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Contribution of landfalling tropical system rainfall to the hydroclimate of the eastern U.S. Corn Belt 1981–2012

Olivia Kellner [a,*], Dev Niyogi [a,b,c], Frank D. Marks [d]

[a] Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, United States
[b] Department of Agronomy – Crops, Soils, Environmental Sciences, Purdue University, United States
[c] Indiana State Climate Office, Purdue University, West Lafayette, IN, United States
[d] NOAA, Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division, Miami, FL, United States

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ABSTRACT

This study provides a climatology (1981–2012) of landfalling tropical systems in the eastern U.S. Corn Belt and investigates the total contribution of these storms to the monthly climatological rainfall in the Midwestern United States. The primary focus is on rainfall impacts from landfalling tropical systems on historic corn yields at the climate division and crop reporting district level. Climatologically dry to drought conditions for historic monthly observed rainfall are identified using the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI). It was found that without landfalling tropical system rainfall, the percentage increase in climatologically dry (or drier) conditions across the domain at state climate division resolution increased from 16% up to over 200%. The study also considers the effects of climatologically wet conditions on crop yields.

Landfalling tropical system rainfall accounts for approximately 20% of the observed monthly rainfall during the tropical storm season (June–November) across the eastern U.S. Corn Belt (1981–2012). Correlation between the annual number of landfalling tropical systems and annual yield by state results in no relationship, but correlation of August monthly observed rainfall by climate division to crop reporting district annual yields has a weak to moderate, statistically significant correlation in Ohio districts 30–60 and Indiana CRD 90. ANOVA analysis suggests that landfalling tropical rainfall may actually reduce yields in some state's climate divisions/crop reporting districts while increasing yield in others. Results suggest that there is a balance between landfalling tropical storms providing sufficient rainfall or too much rainfall to be of benefit to crops. Findings aim to provide information to producers, crop advisers, risk managers and commodity groups so that seasonal hurricane forecasts can potentially be utilized in planning for above or below normal precipitation during phenologically important portions of the growing season.

1. Introduction

Tropical systems (TSs), defined here as hurricanes, tropical storms, tropical depressions, and remnant lows, that impact the tropical and subtropical latitudes of the United States primarily originate in the descending branch of the Hadley cell circulation known as the northeasterly trade winds over the Atlantic Ocean. Climatological assessment of rainfall resulting from TSs has been completed for coastal regions along the Gulf of Mexico and the East Coast of the United States (e.g., Cry (1967), Knight and Davis (2009), Nogueira and Keim (2011), LaRow (2013) and Maxwell et al. (2013)). However, less attention has been given to assessing the contribution of landfalling TSs to the eastern U.S. Corn Belt hydroclimate, especially in regards to agricultural production.

The Midwest region (i.e., the Eastern U.S. Corn Belt – in this study is defined as Wisconsin, Michigan, Illinois, Indiana, Ohio, and Kentucky) of the United States is inclusive of a vast expanse of agriculture land primarily devoted to the growth of soybean and corn. Seasonal rainfall from midlatitude weather systems and convective thunderstorms is typically sufficient for the growth of corn across much of the region. Irrigation is only readily needed in regions of sandy soils (e.g., northern Indiana, southern Michigan, and portions of Illinois), and during climatologically drier periods of the growing season. Corn reaches its critical grain-fill period during the months of August and September (depending on planting date) when heat and moisture stress within a two week window can vastly affect the yield potential of the crop (Nielsen,

* Correspondence to: Indiana State Climate Office, Purdue University, LILY 2-420, 915 W State Street, West Lafayette, IN 47907-2054, United States.
E-mail address: climate@purdue.edu (O. Kellner).

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2011; Takle et al., 2014).

Hydroclimatological analyses are valuable tools allowing for a better understanding of the relationships between crop growth and precipitation in light of potential climate variability and change identified in the last several years (e.g., IPCC (2014) and Charusombat and Niyogi (2011)). As the world's largest producer of corn, the United States Corn Belt is located in a region expected to experience climate variability and change. Climate change projections indicate longer dry spells, heavier rain events, and longer growing seasons resulting from warmer days and warmer nights (Melillo et al., 2014). Being prepared to face climate change begins with understanding climate variability (e.g., anomalous warm/cold and wet/dry conditions) caused by various atmospheric phenomena. This examination of a hydroclimate region helps provide a better understanding of climate variability impacts to precipitation in the climate system, and in this case, a better understanding of climate variability in the Midwest hydroclimate from landfalling TSs.

This analysis investigates landfalling TS rainfall in the Midwest in an effort to understand its' contribution during the hurricane/tropical system season (June 1–November 30) to the Midwest rainfall budget. The period reviewed is 1981–2012 to coincide with the most recent monthly precipitation climate division normals. The normals are used to determine if observed rainfall for a given month can be classified according to the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI) as climatologically dry up to full drought conditions.

The Midwest is selected as the study area because of its contribution to crop production in the United States. Research efforts to determine the contribution of TS rainfall to seasonal rainfall in the United States were completed over the last several years for coastal regions (e.g., Corbosiero et al. (2009), Knight and Davis (2009), LaRow (2013), Maxwell et al. (2013), Nogueira and Keim (2011), Rodgers et al. (2001), and Cry (1967)), however, the Midwest Region and impacts to agricultural production is an area with limited research. Many TSs have traversed far inland impacting the Midwest during the growing season such as Tropical Storm Arlene, Hurricane Katrina, and Hurricane Rita in 2005. Rippey (2010) shows a possible link between corn yield and Atlantic tropical cyclone activity/inactivity in an assessment of the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO), which shows that the number of landfalling TSs may influence crop yields. This study further investigates the conjecture that landfalling TSs serve an important role in the Midwest hydroclimate as related to agriculture.

In addition to the aforementioned studies, Haberlie et al. (2014) recently reported an analysis of TS rainfall in the Eastern Corn Belt similar in intent to this work, but differing in tools, methodology, classification of landfalling TSs, and scope of influence on the Midwest hydroclimate. The primary difference between Haberlie et al. (2014) and this study is that Haberlie et al. (2014) identify the role of landfalling TSs entering the Midwest as “drought-busting events” based on the storm producing a specific precipitation threshold value and the storm's ability to alleviate drought conditions. The drought of 2012 serves as the catalyst for their investigation. In contrast, this study investigates monthly precipitation conditions with and without landfalling TSs affecting Midwest rainfall. The primary goal here is to assess the total climatological contribution of landfalling TS-based monthly rainfall to the climatological normal and the impact this rainfall has on crop production during the hurricane/tropical system season (June–November). The unique ability to ascertain the contribution of landfalling TSs to historic observed Midwest rainfall, and comparing that to the climatological normal rainfall allows the determination of whether landfalling TSs benefit or hinder eastern U. S. Corn Belt crop production. Whether the rainfall is beneficial or harmful to crop production will depend on antecedent soil moisture conditions from any previous rainfall events. Tropical Storm Bill (June 2015) is a good example of what this study aims to highlight by completing a landfalling TS climatology in the Midwest that includes historic yield data. Tropical Storm Bill (2015) provided drought relief in Texas and Oklahoma but brought two to six inches of precipitation across Missouri, Illinois, Indiana, and Ohio of which Illinois, Indiana, and Ohio saw their wettest June on record (1895–2015) (Kellner, 2015). As of July 14, 2015, projections of yield loss due to flooded fields was estimated at $740 million for Indiana (Sites, 2015).

Understanding the total contribution of landfalling TS rainfall in the Midwest and its impact to crop production is linked because of the inherent nature of crop production and soil moisture used by crops for plant growth. Kam et al. (2013) highlight regional impacts of tropical cyclones on soil moisture and drought for the Eastern United States demonstrating their contribution to drought relief across the region depending on antecedent climatological conditions (i.e., severity/type of drought). However, the study does not align findings with historic yield data. Maxwell et al. (2012) highlight the role of tropical cyclones in drought amelioration in Florida, Georgia, and the Carolinas, but also does not investigate observed rainfall alongside historic yield data. Based on this study that includes historic corn yield data, the authors suggest that a timely release of a hurricane season forecast could help identify the potential of landfalling TS rainfall ending a dry spell or drought in the Midwest, or forewarn producers of a wet spell so that they can adjust tile drainage. This type of information (i.e., potential to end a drought or bring anomalously wet conditions) is expected to help agricultural producers, risk managers, and commodity groups make informed decisions related to crop production when a hurricane season outlook is available.

