The Flash Drought of 1936

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ABSTRACT

An exceptional flash drought during the spring and summer of 1936 led to extreme heat waves, large losses of human life and significant reductions of crop production. An analysis of historic precipitation and temperature records shows that the flash drought originated over the southeastern United States (U.S.) in April 1936. The flash drought then spread north and westward through the early summer of 1936 and possibly merged with a flash drought that had developed in the spring over the northern Plains. The timing of the flash drought was particularly ill-timed as most locations were at or entering their climatological peak for precipitation at the onset of flash drought, thus maximizing the deficits of precipitation. Thus, by early July most locations in the central and eastern U.S. were either in drought or rapidly cascading toward drought. The weeks that followed the 1st of July were some of the hottest on record in the U.S., with two major heat waves: first over the Midwest and eastern U.S. in the first half of July and then across the south-central U.S in the month of August. The combination of the flash drought and heat wave led to an agricultural disaster in the north central U.S. and one of the deadliest events in U.S. history.

1. Introduction

Drought is a recurring feature of the natural climate system that has traditionally been classified as one of four, often overlapping categories (Wilhite and Glantz 1985): meteorological (lack of precipitation and often coupled with above-average temperatures), agricultural (depleted soil moisture and stressed crops), hydrological (depleted groundwater and below average streamflow), and socioeconomic (economic losses and human health impacts). In recent years, the term flash drought has been proposed for droughts that develop more rapidly than normal (Svoboda et al. 2002; Otkin et al. 2013; Hunt et al. 2014; Ford et al. 2015; McEvoy et al. 2016; Otkin et al. 2016; Otkin et al. 2019) and is defined by a rapid onset and/or intensification of drought caused by a lack of precipitation in combination with above-average air temperatures, wind speeds, solar radiation, and lower humidity (Otkin et al. 2018). Flash droughts are more likely to occur in regions of transition from humid to semi-arid climate regimes, where precipitation is more variable, and in regions where the landscape is dominated by row crop agriculture (Christian et al. 2019).

Flash droughts (Hoell et al. 2020) can cause disproportionate amounts of damage to ecosystems, infrastructure, and increase levels of mortality if coupled with a heat wave. For example, flash droughts and associated heat waves have occurred on several occasions over the past four decades. Two of the worst from a widespread, impact-based standpoint occurred in 1988 and 2012. The 1988 flash drought developed very quickly in the spring over a large portion of the central and eastern United States (U.S.; Basara et al.

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2020) and led to significantly-reduced production of crops like corn (Zea mays L) over the Midwest. The 2012 flash drought developed very rapidly in early summer, affected almost all of the central U.S. through the summer and early fall, and was associated with temperatures that were well above average (Otkin et al. 2016; Basara et al. 2019).

There have been significant flash droughts in recent years outside the U.S. as well. Perhaps the most climatologically extreme example is the flash drought and subsequent heat-wave that occurred in Russia in 2010 (Barriopedro et al. 2011; Miralles et al. 2014; Christian et al. 2020). The flash drought began in late May and was followed by the worst heat wave on record in Russia by early August. This event led to exceptional loss in wheat production, increased forest fires, and caused thousands of deaths from the heat and poor air quality.

During the 1930s, much of the continental U.S. was affected by some of the most intense droughts on record. In the southern High Plains, the droughts contributed to the formation of the Dust Bowl period and were further prolonged by the dust's impact on drought (Cook et al. 2008; Cook et al. 2009). While the 1930's had several particularly harsh drought years (e.g., 1934), the drought of 1936 was particularly extreme. As will be shown in Section 4, the heat waves associated with this event are among the worst on record for many places in the central U.S.

Heim (2017) demonstrated that most of the U.S. from the Rocky Mountains to the eastern states were in severe to extreme drought in July of 1936 according to the Palmer Drought Severity Index (PDSI; Palmer 1965) and various other reports (Cronin and Beers 1937; Sutch 2009) discuss the tremendous impact of drought to crops in the north central U.S. The Extended Reconstructed Sea Surface Temperature (ERSST; Huang et al. 2014) shows that the Pacific Decadal Oscillation (PDO; Newman et al. 2016) was strongly positive in the spring and summer of 1936, a phenomenon which is thought to have contributed heavily to the prevalence of U.S. drought in the 1930's (McCabe et al. 2004). However, the overall understanding of how the 1936 drought evolved across large swaths of the U.S. is limited. Therefore, the objective of this paper is to further quantify the rapid spatial evolution of the 1936 flash drought event using historic precipitation and temperature data.

