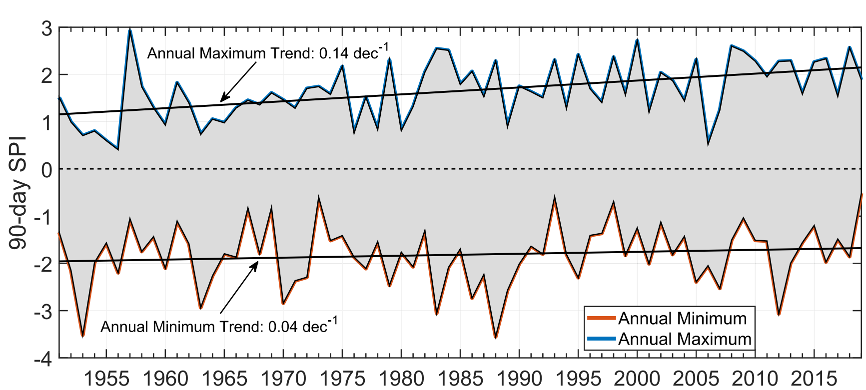


FIG. 6. Annual minimum and maximum 90-day SPI in St. Louis, Missouri, between 1951 and 2019. The red and blue lines indicate trends in annual minimum and maximum SPI, respectively.

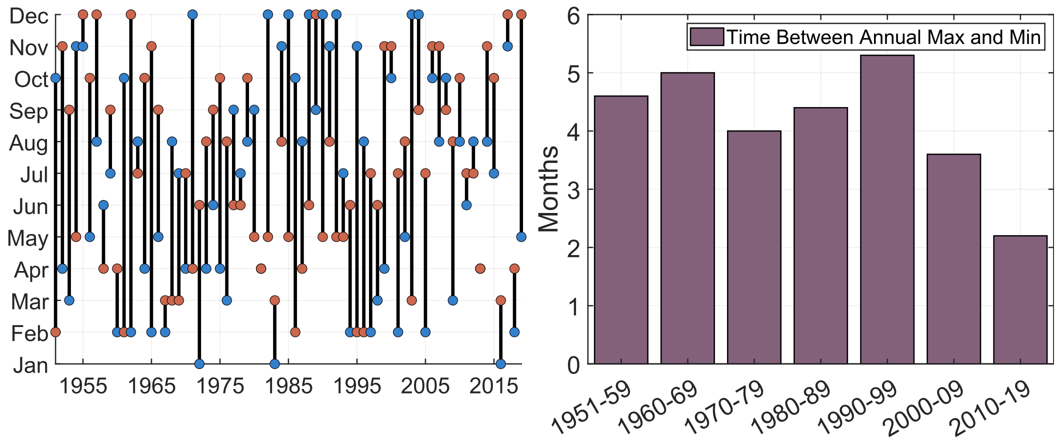


FIG. 7. (left) Points show the month of occurrence of the (red) annual minimum and (blue) annual maximum 30-day SPI in Chicago, Illinois. The black lines connect the end points and indicate the number of months elapsed between annual extremes. (right) The 10-yr average intra-annual transition duration (in months) in Chicago, Illinois.

(Fig. 7b). This compares to a 69-yr average duration of nearly four months in Chicago.

## c. *Transitions*

Along with the evaluation of SPI extremes variability within a calendar year, we examine transitions to account for extremes that occur within a calendar year or span calendar years. A transition begins when SPI crosses a threshold (+1.6 or −1.6) and ends when SPI crosses the opposite threshold (Fig. 1). Transitions are characterized in two ways. The first is the frequency of transition occurrence, which is the total number of transitions in a period of time. The second is the transition duration, which is the time period (in days) that elapses between the SPI extremes. Maps of climatological (1951–2019) transition frequency indicate highest frequency in the northwest Midwest and Great Lakes region, while 90- and 180-day transition frequency exhibit a marked southeast to northwest gradient, with the highest frequency in parts of Minnesota and the Dakotas (Fig. 8). Overall, 30-day SPI transitions have a return interval ranging from once every year in parts of Minnesota, North Dakota, and Indiana, to once every 2.5 years in parts of Kansas and Oklahoma. The 90- and 180-day SPI return intervals range from every 1.7 to 4.6 years, and from 2.8 to 9 years, respectively (Fig. 8).

The higher frequency of transitions in the northwest Midwest is caused in part by a larger overall range of annual maximum and minimum SPI (Fig. 2). Average transition duration does not exhibit a consistent spatial pattern between 30-, 90-, and 180-day SPI (Fig. S2), and overall has a lot of spatial variability. Interestingly, transition duration does not appear to be heavily influenced by transition frequency.