2. Tropical system climatology 1981–2012

Historic seasonal TS maps for the Atlantic Basin are collected from the NOAA National Hurricane Center (NHC) data archive (http://www.nhc.noaa.gov/data/#annual). A total of 116 TSs made landfall in the Continental United States (CONUS) with only 28 entering the Midwest domain. Fig. 1 shows total landfalling TSs affecting the Midwest from1981 to 2012. Annually, 2005 is the year with the highest number of named TSs (28) in the Atlantic Basin, and is also the year with highest number of landfalling TSs affecting the Midwest (5). The years 1982–1984, 1986, 1987, 1990, 1991, 1993, 1997–2000, 2007, 2009, and 2010, experienced no landfalling Midwest TSs, but this is not to say landfalling TSs did not occur outside the Midwest domain. The Midwest averages less than one landfalling TS per year (0.85 a year; median value of 1). The most active month for landfalling TSs affecting the Midwest is September, with 13 TSs impacting the region 1981–2012 (Fig. 2). If a TS affecting the Midwest straddled two months, it was assigned to the month during which it spent the most time, and if the TS equally spanned two months, it was assigned the month the TS made landfall. Out of the six-state domain, Ohio and Kentucky are the states that were most affected by landfalling TSs during 1981–2012. Over the time period, 23 landfalling TSs affecting the Midwest contributed to observed rainfall in these states, followed by the state of Indiana with 17, Illinois with 16, and Wisconsin with 4. The average time a TS spent in the domain is 45.8 h (median value of 44.5 h).

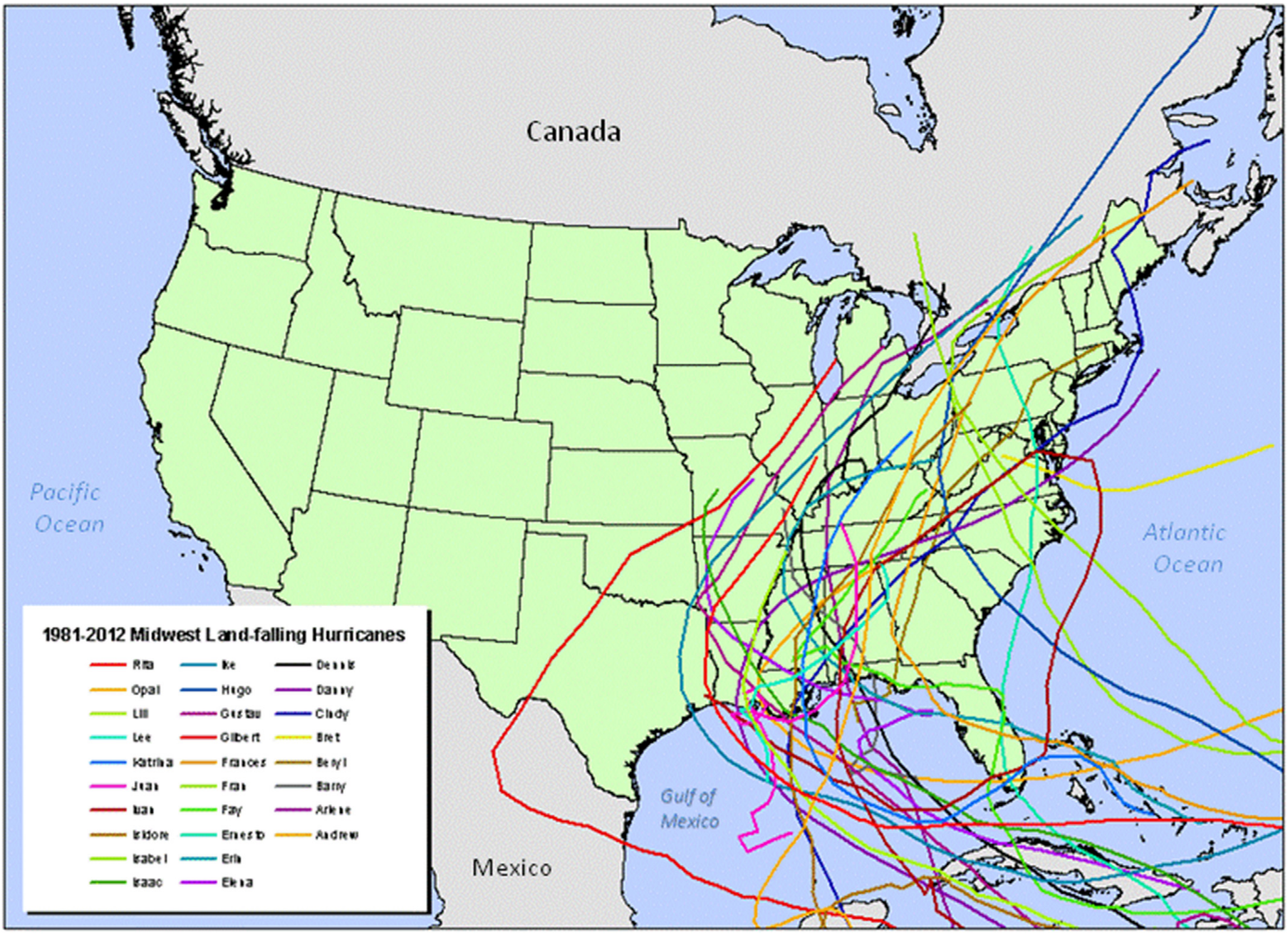

Fig. 1. Landfalling tropical systems to impact the Midwest (1981–2012). Tracks are from 6-hourly HURDAT2 best track data available from the National Hurricane Center.

3. Data and methods

3.1. Data

3.1.1. Tropical systems 1981–2012

HURDAT2 data was collected from 1981 to 2012 for the Atlantic Basin and mapped using a Geographic Information System (GIS). Storms that made landfall in the Continental United States (CONUS) are identified through maps of best track data, and storms are classified as a Midwest landfalling TS if the storm traveled within 150 miles of a state boundary of the domain (Wisconsin, Illinois, Indiana, Ohio, Michigan, and Kentucky) and produced precipitation before HURDAT2 data stopped tracking the central pressure of the storm – or – through the use of archived Weather Prediction Center (WPC) (National Centers for Environmental Prediction (NCEP)) maps of tropical rainfall distribution (available at: http://www.wpc.ncep.noaa.gov/tropical). The distance of 150 miles is selected because it represents one-half the average diameter of a TS as defined by NOAA. According to NOAA, the average TS diameter is 300 miles with outer rain bands a few miles to tens of miles wide and 50–300 miles long (National Oceanic Atmospheric Administration, 1999). Furthermore, this analysis is operationally-based so this distance provides a simple tracking methodology. Once a storm is within 150 miles of the domain based on 6 h latitude and longitude coordinates, climate records are queried for daily precipitation amounts. If a Midwest state is not impacted by a given TS, daily rainfall and monthly observed rainfall values are not used. Table 1 provides a list of all storms meeting the aforementioned criteria. While this approach to identifying TS rainfall in the Midwest domain is quantitative, it is possible that some rainfall resulting from non-TS features is classified as TS rain.

3.1.2. Rainfall

Daily rainfall totals for those dates a TS is present in the domain are collected at the state climate division (SCD) level from the Midwest Regional Climate Center's (MRCC) Application Tools Environment (cli-MATE). The domain has a total of 51 state climate divisions. The rainfall data is from the National Centers of Environmental Information (NCEI) nClimDiv dataset that became operational and available to the public on March 17, 2014 (Vose et al., 2014). The nClimDiv daily dataset is a 5 km gridded dataset based on the Global Historical Climatology Network-Daily (GHCN-D) dataset (Fenimore et al., 2011). It differs from the previous dataset (DRD964x) through use of a grid-based calculation for daily values, incorporating more stations with pre-1903s data, and implementing updated quality-control techniques (National Climatic Data Center (NCDC), 2014). Using a gridded rainfall dataset can result in some rainfall variability impacts to crop yields on a localized field scale not being captured. However, this is not likely to be a major factor since the analysis does not analyze field-scale yield data, only crop reporting district-averaged yield data.