2. Data and Methods

The temperature and precipitation data used for this study are obtained from the Applied Climate Information System (ACIS; Hubbard et al. 2004). Observation sites for monitoring the evolution of the drought were required to have no missing daily precipitation reports within the period from 1 April to 31 August of 1936 and have continuous records from that city for at least 100 years to be eligible for this study. Typically, a flash drought event is characterized as a period of rapid intensification (i.e., occurring within 60 days) of drought where precipitation during the period is at the 20th percentile or lower and coupled with above-average temperatures lasting for several weeks to a few months (Otkin et al. 2018). For this study, a flash drought was determined to have occurred if both of the following conditions are met:

- Total precipitation over a 60-day period was less than 50 percent of average at a location that normally receives an average of no less than 100 mm of precipitation over the 60-day period of record.
- Average temperature over a 60-day period that was more than 0.5°C greater than normal at a given location that also has an average temperature > 10°C during that 60-day period.

The temperature and precipitation thresholds were set to ensure that a minimal amount of substantive precipitation would ordinarily occur and that temperatures are typically warm enough to support modest evaporative demand. We used average temperature over the 60-day period to incorporate minimum temperatures, which can be very important for human health in a heat wave (Kaiser et al., 2007). While a flash drought can occur in less than two months based on criteria set forth in Otkin et al. (2018), in this study it is important to demonstrate that this was of sufficient enough duration to be called an extreme event across a large section of the U.S. While significant impacts to agriculture certainly verified for this event (as shown later), the methodology described above is specific to determining agricultural flash drought.

The evolution of the event was analyzed in the following manner. A total of 90 locations between the front range of the Rocky Mountains and East Coast of the United States were selected for analysis of precipitation and temperature. The period of analysis for all stations began on 15 April 1936 and ended 121 days later on 13 August 1936 and data from that period of analysis were compared against the entire period of record for that location. The dates (15 April to 13 August) were chosen to capture the main part of the growing season and the climatological peak of precipitation. In addition to computing the total precipitation, we also determined the percent of normal precipitation (compared to the 1981-2010 climate normals) and the accumulated precipitation deficit over a moving 60-day window. Of the moving 60-day windows, the one with the greatest precipitation deficit was noted and the last date of that 60-day window was marked as the peak date. The accumulated precipitation deficit is calculated by comparing the 60-day precipitation that occured in 1936 to the climatological average . The temperature anomalies were also computed by taking the average of the daily temperature departures over the same 60-day moving window to better indicate the presence of any extreme anomalies in that period. The temperature anomaly used for verification of flash drought is the temperature anomaly at the time of the peak precipitation deficit. Precipitation and temperature data used in this study are compared to data over the entire period of record through 2019 at each location (Tables 2a-e).

For the analysis, the peak dates are broken into five time periods as shown in Table 1. The first and fifth periods are roughly a week in length with periods 2-4 being roughly two weeks in length. The differing lengths of periods 1 and 5 were set to distinguish between the places where the flash drought was earliest (latest) and to ensure more equity in the number of locations between each period. Agricultural yield and production data are from the USDA National Agricultural Statistics Service (NASS). We used linear regression to determine the trends for corn and spring wheat at the agricultural district level over a thirty-year period from 1931-1960. This period was chosen as all crop reporting districts analyzed had data over this period, which was not the case for all locations prior to 1930.

Table 1. Grouping of the peak accumulation deficit dates and the corresponding color to the dots shown in Figure 1.

Period	Date Range	Color
1	13 June – 20 June	Blue
2	21 June - 7 July	Yellow
3	8 July – 22 July	Orange
4	23 July – 6 August	Dark Red
5	7 August – 13 August	Black

3. Results

a. Flash Drought

Figure 1 demonstrates that across a large portion of the southeastern and middle Atlantic region of the U.S., precipitation essentially ceased for approximately two months starting in mid-April of 1936. The precipitation accumulation deficits (mm) and percent of normal values in Period 1 were most extreme in the southeastern U.S. cities of Birmingham, AL, Atlanta, GA, Tupelo, MS, Columbia, SC, and Charlottesville, VA, which all had their driest 60-day period on record occur in 1936 for the date ending with the peak of the accumulation deficit (Table 2a). For many locations in this region, April and May are climatologically the wettest time of year, so the onset of drought may have impacted vegetation more than if it had started later during the growing season. Further, temperature values across the region were generally 0.5 to 2.0°C above average over the period, sufficient to drive anomalous drying of the soil with enhanced evaporative demand, and to meet the temperature criteria for flash drought. The exceptions were New York, NY, Avoca, PA, and Richmond, VA, which all had percent of normal precipitation values too high to meet flash drought criteria even though precipitation was below average.