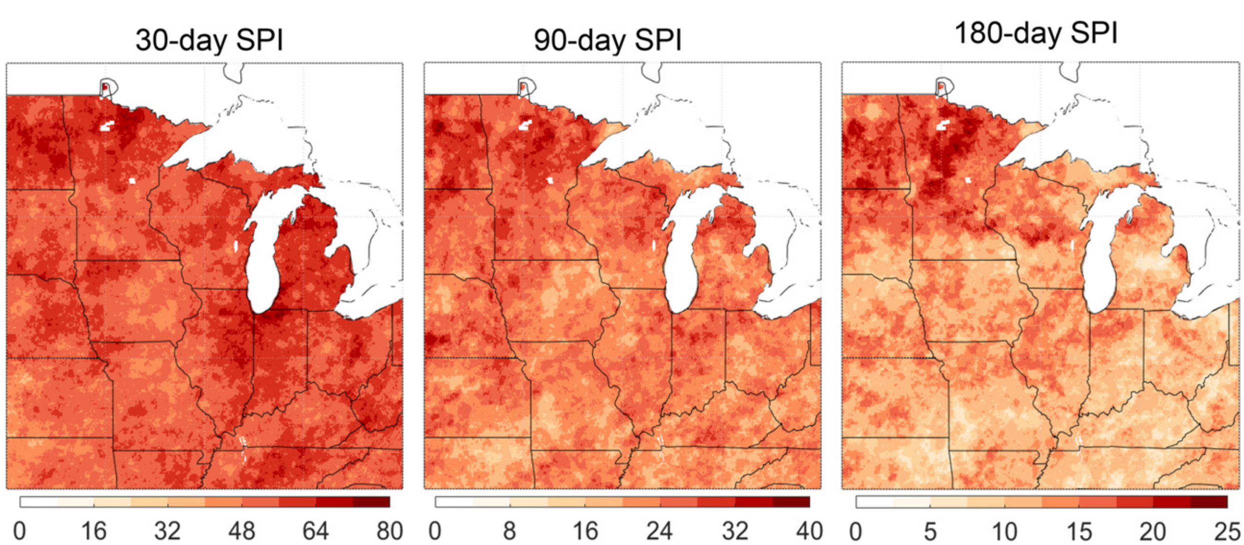


FIG. 8. Climatological (1951–2019) interannual transition frequency in (left) 30-, (center) 90-, and (right) 180-day SPI.