Daily precipitation data for a SCD is collected from the day a TS enters the Midwest domain until the date the TS exits the domain

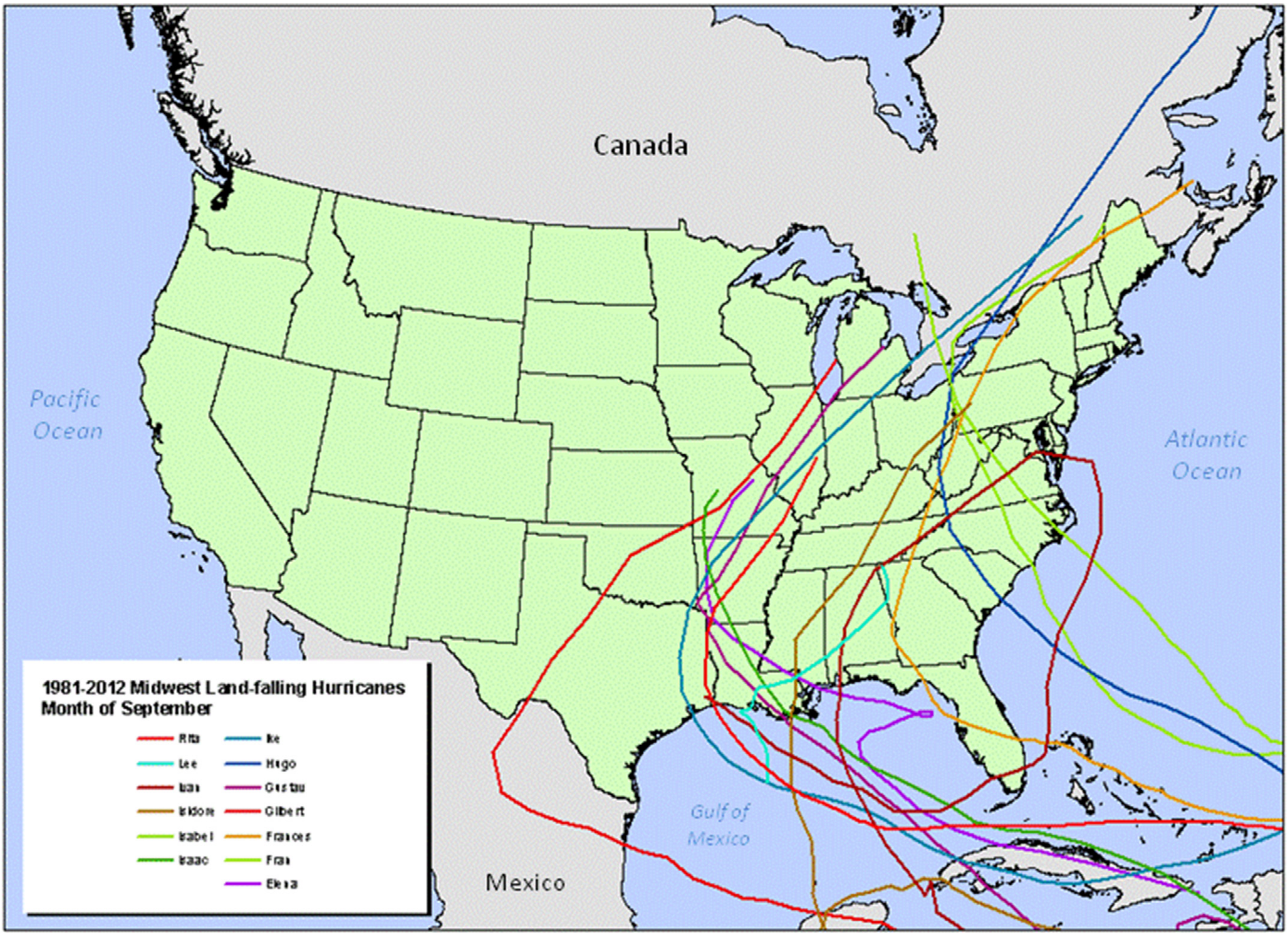

Fig. 2. Landfalling hurricanes impacting the Midwest (1981–2012) during the month of September. Tracks are from 6-hourly HURDAT2 best track data available from the National Hurricane Center.

Table 1
Landfalling tropical systems and the states impacted by rainfall. H=hurricane strength at landfall. TS=a tropical system at landfall.

Year	Name	Date	States	Year	Name	Date	States
1981	TS Bret	June 29–July 1	IL, IN, KY, OH	2003	H Isabel	Sep. 6–19	OH, MI
1985	H Danny	Aug. 12–18	KY	2004	H Frances	Aug. 25–Sep. 8	KY, OH
1985	H Elena	Aug. 28–Sep. 4	IL, IN, KY	2004	H Ivan	Sep. 2–24	KY, OH
1985	H Juan	Oct. 26–Nov. 1	IL, IN, KY, MI, OH, WI	2005	TS Arlene	June 8–13	IL, IN, KY, MI, OH
1988	H Gilbert	Sep. 8–19	IL, IN, MI, OH, WI	2005	H Cindy	July 3–7	KY
1989	H Hugo	Sep. 10–22	KY, OH	2005	H Dennis	July 4–13	IL, IN, KY, OH
1992	H Andrew	Aug. 16–28	IL, IN, KY, OH	2005	H Katrina	Aug. 23–30	IL, IN, KY, OH
1994	TS Beryl	Aug. 14–19	KY, OH	2005	H Rita	Sep. 18–26	IL, IN, KY, MI, OH
1995	H Erin	July 21–Aug. 6	IL, IN, KY, OH	2006	H Ernesto	Aug. 24–Sep. 1	KY, OH
1995	H Opal	Sep. 27–Oct. 5	IN, KY, MI, OH	2008	TS Fay	Aug. 15–26	KY, OH
1996	H Fran	Aug. 23–Sep. 8	OH, MI	2008	H Gustav	Aug. 25–Sep. 4	IL, IN, KY, MI, WI
2001	TS Barry	Aug. 2–7	IL, IN, KY	2008	H Ike	Sep. 1–14	IL, IN, MI, OH, WI
2002	H Isidore	Sep. 14–27	IL, IN, KY, MI, OH	2011	TS Lee	Sep. 2–5	IL, IN, KY, MI, OH
2002	H Lili	Sep. 21–Oct 4	KY	2012	H Isaac	Aug. 21–Sep. 1	IL, IN, KY, OH

to determine the total storm rainfall. If more than one landfalling TS enters the Midwest domain in a given month, the TS rainfall totals are combined to determine the total monthly observed precipitation attributable to landfalling TSs (from now on “tropical system rain” or TSR). Monthly observed rainfall (from now on MOR) and the monthly climate normals (1981–2010) (from now on NORM) for precipitation are also compiled at the SCD level. The NORMs are reduced by 15% (i.e., NORM – (NORM*0.15)) to find the threshold value of observed precipitation below which would be considered an “incipient dry spell” or greater conditions (i.e., mild, moderate, severe, or extreme drought) for a given month (from now on DRO) following Palmer (1965). Reducing NORMs by 15% is broadly representative of the PDSI drought classification of “incipient dry spell” or greater without rainfall associated with a landfalling TS. The PDSI index incorporates temperature, precipitation, and soil data to determine water supply and demand helping to make it suitable for unirrigated cropland (Palmer, 1965). The PDSI is selected because it is the primary agricultural drought indicator and this study's focus is TSR influences (if any) on crop production. The SPI is assessed in this study as well as it has rapid response to precipitation surplus or deficits. The SPI responds relatively quickly, compared to PDSI, because it considers only observed precipitation and is based on the standardized probability of observing a specific amount of precipitation across short- and long-term temporal scales with a focus on application to water availability and use (Guttman, 1998). Under the SPI, an SCD is marked as DRO when the SPI index value exceeds −0.51 (i.e., “abnormally dry” or drier). The MOR is then compared to DRO values to determine which climate divisions in the domain are drier than normal or in drought conditions. Another dataset, MOR minus TSR (from now on MOR_TSR), is computed to determine the monthly observed rainfall in a given SCD had a landfalling TS not entered the Midwest domain. The MOR_TSR values above DRO indicate that the Midwest TSR brought any MOR below normal at the time to normal values or greater.

3.1.3. Crop production

Corn yield data is compiled at county level across the United States with regional summaries provided at CRD levels. Most CRD boundaries coincide with the SCD boundaries in a given state, making annual crop yields at CRD spatial scales suitable for complementary rainfall analysis with the precipitation data obtained at SCD spatial scales. All yield data at the CRD level is detrended through a one-year lag linear regression and tested with the Durbin-Watson statistic to ensure no autocorrelation exists in the detrended yield time series (Montgomery et al., 2006). The predicted 2012 yield is used as the detrending benchmark.

For the period in review, the state with the average highest annual detrended yield times series is Illinois (141.4 bushels/acre), followed by Wisconsin (134.7 bushels/acre), Ohio (134.0 bushels/acre), Indiana (133.1 bushels/acre), Michigan (125.3 bushels/acre), and Kentucky (110.1 bushels/acre).

3.2. Statisical methods

3.2.1. ANOVA and correlation

ANOVA and correlation are completed to investigate relationships that may exist between TSR and crop production in the Midwest. ANOVA is used to investigate the role of TSR on crop production through yield residuals (a value representing how far above or below the observed yield is from the mean yield of a developed linear regression equation for all yields) in the following three analyses: (i) years when a landfalling TS passed through a state and/or climate division in the Midwest versus years when a storm did not pass through a state and/or climate division; (ii) years when a landfalling TS passed through a state and/or climate division in the Midwest during August only versus all other years; and (iii) years when a landfalling TS passed through a state and/or climate division in the Midwest during September only versus all other years. Correlation of the number of landfalling TSs impacting a state per year within the Midwest domain to the reported average annual yield of that state is completed, along with correlation of SCD August MOR to reported annual yields for each corresponding CRD and September MOR to reported annual yields for each corresponding CRD.