Shortly thereafter flash drought also began developing a bit further north and west into the states of Tennessee, Kentucky, West Virginia, and into the southern portions of Illinois, Indiana, and Ohio. At around the same time as drought was spreading in the southern and eastern U.S., flash drought was also developing in the northern Plains. Of the sixteen locations of Period 2, fourteen experienced a flash drought in the 60-day period with a peak date between 21 June and 7 July. The majority of locations in Period 2 had less than 30 percent of normal precipitation and half of the locations had their driest 60-day period on record ending on the peak date shown in Table 2b. Two of those locations are Bowling Green, KY and Nashville, TN, which had accumulated precipitation deficits in excess of 200 mm. The lowest percent of normal was found in Bismarck, ND, which had only 9.4 percent of normal for the 60-day period ending 3 July. Temperatures were above the threshold for flash drought in each Period 2 location except for Dover, DE. The locations in the northern Plains were exceptionally above average, with 60-day temperatures coming in from 3.8 to 4.2°C above average.

By the latter half of May, drought was beginning to spread further north into the U.S. Corn Belt, upstate New York, and into other parts of the northern Plains. Of the 18 locations that had their peak precipitation accumulation deficit in Period 3, only four did not verify as having a flash drought, and only one of those (Williamsport, PA) was because precipitation exceeded the climatological average precipitation for that location and time period. Several locations had less than 25 percent of normal precipitation and three locations (Lincoln, IL, Peoria, IL and Pierre, SD) had under 10 percent of normal precipitation. The largest accumulation deficit was in Lincoln, IL which had a deficit of 206 mm over the 60-day period ending 15 July. A total of eight locations had their driest 60-day period across their climatological record ending on the date shown in Table 2c, including Lincoln, IL, Peoria, IL, West Lafayette, IN, Lexington, KY, Lincoln, NE, Pittsburgh, PA, Pierre, SD, and Syracuse, NY. Temperatures in the eastern part of the U.S. (that had a peak precipitation deficit in Period 3) were less above average than those in the Midwest, but were sufficiently above average (~ 0.5 to 1.0°C) to produce enhanced evaporative demand and verify as having a flash drought. The warmest location relative to average was Pierre, SD, which averaged an astonishing 6.0°C above average over the 60-day period ending on 22 July.

The spatial expansion of drought continued into late May and early June, with 23 locations having the peak precipitation accumulation deficit in the last week of July or the first week of August. While there is some geographic overlap with the locations that had a peak deficit in Period 3 (ending 22 July) in the Corn Belt region from central Nebraska into Indiana, most of the spatial expansion that occurred at the end of May and beginning of June was to the west and southwest into Missouri, Kansas, and Oklahoma. There was also additional expansion in the northern Plains with Glasgow, MT, Fargo, ND, and Sheridan, WY also having