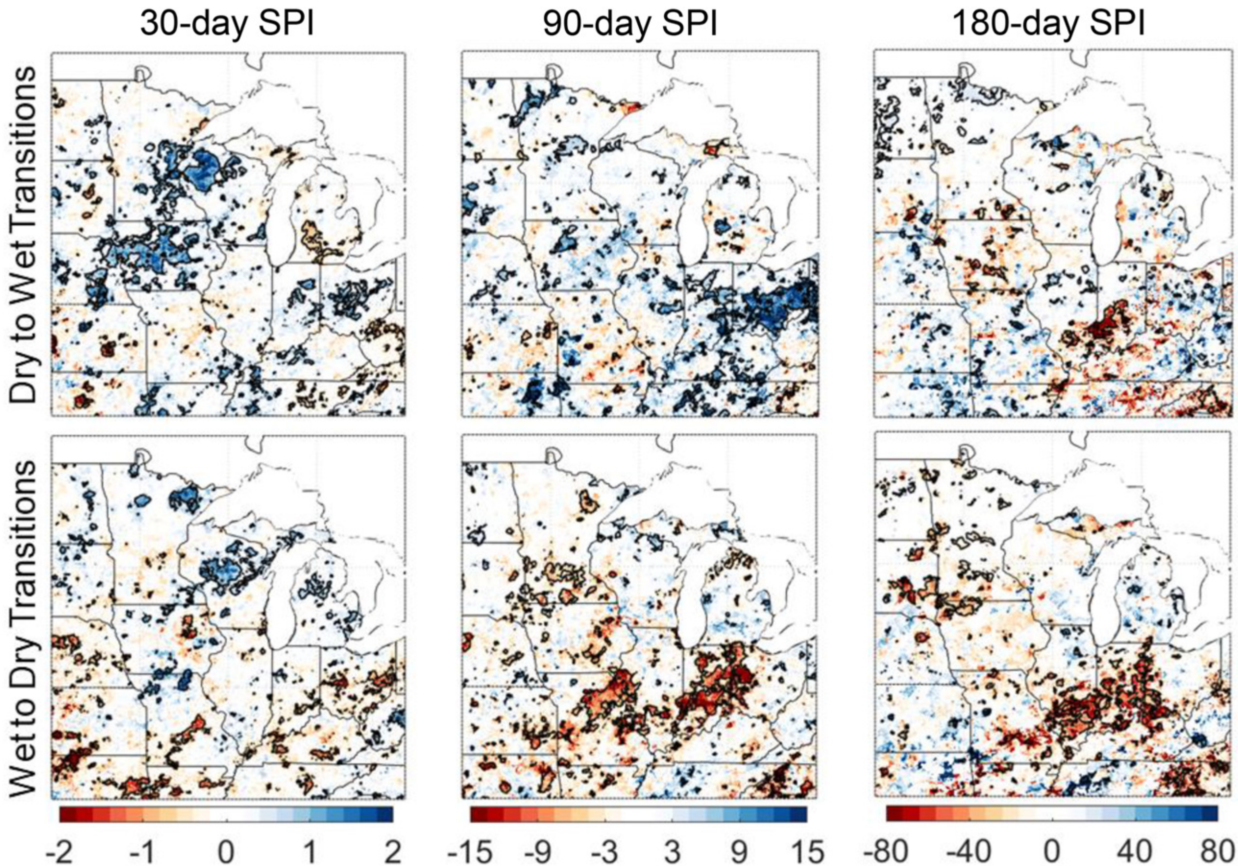


FIG. 9. Interannual transition duration trends (days per decade), calculated from 1951 to 2019. Trends are shown for (left) 30-, (center) 90-, and (right) 180-day SPI. The black contours denote areas with statistically significant duration trends.

To better understand recent changes in transitions, we assessed trends in transition duration and changes in frequency. Transitions do not occur every year in most places in the Midwest. In fact, transitions may be clustered in time, with multiple transitions in one calendar year and no transitions in years prior or subsequent. This complicates trend calculation over time. Therefore, we compute the change in transition duration, but substitute events for time as the increment. To do this, for each nClimDiv grid cell we align all transition events chronologically, and then compute the duration trend over the series of events. Therefore, the resulting event duration trend is in units of days per transition instead of days per year, as was the case for intra-annual variability.

Figure 9 shows the spatial patterns of dry to wet and wet to dry transition duration across the Midwest. Areas in the Upper Midwest, including parts of Wisconsin, Iowa, and Minnesota exhibit significant increases in both wet to dry and dry to wet 30-day SPI transition duration, meaning more time is elapsing between wet and dry extremes in this area. Very few areas are exhibiting significant negative duration trends for 30-day SPI. Duration trends for 90- and 180-day SPI are more spatially coherent, including significant increasing dry to wet transition duration trends in eastern Indiana and much of Ohio. On the other side, wet to dry transitions exhibit significant decreasing duration trends (i.e., shorter time between extremes) in a large part of Missouri, Illinois, Indiana, and Ohio for both 90- and 180-day SPI. Both significant increasing and decreasing duration trends are on the order of 5–15 days per event. The juxtaposition of increasing dry to wet transition duration and decreasing wet to dry transition duration in parts of Indiana and Ohio suggests that in this area transitions from dry to wet conditions are occurring more slowly while transitions from wet to dry conditions are occurring more rapidly. Concurrently, the significant decreasing 90- and 180-day SPI transition duration trends in southern Illinois and eastern Missouri are consistent with increased annual SPI range (Fig. 5), suggesting that this area has experienced larger precipitation variability along with a more rapid transition to extremely dry conditions.

It is critical to note that the trends in Fig. 9 are calculated over transition events and not over time, which can complicate interpretation of the results. One can imagine a situation with a significant trend in transition duration but where all transitions occur in the first 20–30 years of the study period. Therefore, a more comprehensive assessment of changing extreme transition risk would include both duration and frequency. To meet this need we complement duration trends with assessment of changes in the frequency of wet to dry and dry to wet