3.2.2. Adjustments to dataset

During the study period 1981–2012, major drought conditions occurred periodically across the domain with more significant impacts to agricultural production during some years compared to others. Five different years experiencing major drought across much of the U. S. Corn Belt (1983, 1988, 1991, and 2012) were identified and excluded from yield analysis due to the increased amount of yield loss. Drought events are anomalous hydroclimate events, and the goal of this paper is not to identify “drought-busting events” (e.g., Haberlie et al. (2014)). Instead, the role of landfalling TSs are identified in this study to present a broader hydroclimatology of the Midwest. States with some to all SCDs in the Midwest experiencing dry conditions despite observing TSR during major droughts between 1981 and 2012 include Illinois (1988 and 2012), Michigan (1988 and 2012), Indiana (1988 and 2012), Ohio (1988 and 2012), Kentucky (2012), and Wisconsin (2012) (Fig. 3). The yield data for these years is removed from analysis. While the 1983 and 1991 droughts did not impact the entire domain, some states were impacted enough that all yield data was removed for these years. This also keeps the datasets as far removed from bias as possible (yields greater than one standard deviation below the mean).

To investigate the role of landfalling TSs in the Midwest hydroclimate and their contribution to climatological normal rainfall at SCD level, rainfall records had to be collected for each month and year a landfalling TS impacted one or more states. This resulted in a total of 811 separate records of SCD rainfall. Note that records are only collected in those states/climate divisions impacted by a landfalling TS, so not all years and records are collected and investigated for each SCD.

4. Results

4.1. Monthly climatological rainfall

The amount of TSR is calculated as a percentage of the total monthly observed rainfall for a SCD during the months of June through November (no storms were documented in the domain during the month of May 1981–2012). SCDs with greater than 20% of MOR attributable to TSR denote the months of August and September as the months receiving more than 20% of monthly rainfall from TSRs (crucial months for grainfill depending on planting date). For all SCDs observing TSR in August, the average TSR percentage of August rainfall is 21.3% and the average percentage of September rainfall is 26.4%. It should be noted that the 1981–2010 monthly precipitation climate normals for September in each state except Michigan are less than those for the month of August by an average (excluding Michigan) of 0.30 in. This is why the percentage TSR across the region in September is larger than in August, otherwise TSR in September would be closer to that observed in August. For TSs entering the Midwest domain from June to November 1981–2012, the average TSR observed rainfall is 19.8%. These findings are close to that of Kam et al. (2013) who found that tropical cyclones account for 17% of seasonal rainfall in their climatology of similar years (1980–2007).

4.2. ANOVA: crop residuals and tropical systems

ANOVA ($\alpha=0.1$ and $\alpha=0.2$) completed for crop residuals (percentage of yield above or below trend as determined through linear regression from a detrended yield time series) during storm years and no storm years results in statistically significant relationships that are itemized in Table 2(a) and mapped in Fig. 4. The noted statistically significant relationships are significant if the F-value is greater than the F-critical value. This supports rejection of the null hypothesis that there is no difference between the groups; therefore, the difference between the mean observed residual values between the two groups is large enough to indicate significance. For those ANOVA findings where the F-value exceeded the F-critical value, the p-values were all ≤ 0.2 or 0.1, upholding the rejection of the null hypothesis where the mean values of the two groups are different enough to warrant significance. ANOVA for crop residuals during August storm and no

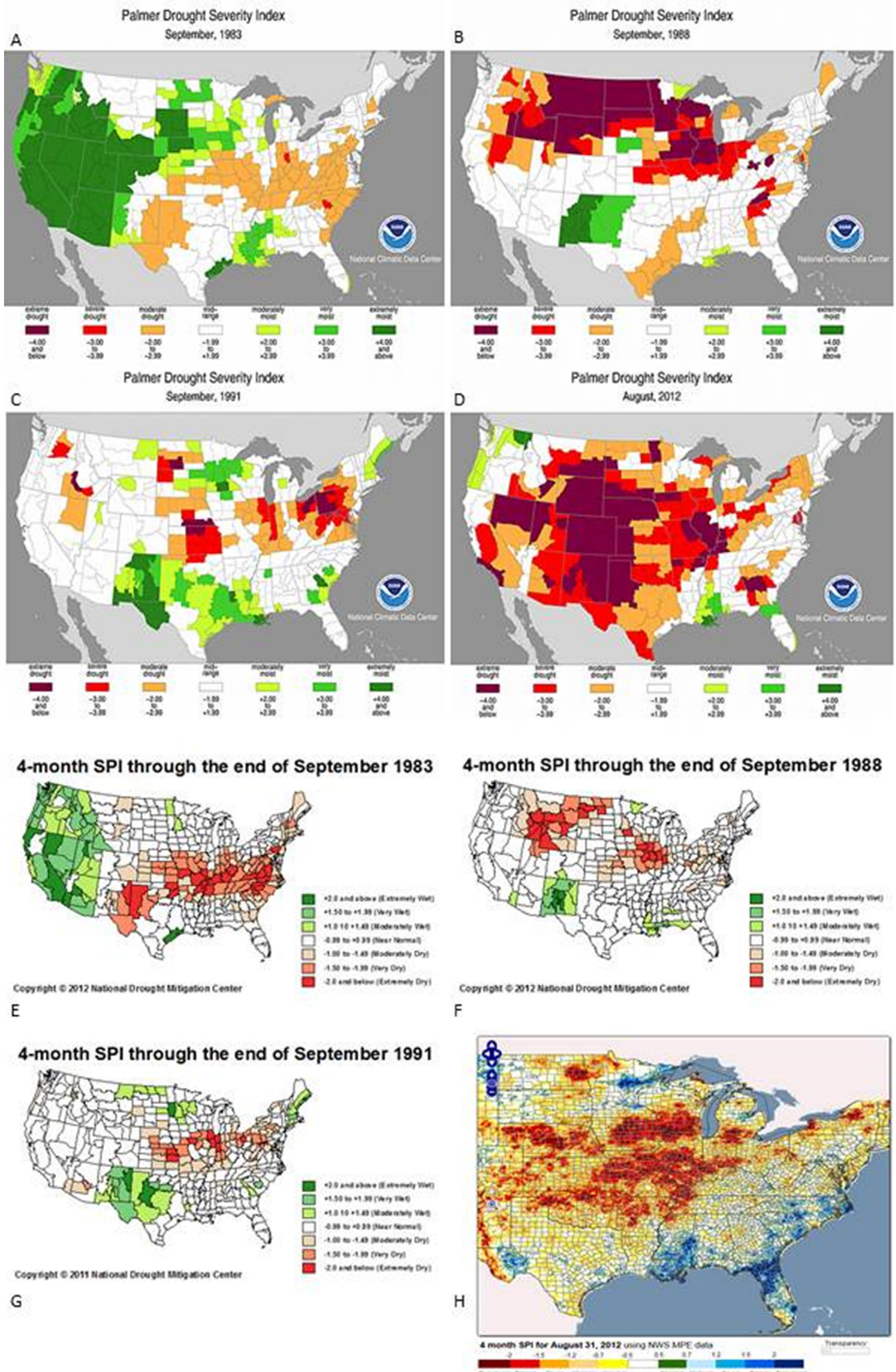

Fig. 3. (A–D) PDSI maps showing drought conditions during August or September of the 1983, 1988, 1991, and 2012 growing seasons. These years are removed from analysis due to much below normal yields. **(E–H)** Four-month SPI maps showing drought conditions during August or September of the 1983, 1988, 1991, and 2012 growing seasons. PDSI maps from the National Climatic Data Center; 4-month SPI maps from the National Drought Mitigation Center and the High Resolution Drought Trigger Tool user interface.

Table 2
States and those crop reporting districts (CDRs) in the Midwest with statistically significant relationships between the crop residuals during years in which (a) a landfalling tropical system entered or did not enter the domain; (b) a landfalling tropical system entered or did not enter the domain in August; and (c) a landfalling tropical system entered the domain during the month of September and did not during the month of September at $\alpha=0.2$ and $\alpha=0.1$. Those states that are significant at $\alpha=0.1$ are also significant at $\alpha=0.2$. If a state is not listed, no relationship was found.