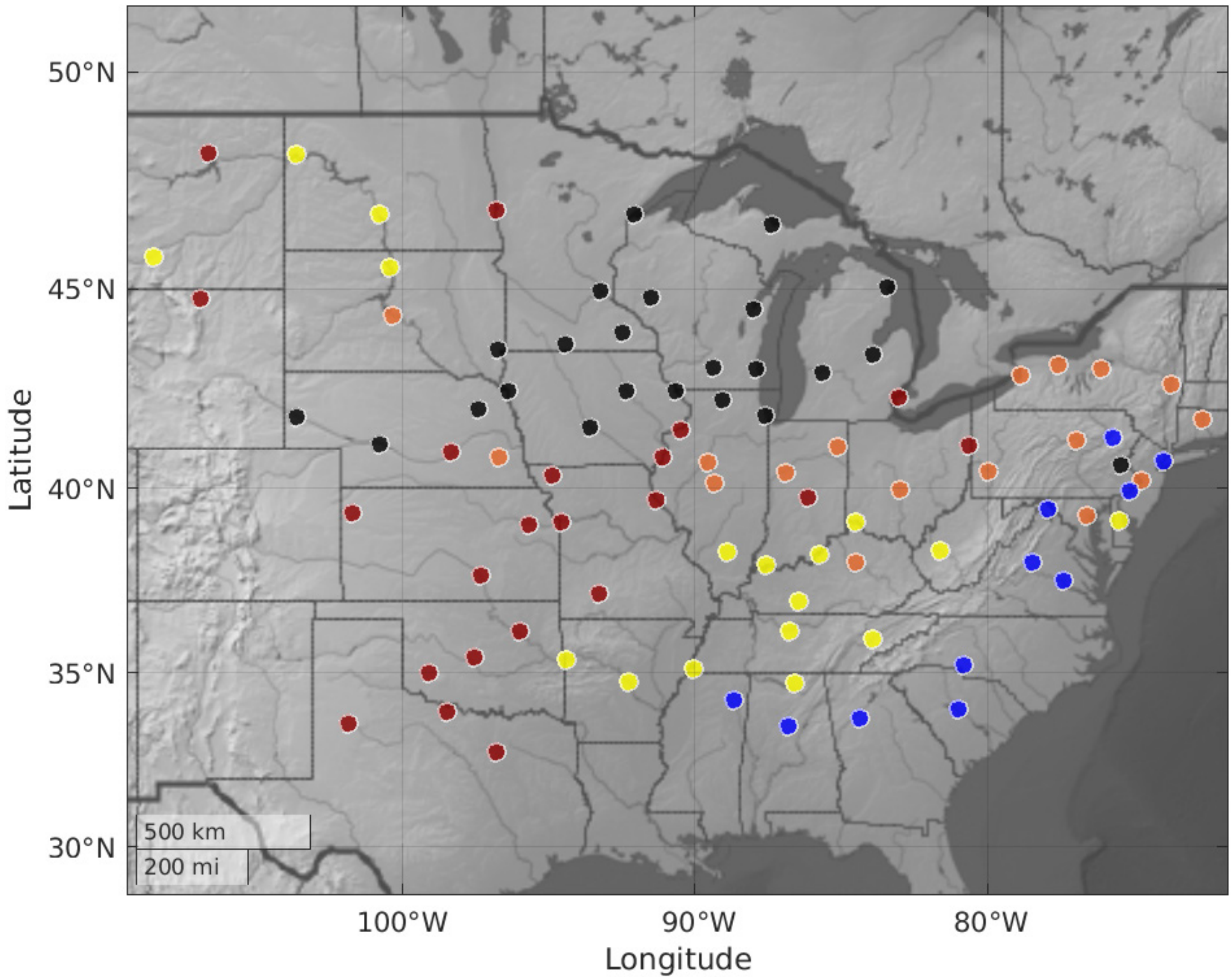

Figure 1. A map showing the date of peak precipitation deficit (mm) by location. Colors correspond to the following date ranges: Blue (13 June to 20 June), Yellow (21 June to 7 July), Orange (8 July to 22 July), Dark Red (23 July to 6 August), Black (7 August to 13 August). Additional information can be found in Tables 2a-e.

their peak precipitation accumulation deficit during Period 4. Only Youngstown, OH had more than 50 percent of normal precipitation of the locations the peaked in Period 4 and most had less than 25 percent of normal precipitation, thus easily meeting the precipitation deficit criteria for flash drought (Table 2d).

In Hobart, OK and Oklahoma City, OK, near zero precipitation fell as record low totals of just 1 and 2 mm fell respectively over a 60-day period ending in early August. This corresponded to an astounding 0.5 and 1.1 percent of normal precipitation respectively over a 60-day period, with accumulated precipitation deficits of 147 and 186 mm. Total precipitation at locations in Kansas and Missouri in Period 4 were only marginally better and the accumulation deficits were higher, with Topeka, KS, Kansas City, MO, and Maryville, MO having deficits in excess of 200 mm (213, 228, and 221 mm respectively). Across the five Corn Belt locations (Burlington and Des Moines, IA, Moline, IL, Indianapolis, IN, and Grand Island, NE) that peaked in late July to early August, four had less than 25 percent of normal precipitation and deficits ranged from 153 mm at Grand Island, NE to 193 mm at Indianapolis, IN. At eleven locations that had peak precipitation accumulation deficits in Period 4, it was also the driest 60-day period on record ending on the date shown in Table 2d. With the exception of Detroit, MI and Lubbock, TX, temperature values above the threshold for flash drought and in most cases, temperatures were in excess of 2.5°C above average during the 60-day period of peak accumulation deficits.