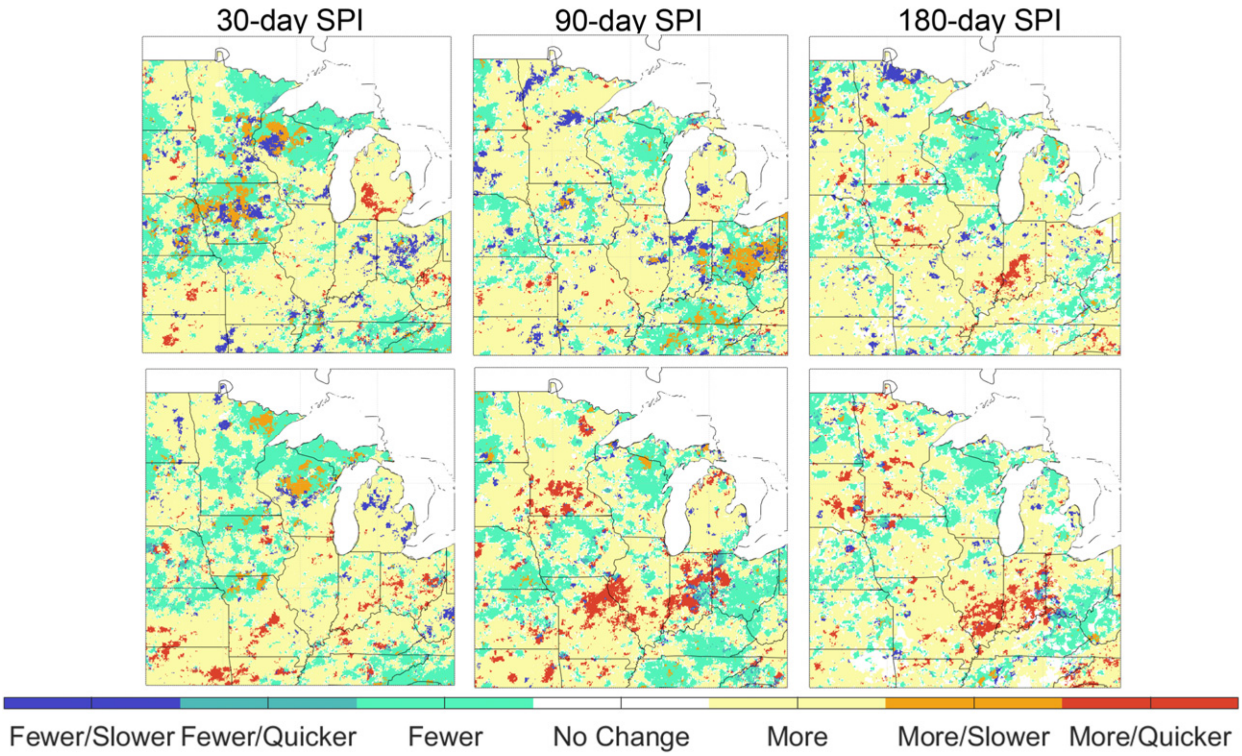


FIG. 10. Areas are colored depending on the joint change in interannual transition duration and frequency. Areas in which transitions are denoted as happening ''quicker'' are those with statistically significant, negative duration trends.

transitions. Specifically, we subtract total transition frequency in the period 1952–84 from the total transition frequency in the later period 1985–2019. Maps of frequency changes are shown in Fig. S3; we did not compute statistical significance of the changes because 1) the small number of events (i.e., few degrees of freedom) make for nonrobust significance estimates and 2) the frequency changes are only used to complement transition duration trends. That is, we are most interested in those areas in which transitions are happening more or less frequently *and* more or less quickly.

We combine the transition duration and frequency changes to evaluate the overall changing risk of transitions in precipitation extremes in the Midwest (Fig. 10). Areas of the Midwest are colored in Fig. 10 depending on the combination of duration and frequency changes. Red shading, for example, indicates an area with both a statistically significant negative (decreasing) duration trend and a positive frequency trend. In other words, red areas are those in which transitions are happening both more frequently and more rapidly. Orange shading indicates areas with more frequent transitions with significantly higher duration (i.e., slower onset). Yellow shading indicates more frequent transitions with no significant trend in duration. White shading indicates no change in frequency or duration. Green shading indicates areas with less frequent transitions with no significant trend in duration. Teal shading indicates areas with less frequent transitions but significantly shorter duration, and blue shading indicates areas with less frequent transitions with significantly longer duration. For 30-day SPI, most of the eastern and southeastern areas of the Midwest have experienced increased transition frequency with no significant change in duration, while the northwestern quadrant has mostly experienced decreased frequency, also with no significant change in duration. In contrast, the larger red areas in the 90- and 180-day SPI maps in Fig. 10 indicate parts of Missouri, Illinois, Indiana, and Ohio have experienced more frequent and more rapid wet to dry transitions over the last few decades.