	Average crop residual with storm	Average crop residual with no storm
a. Storm year versus no storm year – $\alpha=0.1$, $p\le0.1$		
Kentucky: CRD 10	12.8	0.1
Storm year versus no storm year – $\alpha=0.2$, $p\le0.2$		
Indiana: CRD 30	−1.2	6.2
Kentucky: CRD 20	9.5	1.3
b. August storm year versus no storm in august year – $\alpha=0.1$, $p\le0.1$		
	Average crop residual with storm	Average crop residual with no storm
Illinois: CRD 10	−5.2	5.7
Illinois: CRD 20	−6.1	6.3
Illinois: CRD 40	−4.9	6.4
Kentucky: CRD 10	13.7	3.6
August storm year versus no storm in August year – $\alpha=0.2$, $p\le0.2$		
Ohio: CRD 30	11.8	1.1
Illinois: CRD 30	−5.8	5.6
Kentucky: CRD 20	11.2	2.7
c. September storm year versus no storm in September year – $\alpha=0.2$, $p\le0.2$		
	Average crop residual with storm	Average crop residual with no storm
Indiana: CRD 30	−3.6	5.4

storm years results in statistically significant relationships as shown in Fig. 5 with residuals provided in Table 2(b). ANOVA for crop residuals during September storm and no storm years results in statistically significant relationships which are provided in Table 2(c) and mapped in Fig. 6. There are no CDRs that are statistically significant with $\alpha=0.2$ for September storm and no storm years. ANOVA with $\alpha=0.1$ and $\alpha=0.2$ is completed because the motivation for this research stems from an ongoing project where the goal is to develop user tools addressing broader possibilities that are useful to the agroclimatic community rather than an exact statistical outcome. This is done because growers consider a wide range of factors when assessing risk and opportunity. Similar to the season outlooks provided by the Climate Prediction Center, the results here are to provide a qualitative higher than normal or lower than normal guidance – which is still useful to the producer. Traditional alphas of 0.05 and 0.1 would make results quite narrow and limit the potential benefit of the findings presented here.

4.3. ANOVA: observed rainfall of tropical storm season

Monthly observed rainfall for the months of June-November is summed for each year and state and then separated into two groups for ANOVA analysis. Group one includes only those years that a landfalling TS impacted the Midwest domain during the TS season and group two includes only those years when no landfalling TS impacted the domain. The states of Kentucky and Wisconsin each have a statistically significant relationship ($\alpha=0.05$) between the differences in observed seasonal rainfall in storm years and non-storm years (F-value exceeds F-critical value and $p=0.01$ and 0.04, respectively). Kentucky averages 24.2 in. of rainfall when landfalling TSs enter the domain but only 21.4 in. during TS seasons with no storms. TSR results in an 11.6% increase in the seasonal total observed rainfall when a landfalling TS moves through Kentucky. Wisconsin averages 19.4 in. during TS seasons when landfalling TSs are present in the domain and/or state, but averages 22.1 in. during a no-TS year. This is a 12.2% decrease in observed rainfall when TSs pass through Wisconsin. While these findings for Wisconsin are significant, only four events contribute to this result, limiting the weight of this finding.

4.4. Correlation

Correlation of the number of landfalling TSs impacting a Midwest state within the domain per year to the reported annual yield of that state results in no statistically significant relationships despite similar high and low points in moving averages (Fig. 7). However, correlation of August and September monthly rainfall to reported annual yields at the SCD and CRD level, does return some statistically significant relationships for August. Indiana CRD 90 has a moderate to strong significance ($r=0.3645$, $p=0.04$) between August rainfall and annual yields. Ohio CRDs 30–60 (which is Ohio SCDs 6 and 7) also have moderate to strong significance for the month of August ($r=0.4043$, 0.5135, 0.4483, and 0.3973 with $p=0.02$, 0.003, 0.01, and 0.03, respectively). For correlation of observed September rainfall and historic yield there were no statistically significant relationships between observed rainfall and the detrended yield time series. A correlation does exist between historic detrended yield time series and observed rainfall inclusive of landfalling TSs in the Midwest. This establishes a generalized working relationship between landfalling TSR and yield, and shows that no landfalling TSR rainfall results in decreased yield in the respective CRDs where these relationships are present. In terms of agricultural application, this correlation will likely provide producers the understanding of a possible greater (lesser) than expected yield with an active (quiet) hurricane season forecast. However, it is important to highlight that other factors further contribute to the characteristics and behavior of the local hydroclimate such as soil moisture and soil type that may contribute to yield more than just rainfall alone.

4.5. Palmer Drought Severity Index and Standardized Precipitation Index analysis

4.5.1. Palmer Drought Severity Index analyses – climatologically dry conditions

Monthly observed rainfall is compared to DRO values to determine which climate divisions in the domain remain in dry conditions even after TSR (incipient dry conditions up to drought conditions). Illinois had 65 climate division records of observed rainfall 1981–2012 in dry conditions despite TSs moving through the region. Without any landfalling TSs, 17 more climate divisions would have been categorized as experiencing dry conditions. This is a total of 82 climate division records being categorized in dry condition status (or drier) that benefitted from landfalling TSs entering the Midwest. The number of Illinois SCDs not experiencing dry conditions is 71. This means that 53.6% of SCDs in Illinois impacted by a landfalling TS would have been categorized as experiencing dry conditions (or drier) without TSR from a landfalling TS entering the Midwest (Table 3). Illinois shows the highest percentage of SCDs that would have been categorized as experiencing climatologically dry conditions without TSR from landfalling TSs, followed by Ohio (50.4%), Indiana (48.8%), Wisconsin (47.2%), and Kentucky (42.0%). It is found in this study that the Upper Peninsula of Michigan experiences more climatologically dry conditions than wet conditions, giving Michigan a bias to dry conditions more often than the other states without TSR. Additionally, the Upper Peninsula is a region of low corn yield production and was only impacted by one landfalling TS in mid-September (Hurricane Gilbert 1988) during the time frame of this study when most crops are in dry-down stages. Thus, Michigan is

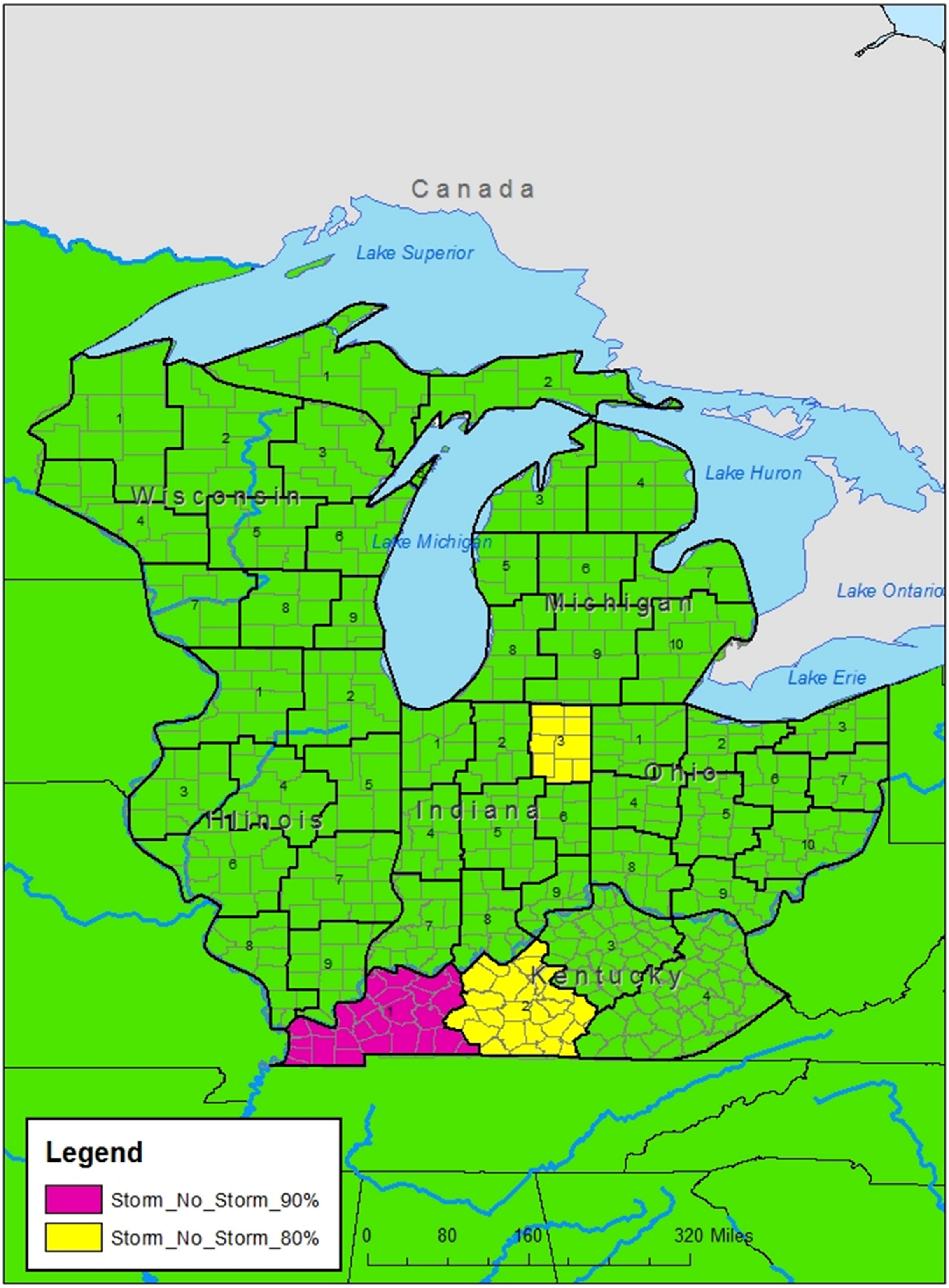

Fig. 4. Crop reporting districts with statistically significant differences between the mean residual of crop production during years with tropical storm passage and years without tropical storm passage during the hurricane season.

not considered in this comparison.