## 4. Discussion and conclusions

The U.S. Midwest has experienced positive (i.e., increasing) trends in total annual precipitation and precipitation intensity over the last century (Winkler et al. 2012; Janssen et al. 2014; Angel et al. 2020). Consistent with increased precipitation, the overall frequency of meteorological drought has decreased in the region over the same time period (Strzepek et al. 2010; Maxwell et al. 2016). However, both observations and model projections indicate recent and future seasonality in Midwest precipitation changes and overall more variability (Pryor et al. 2013; Dai et al. 2016; Swain and Hayhoe 2015; Zhao et al. 2020). Dai et al. (2016) in particular find opposing seasonal precipitation trends in the Midwest, with increasing precipitation in the early growing season and decreasing precipitation in the late growing season. Our results corroborate these previous studies, as we find observation-based evidence of long-term increases in annual median SPI across the Midwest.

However, trends in the annual maximum SPI are generally larger than those in annual minimum SPI. Areas of Iowa, Missouri, Illinois, and Indiana exhibit a significant, positive trend in annual maximum SPI without an accompanying significant annual minimum SPI trend. Consequently, areas such as eastern Missouri and southern Illinois show significant increases in intra-annual SPI variability over the last seven decades in response to increasing wet extreme magnitude with no significant change in dry extreme magnitude. Previous studies demonstrate the considerable economic and environmental impacts of increased seasonal precipitation variability and extremes magnitude in this region (Loecke et al. 2017; Tomasek et al. 2017; Swanston et al. 2018). For example, Baeumler and Gupta (2020) show that river nitrogen loads in the Midwest are directly attributable to precipitation in the region. Increased precipitation can increase river nitrogen loads, which can also proliferate the presence of harmful algal blooms if followed closely by a dry extreme (Chapra et al. 2017).

Along with changes in intra-annual precipitation variability, we also document recent changes in precipitation extremes transitions. Specifically, we find both 90- and 180-day wet to dry transitions are increasing in frequency across southern Illinois, Indiana, and Ohio, while also decreasing in duration. This indicates that at 90- and 180-day time scales, dry extremes follow wet extremes with significantly decreasing transition time. These findings are in line with studies on rapid-onset or "flash" drought in the Midwest (Ford and Labosier, 2017; Basara et al. 2019). As Otkin et al. (2018) describe in their review, flash droughts are associated with precipitation deficit compounded by elevated atmospheric evaporative demand, resulting in a rapid depletion of soil moisture and resultant moisture stress to crops and native vegetation. Although we do not explicitly assess flash drought in this study, our results suggest that in the south-central part of the Midwest, dry extremes are following wet extremes with decreasing transition time. This also results in a decrease in warning time, which can exacerbate drought impacts (Otkin et al. 2015).

It is important to note the study limitations, including both the methods for identifying transitions and for assessing trends. We chose to examine wet and dry extremes and the transition between them using SPI over 30-, 90-, and 180-day intervals. Certainly, longer-interval (e.g., 12, 18, 24 months) extremes are an important component of the Midwest climate, and transitions in multiyear extremes are worthy of further investigation. However, extremes on subseasonal to seasonal time scales, and the significant impacts thereof, were the ultimate motivation of this study. The transition identification methods used here, adopted from DL20, can characterize extremes that span multiple calendar months, seasons, and years, which is an advantage over previous related studies. However, using the method to identify transitions in precipitation extremes results in a time series of sporadically occurring events that does not lend itself to straightforward statistical manipulation. To circumvent the issue of statistical significance estimation for trend analysis, we used bootstrap resampling to estimate confidence intervals. Likewise, we calculated transition duration trends in units of days per event instead of days per year.

Overall, we find that the Midwest has gotten wetter over the last seven decades, and that in general the annual maximum and median SPI values have increased at a larger magnitude than the annual minimum SPI. We find large areas of the southern Midwest have experienced a significant increase in the annual SPI range and corresponding magnitude of variability between annual minimum and maximum precipitation extremes. When assessing extremes and transitions between extremes that can span multiple calendar years, we find wet to dry transitions in the southern Midwest have largely increased in speed and frequency. That is, dry extremes are following wet extremes with less time between, resulting in a more rapid wet to dry transition. These findings follow numerous studies indicating increased precipitation and precipitation variability in the Midwest, in the form of seasonally diverging precipitation trends. Although this study was focused on the detection and statistical analysis of variability and transitions in precipitation extremes, further studies will focus on the drivers of such changes in variability and transitions. For example, Dong et al. (2018) find competing impacts of thermodynamic and dynamic responses to global warming on subseasonal precipitation variability in the United States. It remains to be seen how dynamic and thermodynamic processes act and interact to influence precipitation extremes and transitions between them. Additionally, future investigation should focus on projected changes in precipitation extremes, transitions between extremes, and overall Midwest precipitation variability as a response to continued warming.

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*Data availability statement.* Daily nClimDiv precipitation used in this study can be accessed via NOAA National Centers for Environmental Information: ftp://ftp.ncdc.noaa.gov/pub/data/cirs/climdiv/.

## REFERENCES

Angel, J. R., and Coauthors, 2018: Midwest. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment*, Vol. II, D. R. Reidmill et al, Eds., U.S. Global Change Research Program, 863–931, https://doi.org/10.7930/NCA4.2018.CH21.

——, M. Markus, K. A. Wang, B. M. Kerschner, and S. Singh, 2020: Precipitation frequency study for Illinois. Illinois State Water Survey Bulletin 75, 130 pp., http://hdl.handle.net/2142/106653.

Baeumler, N. W., and S. C. Gupta, 2020: Precipitation as the primary driver of variability in river nitrogen loads in the Midwest United States. *J. Amer. Water Resour. Assoc.*, **56**, 113–133, https://doi.org/10.1111/1752-1688.12809.

Basara, J. B., J. I. Christian, R. A. Wakefield, J. A. Otkin, E. H. Hunt, and D. P. Brown, 2019: The evolution, propagation, and spread of flash drought in the Central United States during 2012. *Environ. Res. Lett.*, **14**, 084025, https://doi.org/10.1088/1748-9326/ab2cc0.

Casson, N. J., and Coauthors, 2019: Winter weather whiplash: Impacts of meteorological events misaligned with natural and human systems in seasonally snow-covered regions. *Earth's Future*, **7**, 1434–1450, https://doi.org/10.1029/2019EF001224.

Changnon, S. A., Jr., and W. E. Easterling, 1989: Measuring drought impacts: The Illinois case 1. *J. Amer. Water Resour.*, **25**, 27–42, https://doi.org/10.1111/j.1752-1688.1989.tb05663.x.

Chapra, S. C., and Coauthors, 2017: Climate change impacts on harmful algal blooms in US freshwaters: A screening-level assessment. *Environ. Sci. Technol.*, **51**, 8933–8943, https://doi.org/10.1021/acs.est.7b01498.

Chen, H., S. Wang, and Y. Wang, 2019: Exploring abrupt alternations between wet and dry conditions on the basis of historical observations and convection-permitting climate model simulations. *J. Geophys. Res. Atmos.*, **125**, e2019JD031982, https://doi.org/10.1029/2019JD031982.

Christian, J., K. Christian, and J. B. Basara, 2015: Drought and pluvial dipole events within the great plains of the United States. *J. Appl. Meteor. Climatol.*, **54**, 1886–1898, https://doi.org/10.1175/JAMC-D-15-0002.1.

Cohen, J., 2016: An observational analysis: Tropical relative to Arctic influence on midlatitude weather in the era of Arctic amplification. *Geophys. Res. Lett.*, **43**, 5287–5294, https://doi.org/10.1002/2016GL069102.

Dai, S., M. D. Shulski, K. G. Hubbard, and E. S. Takle, 2016: A spatiotemporal analysis of Midwest US temperature and precipitation trends during the growing season from 1980 to 2013. *Int. J. Climatol.*, **36**, 517–525, https://doi.org/10.1002/joc.4354.

DeGaetano, A. T., and L. Lim, 2020: Declining US regional and continental trends in intra-annual and interannual extreme temperature swings. *Int. J. Climatol.*, **40**, 2830–2844, https://doi.org/10.1002/joc.6369.

Di Liberto, T., 2019: Flash drought engulfs the U.S. Southeast in September 2019. Climate.gov, 9 October 2019, https://www.climate.gov/news-features/event-tracker/flash-drought-engulfs-us-southeast-september-2019#:~:text=A%20potent%20combination%20of%20record,Ohio%20Valleys%20during%20September%202019.

Dixon, B. L., and K. Segerson, 1999: Impacts of increased climate variability on the profitability of Midwest agriculture. *J. Agric. Appl. Econ.*, **31**, 537–549, https://doi.org/10.1017/S1074070800008828.

Dong, L., L. R. Leung, and F. Song, 2018: Future changes of subseasonal precipitation variability in North American during winter under global warming. *Geophys. Res. Lett.*, **45**, 12 467–12 476, https://doi.org/10.1029/2018GL079900.