4.5.2. StandardizeD Precipitation Index analysis – climatologically dry conditions

To determine the role of TSR in alleviating climatologically dry conditions as determined by the SPI, the 1-month SPI is computed using MOR and then computed once again with MOR_TSR. The number of SCDs entering DRO status after TSR is subtracted from MOR are counted and compared to those SCDs in climatologically dry status with MOR. The 1-month SPI is selected because climatological rainfall analysis is being completed on a monthly basis, and landfalling TSs are more active in certain months (e.g., August

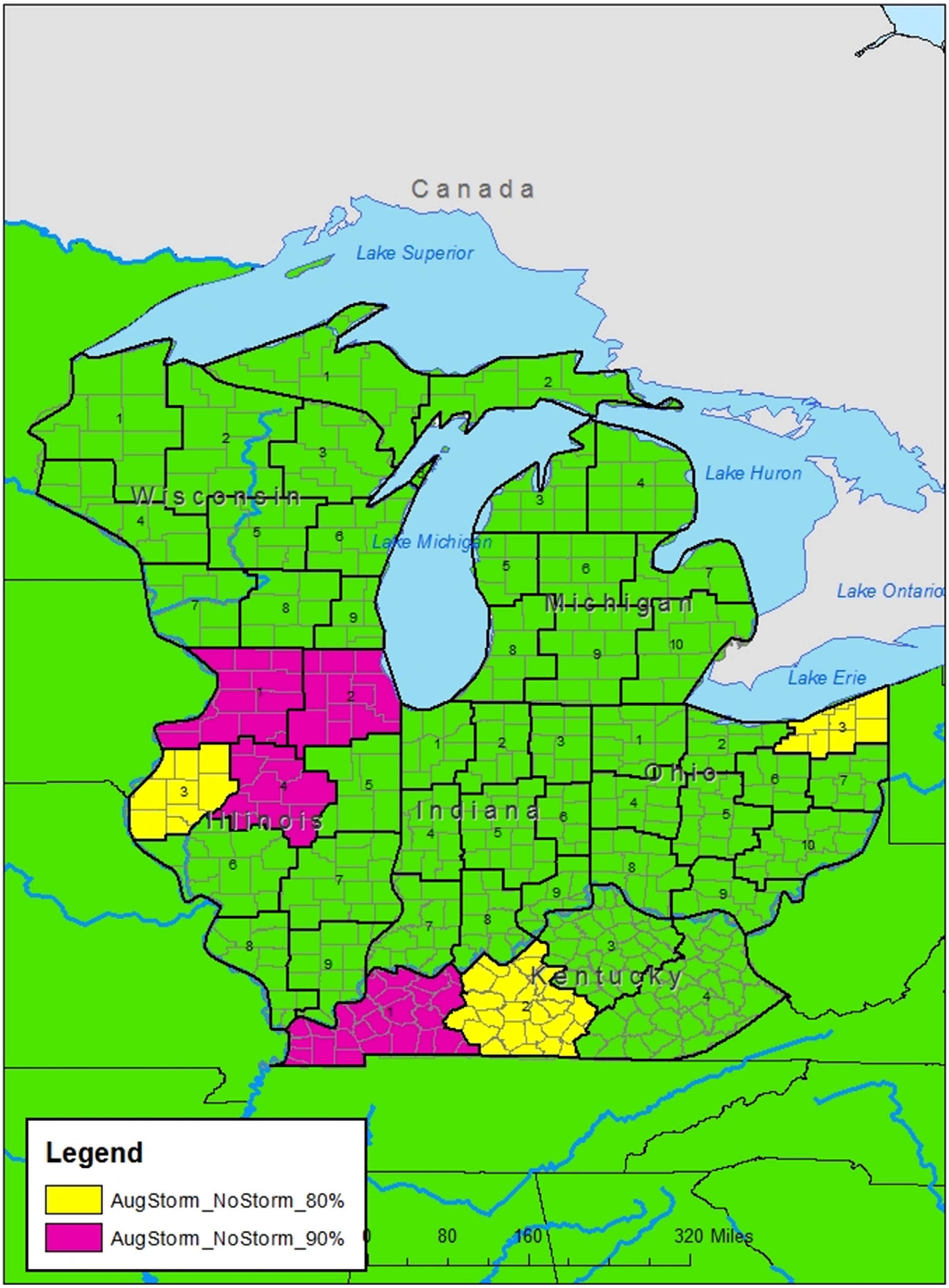

Fig. 5. Crop reporting districts with statistically significant (α=0.1 and α=0.2) differences between the mean residual of crop production during years with tropical storm passage during August vs. all other years. Note that those crop reporting districts that are significant at α=0.2 are also significant when α=0.1.

and September) than other months in the climatology. A longer SPI would smooth out the short-term impacts to potential crop yields from rainfall provided by these storms. Using SPI, Illinois had 68 SCDs with observed rainfall during the years 1981–2012 classified as dry despite TSs moving through the region. Without any landfalling TSs, 11 more SCDs would have been in climatologically dry condition status for a total of 79 SCDs in drought status benefitting from landfalling TS rainfall. The number of Illinois SCDs not experiencing drier conditions is 74. This means that 51.6% of SCDs would have been categorized as experiencing dry (or drier) conditions without landfalling TSR. Unlike PDSI, Indiana at 55.6% (not Illinois) shows the highest percentage of SCDs that