Ford, T. W., and C. F. Labosier, 2014: Spatial patterns of drought persistence in the southeastern United States. *Int. J. Climatol.*, **34**, 2229–2240, https://doi.org/10.1002/joc.3833.

——, and ——, 2017: Meteorological conditions associated with the onset of flash drought in the eastern United States. *Agric. For. Meteor.*, **247**, 414–423, https://doi.org/10.1016/j.agrformet.2017.08.031.

Francis, J. A., N. Skific, and S. J. Vavrus, 2018: North American weather regimes are becoming more persistent: Is Arctic amplification a factor? *Geophys. Res. Lett.*, **45**, 414–422, https://doi.org/10.1029/2018GL080252.

Hatfield, J. L., R. M. Cruse, and M. D. Tomer, 2013: Convergence of agricultural intensification and climate change in the Midwestern United States: Implications for soil and water conservation. *Mar. Freshwater Res.*, **64**, 423–435, https://doi.org/10.1071/MF12164.

Hayes, M. J., M. D. Svoboda, D. A. Wiihite, and O. V. Vanyarkho, 1999: Monitoring the 1996 drought using the standardized precipitation index. *Bull. Amer. Meteor. Soc.*, **80**, 429–438, https://doi.org/10.1175/1520-0477(1999)080<0429:MTDUTS>2.0.CO;2.

Janssen, E., D. J. Wuebbles, K. E. Kunkel, S. C. Olsen, and A. Goodman, 2014: Observational-and model-based trends and projections of extreme precipitation over the contiguous United States. *Earth's Future*, **2**, 99–113, https://doi.org/10.1002/2013EF000185.

Ji, Z., N. Li, and X. Wu, 2018: Threshold determination and hazard evaluation of the disaster about drought/flood sudden alternation in Huaihe River basin, China. *Theor. Appl. Climatol.*, **133**, 1279–1289, https://doi.org/10.1007/s00704-017-2257-8.

Katsanos, D., A. Retalis, F. Tymvios, and S. Michaelides, 2018: Study of extreme wet and dry periods in Cyprus using climatic indices. *Atmos. Res.*, **208**, 88–93, https://doi.org/10.1016/j.atmosres.2017.09.002.

Kunkel, K. E., K. Andsager, and D. R. Easterling, 1999: Long-term trends in extreme precipitation events over the conterminous United States and Canada. *J. Climate*, **12**, 2515–2527, https://doi.org/10.1175/1520-0442(1999)012<2515:LTTIEP>2.0.CO;2.

Lanzante, J. R., 1996: Resistant, robust and nonparametric techniques for the analysis of climate data: Theory and examples, including applications to historical radiosonde station data. *Int. J. Climatol.*, **16**, 1197–1226, https://doi.org/10.1002/(SICI)1097-0088(199611)16:11<1197::AID-JOC89>3.0.CO;2-L.

Liu, L., and B. Basso, 2020: Impacts of climate variability and adaptation strategies on crop yields and soil organic carbon in the US Midwest. *PLOS One*, **15**, e0225433, https://doi.org/10.1371/journal.pone.0225433.

Loecke, T. D., A. J. Burgin, D. A. Riveros-Iregui, A. S. Ward, S. A. Thomas, C. A. Davis, and M. A. St. Clair, 2017: Weather whiplash in agricultural regions drives deterioration of water quality. *Biogeochemistry*, **133**, 7–15, https://doi.org/10.1007/s10533-017-0315-z.

Lowery, B., C. Cox, D. Lemke, P. Nowak, K. Olson, and J. Strock, 2009: The 2008 Midwest flooding impact on soil erosion and water quality: Implications for soil erosion control practices. *J. Soil Water Conserv.*, **64**, 166A, https://doi.org/10.2489/jswc.64.6.166A.

Mallya, G., L. Zhao, X. C. Song, D. Niyogi, and R. S. Govidaraju, 2013: 2012 Midwest drought in the United States. *J. Hydrol. Eng.*, **18**, 737–745, https://doi.org/10.1061/(ASCE)HE.1943-5584.0000786.

Maxwell, J. T., G. L. Harley, and S. M. Robeson, 2016: On the declining relationship between tree growth and climate in the Midwest United States: The fading drought signal. *Climatic Change*, **138**, 127–142, https://doi.org/10.1007/s10584-016-1720-3.

McKee, T. B., N. J. Doesken, and J. Kleist, 1993: The relationship of drought frequency and duration of time scales. *Proc. Eighth Conf. on Applied Climatology*, Anaheim, CA, Amer. Meteor. Soc., 179–184.