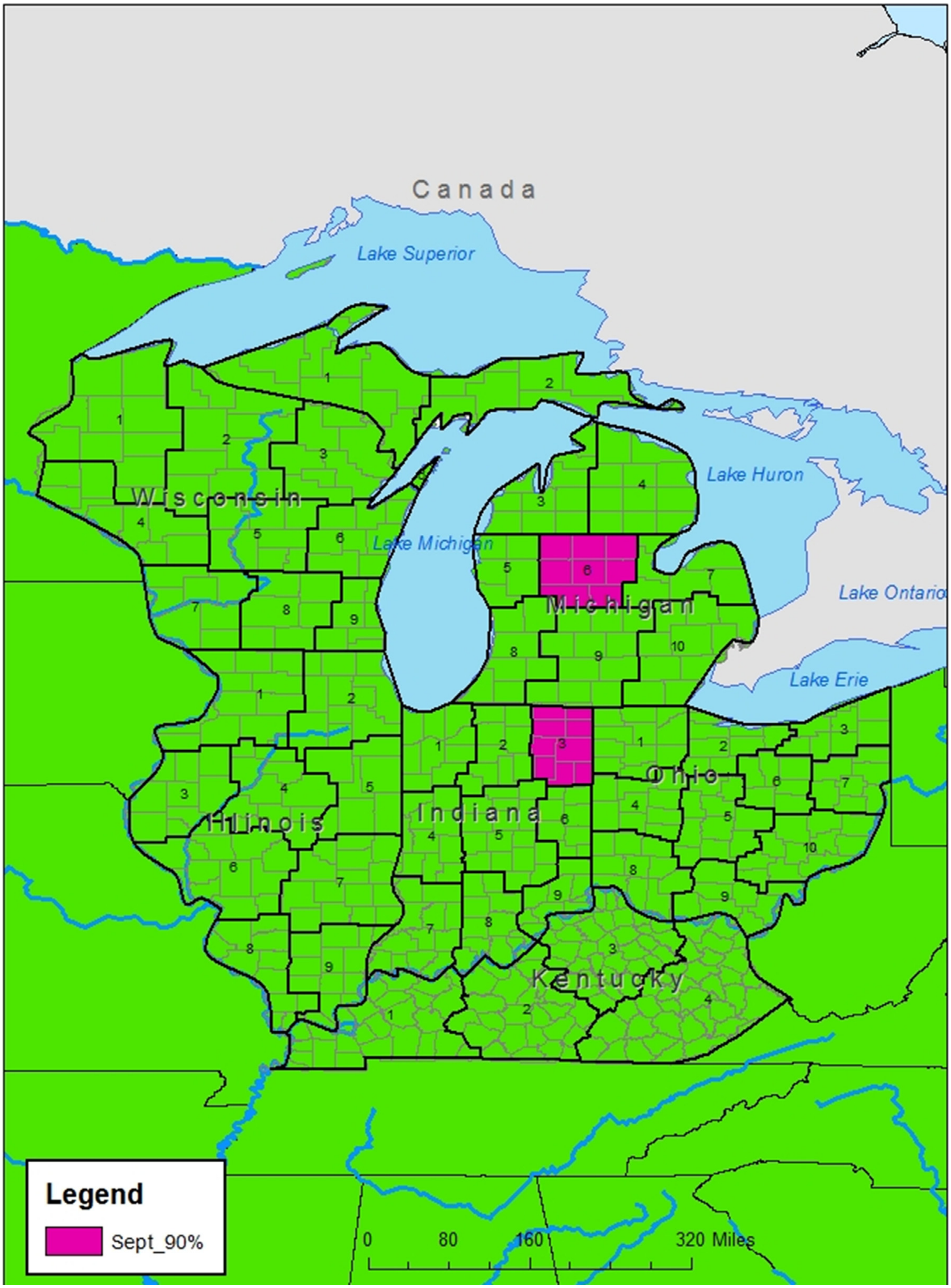

Fig. 6. Same as Fig. 5 except for September $\alpha=0.1$.

would be categorized as experiencing drier conditions without landfalling TSR, followed by Illinois (51.6%), Ohio (37.9%), Kentucky (38%), and Wisconsin (33.3%). Once again, Michigan experiences more climatologically dry conditions than wet conditions, giving Michigan a bias towards drier conditions without TSR. Thus, it should not be considered the second highest state. Table 3 summarizes this information for PDSI and SPI for all states in the domain.

5. Conclusions

The intent of this climatology is to determine the contribution of landfalling TSR to the climatological normal amount of rainfall

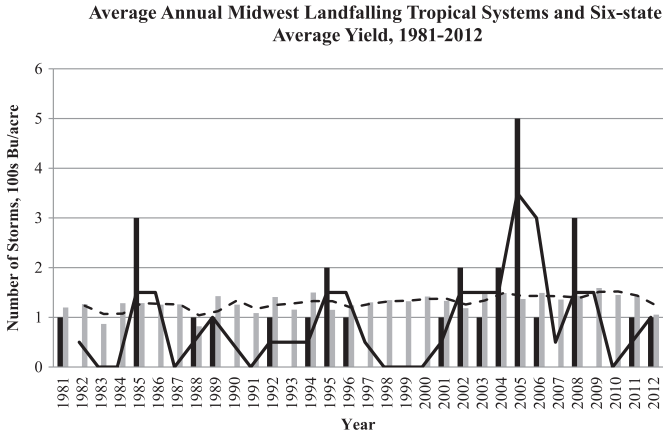

Fig. 7. Bar graph showing the average number of landfalling tropical systems per year in the Midwest domain (black bars) alongside the six-state average yield in bushels per acre (grey, in hundreds of bushels an acre). The solid black line is the two-year moving average of total landfalling tropical systems within the domain. The dashed black line is the two-year moving average of the six-state average annual yield. No relationship is found between the average number of storms per year within the domain and the average total yield of the domain.

across the Midwest at the CRD/SCD scale during the years 1981–2012. This study contributes to the efforts to help agricultural producers in the region make more informed farm-related decisions when presented with seasonal rainfall forecasts and hurricane season outlooks. Understanding that there is a lesser (or greater) likelihood for TSR in a given season can help farmers plan irrigation schedules (or drainage adjustments) and field work days more effectively (e.g., Takle et al. (2014)). This study shows that landfalling TSs are an important part of the Midwest hydroclimate from June to November in that rainfall from these systems serve to alleviate incipient dry spells up to drought conditions in roughly 33–56% of SCDs. The greatest contribution of TSR is during the months of August and September across the domain; months during which crop yields are highly sensitive to heat and moisture stress.

The Midwest (defined in this analysis by the states of Wisconsin, Illinois, Indiana, Ohio, Michigan, and Kentucky) on average experiences slightly less than one landfalling TS event a year (0.85) for the years 1981–2012. While the year 2005 is the most active year in the Midwest for landfalling TSs (5), there are 15 years within the 1981–2012 timeframe that were not impacted by these storms. In the Midwest, TSs occurred most often in September, followed by August. Ohio and Kentucky are the states most frequently impacted by landfalling TSs with Wisconsin being the least impacted. Landfalling TSs spend on average 44.5 h (~2 days) in the Midwest from time of entry to exit of the domain.

Monthly observed rainfall for June–November is reviewed and the percentage of TSR to total MOR is computed. August and September are investigated in more detail to determine if landfalling TSs in the eastern U.S. Corn Belt are important contributors to monthly rainfall budgets and crop production. These two months are selected because it is found that TSR accounts for 21–26% of MOR across the domain during these two months when monthly rainfall is reviewed in regards to the contribution of each landfalling TS in each season/year. Overall, for the time frame reviewed, TSR in the Midwest from landfalling TSs contributes up to approximately 11% of August rainfall across SCDs in the southeast portion of the domain (Fig. 8). During September, up to approximately 17.3% of observed rainfall is attributable to landfalling TSR in the Midwest, with a split in higher percentages spanning from west-central Illinois to northeast Illinois and northwest Indiana, and across eastern Kentucky and Ohio (Fig. 9).

It is apparent from this climatology that without TSR, drier conditions would be more prevalent across the Midwest. Of all Midwestern states, the percentage increase in the number of SCDs not in climatologically dry to drought status with TRS rainfall (PDSI and SPI) is greatest in the state of Ohio while Kentucky is impacted the least. However, Kentucky's SCDs encompass a much larger land area than in other states which serves to make drought impact greater than it appears. The one-month SPI analysis reaches the same conclusions.

ANOVA of tropical system (i.e., hurricane season) season rainfall of storm to no storm years shows the significance of tropical systems for the rainfall climatology of Ohio, Kentucky, and Wisconsin. ANOVA analysis of historic, detrended yield time series residual data further shows that TSR during some months appears to be beneficial for corn production (higher yields) in some states while being detrimental (reduced yields) in other states despite partial contribution of TSR to alleviate dry spell or drought conditions. In the Midwest it may be that the prolonged and often greater amounts of rainfall associated with landfalling TSs may be detrimental to increased production due to saturated soils.

Table 3
Summary of state climate division (SCD) records during those months and years the Midwest domain was impacted by a landfalling tropical system. The role of tropical storm system rainfall (TSR) in alleviating drought conditions is expressed as a percentage of total records. PDSI is the top table and SPI is the bottom table.

Palmer Drought Severity Index						
State	**Illinois**	**Indiana**	**Ohio**	**Michigan**	**Wisconsin**	**Kentucky**
Total SCDs impacted by TSs when MOR is in drought status	65	42	54	30	7	23
Total SCDs impacted by TSs in State added to drought if TSR removed (in drought without TSR)	17	37	67	31	10	19
Total SCDs in drought when TSR removed	82	79	121	61	17	42
Percentage of total SCDs in drought when TSR removed (%)	53.6	48.8	50.4	50.8	47.2	42.0
Percentage increase of SCDs in drought when TSR removed (%)	26.2	88.1	124.1	103.3	142.9	82.6
Total SCDs impacted by TCs by state 1980–2012	153	162	240	120	36	100
Standardized Precipitation Index						
State	**Illinois**	**Indiana**	**Ohio**	**Michigan**	**Wisconsin**	**Kentucky**
Total SCDs impacted by TSs when MOR is in drought status	68	57	45	26	4	22
Total SCDs impacted by TSs in State added to drought if TSR removed (in drought without TSR)	11	33	46	14	8	16
Total SCDs in drought when TSR removed	79	90	91	40	12	38
Percentage of total SCDs in drought when TSR removed (%)	51.6	55.6	37.9	33.3	33.3	38.0
Percentage increase of SCDs in drought when TSR removed (%)	16.2	57.9	102.2	53.8	200.0	72.7
Total SCDs impacted by TCs by state 1980–2012	153	162	240	120	36	100

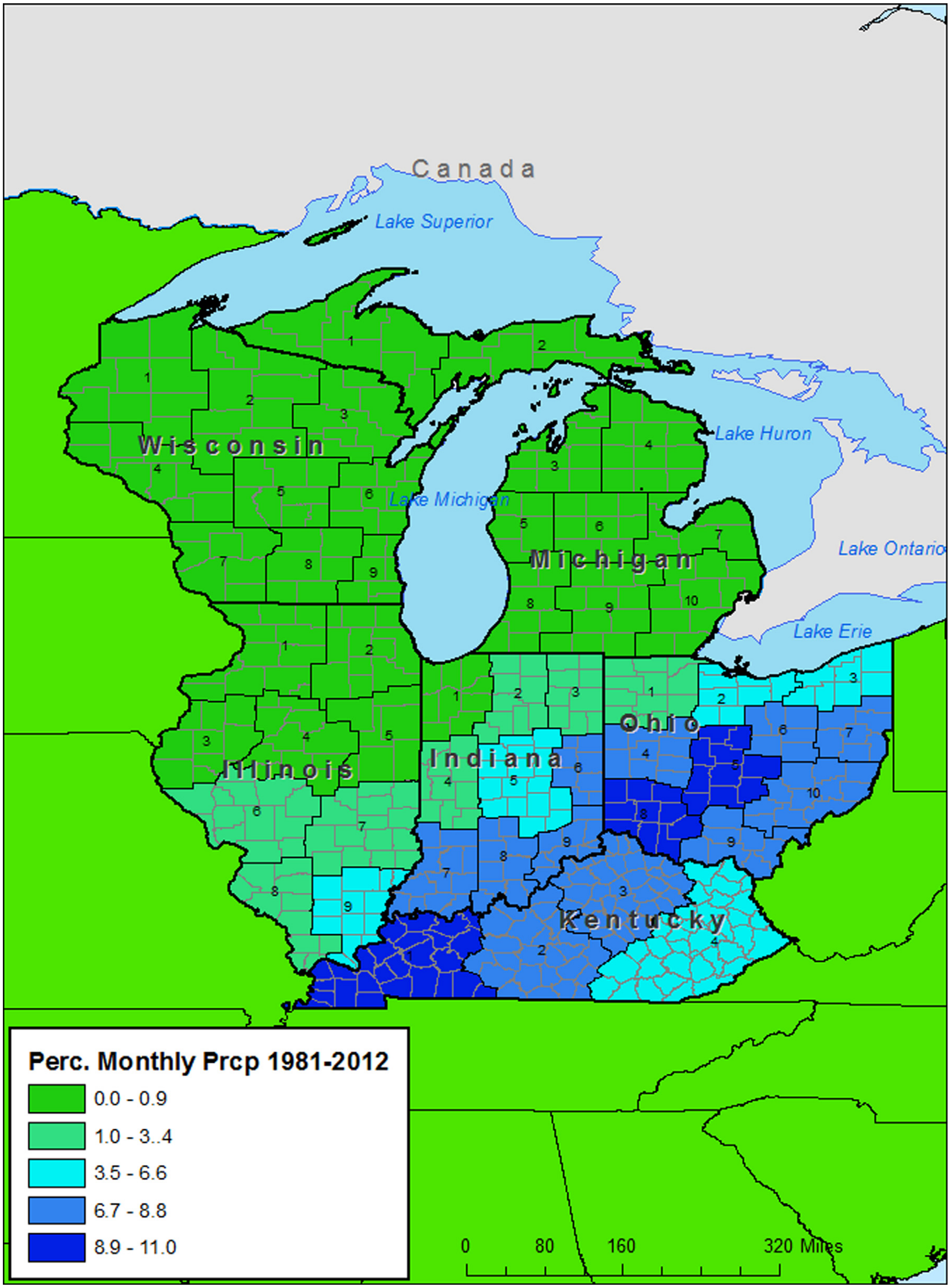

Fig. 8. Percentage total of August landfalling TSR in the Midwest domain to observed August rainfall in the Midwest domain 1981–2012.

A moderate to strong correlation of August rainfall to annual yield is found in this study highlighting the importance of August rainfall to overall yield in certain regions. More specifically, this study finds that yields in the southern part of the domain (Kentucky) improve when TSR occurs in August. Yields in Kentucky also improve when TSR is observed during the storm season. Correlation shows positive, moderate relationships between yield and TSR in August for Indiana CRD 90 and Ohio CRDS 30–60.

This study shows that landfalling TSs play an important role in the hydroclimate and crop production in the Midwest when they enter the domain under antecedent climatologically dry conditions and in terms of the total contribution the systems make to

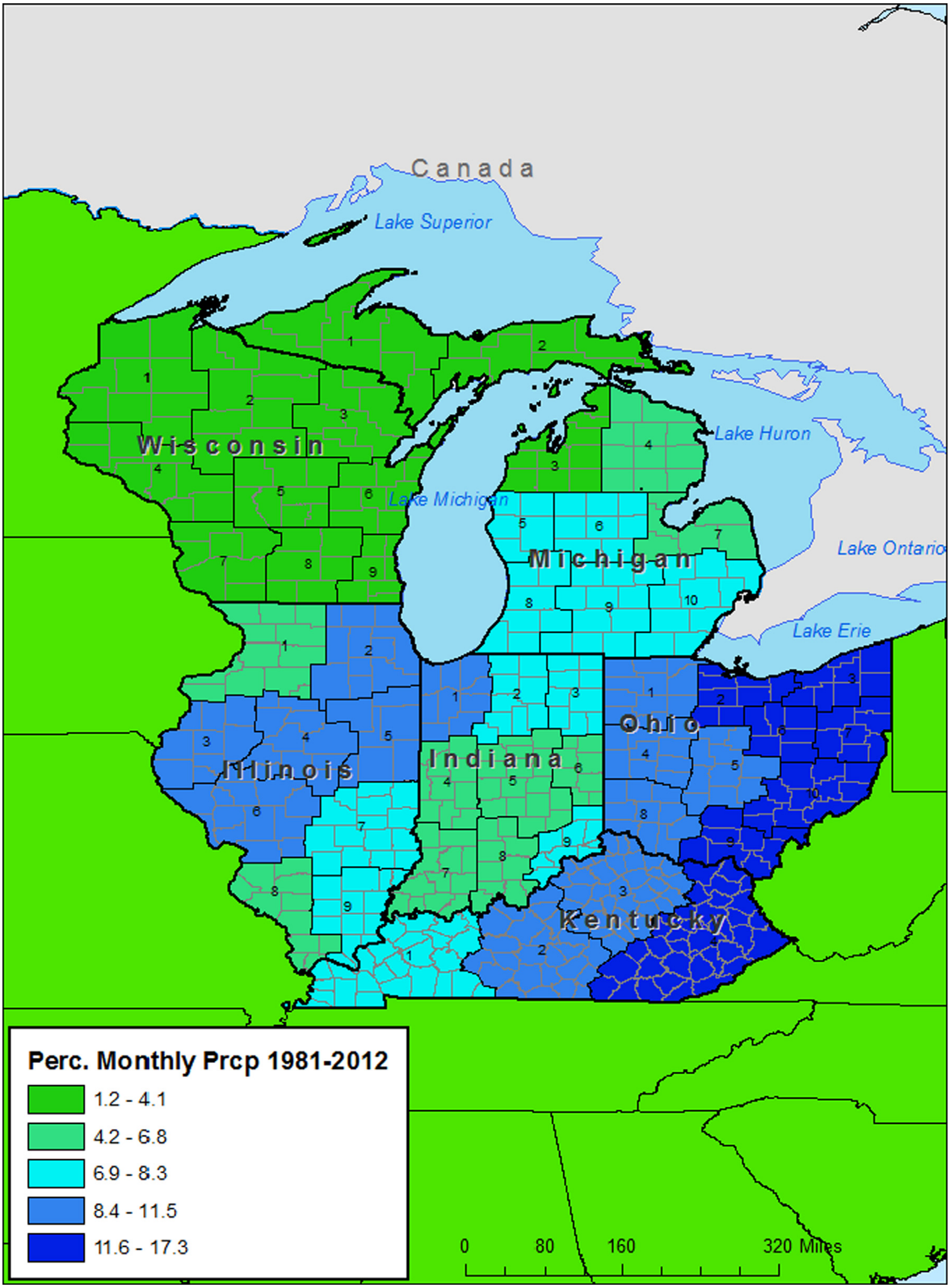

Fig. 9. Same as Fig. 8 except for September.

climatologically normal rainfall, especially in Ohio and Kentucky. The findings of this study aim to serve as guidance to producers and commodity trades when complemented with a tropical cyclone forecast. Findings will be incorporated into the decision support tool suite of products developed by the Useful to Usable (AgClimate4U.org) agricultural and food research initiative.

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