Menne, M. J., and Coauthors, 2012: Global Historical Climatological Network-Daily (GHCN-Daily), version 3. NOAA National Climatic Data Center, https://doi.org/10.7289/V5D21VHZ.

NOAA/NCEI, 2011: State of the Climate: National Climate Report for May 2011. Accessed 18 August 2020, https://www.ncdc.noaa.gov/sotc/national/201105/supplemental/page-3.

——, 2012: NCDC releases 2012 billion-dollar weather and climate disasters information. Accessed 18 August 2020, https://www.ncdc.noaa.gov/news/ncdc-releases-2012-billion-dollar-weather-and-climate-disasters-information#:~:text=With%2011%20events%2C%202012%20also,drought%20at%20approximately%20%2430%20billion.

Otkin, J. A., M. C. Anderson, C. Hain, and M. Svoboda, 2015: Using temporal changes in drought indices to generate probabilistic drought intensification forecasts. *J. Hydrometeor.*, **16**, 88–105, https://doi.org/10.1175/JHM-D-14-0064.1.

——, M. Svoboda, E. D. Hunt, T. W. Ford, M. C. Anderson, C. Hain, and J. B. Basara, 2018: Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bull. Amer. Meteor. Soc.*, **99**, 911–919, https://doi.org/10.1175/BAMS-D-17-0149.1.

Pryor, S. C., R. J. Barthelmie, and J. T. Schoof, 2013: High-resolution projections of climate-related risks for the Midwestern USA. *Climate Res.*, **56**, 61–79, https://doi.org/10.3354/cr01143.

Strzepek, K., G. Yohe, J. Neumann, and B. Boehlert, 2010: Characterizing changes in drought risk for the United States from climate change. *Environ. Res. Lett.*, **5**, 044012, https://doi.org/10.1088/1748-9326/5/4/044012.

Svoboda, M., and Coauthors, 2002: The Drought Monitor. *Bull. Amer. Meteor. Soc.*, **83**, 1181–1190, https://doi.org/10.1175/1520-0477-83.8.1181.

Swain, D. L., B. Langenbrunner, J. D. Neeling, and A. Hall, 2018: Increasing precipitation volatility in twenty-first century California. *Nat. Climate Change*, **8**, 427–433, https://doi.org/10.1038/s41558-018-0140-y.

Swain, S., and K. Hayhoe, 2015: CMIP5 projected changes in spring and summer drought and wet conditions over North America. *Climate Dyn.*, **44**, 2737–2750, https://doi.org/10.1007/s00382-014-2255-9.

Swanston, C., and Coauthors, 2018: Vulnerability of forests of the Midwest and Northeast United States to climate change. *Climatic Change*, **146**, 103–116, https://doi.org/10.1007/s10584-017-2065-2.

Tomasek, B. J., M. M. Williams, and A. S. Davis, 2017: Changes in field workability and drought risk from projected climate change drive spatially variable risks in Illinois cropping systems. *PLOS One*, **12**, e0172301, https://doi.org/10.1371/journal.pone.0172301.

Voiland, A., 2019: A flash drought dries the Southeast. NASA Earth Observatory, https://earthobservatory.nasa.gov/images/145762/a-flash-drought-dries-the-southeast.

Vose, R. S., and Coauthors, 2014: Improved historical temperature and precipitation time series for U.S. climate divisions. *J. Appl. Meteor. Climatol.*, **53**, 1232–1251, https://doi.org/10.1175/JAMC-D-13-0248.1.

Willmott, C. J., and S. M. Robeson, 1995: Climatologically aided interpolation (CAI) of terrestrial air temperature. *Int. J. Climatol.*, **15**, 221–229, https://doi.org/10.1002/joc.3370150207.

Winkler, J. A., R. W. Arritt, and S. C. Pryor, 2012: Climate projections for the Midwest: Availability, interpretation and synthesis. U.S. National Climate Assessment Midwest Technical Input Rep., 24 pp., http://glisa.umich.edu/media/files/NCA/MTIT_Future.pdf.

Yazd, S. D., S. A. Wheeler, and A. Zuo, 2019: Key risk factors affecting farmers' mental health: A systematic review. *Int. J. Environ. Res. Public Health*, **16**, 4849, https://doi.org/10.3390/ijerph16234849.

Zhao, C., F. Brissette, J. Chen, and J. L. Martel, 2020: Frequency change of future extreme summer meteorological and hydrological droughts over North America. *J. Hydrol.*, **584**, 124316, https://doi.org/10.1016/j.jhydrol.2019.124316.