With the exception of Allentown, PA, all of the 22 locations that peaked in Period 5 (7 to 13 August 1936) were in the north central U.S. ranging from Scottsbluff, NE in the west to Alpena, MI in the east. Only Allentown, PA had more than 50 percent of normal precipitation and most of the locations had less than 20 percent of normal with precipitation. Indeed, 14 of the locations had their driest ever 60-day period on record on record for the date ending in Table 2e, and four of those (Fairmont, MN, Minneapolis,

Table 2a. The peak date for a precipitation deficit, total precipitation (mm), total precipitation accumulation deficit (mm), the percent of normal, the temperature anomaly (°C) over a 60-day period ending on the peak accumulation deficit date shown in column 3, whether flash drought verified for Period 1 locations, and the year the period of record began for each respective city . Bold values for precipitation indicate it was the driest such 60-day period on record over the period of record for a 60-day period ending on that date for that particular station. Bold and italicized font indicates it is the second driest. An asterisk indicates there are gaps in the period of record. Locations are listed in alphabetical order by state. All Period 1 locations are depicted by blue circles in Figure 1.

City/Town	State	Peak Date	Total Prec	Prec Deficit	% of Normal	Temp Anomaly	Flash Drought	Start
Birmingham	AL	29 June	***53***	-181	22.6	2.1	Yes	1895
Atlanta	GA	17 June	**30**	-148	16.9	1.3	Yes	1878
Tupelo*	MS	17 June	**46**	-211	18.0	1.1	Yes	1930
Charlotte	NC	19 June	**25**	-144	15.0	2.4	Yes	1878
New York	NY	17 June	137	-81	62.9	0.2	No	1869
Avoca	PA	15 June	125	-58	68.3	1.3	No	1901
Philadelphia	PA	15 June	67	-112	37.5	0.5	Yes	1872
Columbia	SC	17 June	**14**	-153	8.5	0.5	Yes	1887
Charlottesville*	VA	17 June	**58**	-151	27.9	1.5	Yes	1893
Richmond	VA	17 June	97	-90	51.9	-0.7	No	1887
Martinsburg*	WV	13 June	72	-119	37.5	2.3	Yes	1891

MN, Norfolk, NE, and Milwaukee, WI) had under 10 percent of normal precipitation. Accumulated precipitation deficits generally exceeded 150 mm, with Waterloo, IA and Fairmont, MN exceeding 200 mm. With the exception of Chicago, IL and Milwaukee, WI, which are adjacent to Lake Michigan, the corresponding 60-day average temperatures were more than 0.5°C above average, and in most locations temperatures were more than 2.0°C above average. In the western Corn Belt locations of Sioux City, IA, Norfolk, NE, and Sioux Falls, SD, temperatures were in excess of 4.0C above average.

One hypothesis for the difference in average temperature between locations right along the Great Lakes versus inland is that the relatively rapid heating of the land compared to the Great Lakes allowed for a more pronounced lake breeze during this period of time for locations immediately by the

Table 2b. Period 2 locations, depicted by yellow circles on Figure 1. Refer to the caption from Table 2a for further detail.

City/Town	State	Peak Date	Total Prec	Prec Deficit	% of Normal	Temp Anomaly	Flash Drought	Start
Huntsville*	AL	21 June	**44**	-192	18.7	1.8	Yes	1894
Forth Smith	AR	29 June	110	-129	46.1	2.1	Yes	1882
Little Rock	AR	27 June	115	-102	53.1	0.7	No	1875
Dover	DE	23 June	139	-46	75.1	0.4	No	1893
Mt. Vernon*	IL	20 June	52	-180	22.6	2.5	Yes	1895
Evansville	IN	20 June	61	-180	25.2	1.8	Yes	1897
Bowling Green	KY	21 June	**26**	-225	10.4	3.1	Yes	1893
Billings	MT	4 July	47	-58	44.7	4.2	Yes	1934
Bismarck	ND	3 July	**13**	-130	9.4	3.3	Yes	1874
Williston*	ND	7 July	43	-77	35.9	3.8	Yes	1894
Cincinnati	OH	28 June	**35**	-190	15.7	1.6	Yes	1871
Mobridge*	SD	24 June	**26**	-125	17.1	3.8	Yes	1911
Knoxville	TN	29 June	**53**	-154	25.6	2.6	Yes	1871
Memphis	TN	28 June	80	-145	35.4	0.7	Yes	1872
Nashville	TN	21 June	**41**	-206	16.6	2.1	Yes	1871
Charleston*	WV	27 June	**55**	-171	24.3	2.4	Yes	1892

Table 2c. Period 3 locations, depicted by orange circles on Figure 1. Refer to the caption from Table 2a for further detail.

City/Town	State	Peak Date	Total Prec	Prec Deficit	% of Normal	Temp Anomaly	Flash Drought	Start
Hartford	CT	18 July	92	-125	42.6	-0.1	No	1905
Lincoln*	IL	15 July	**20**	-206	8.8	2.8	Yes	1906
Peoria	IL	18 July	**15**	-174	8.0	2.3	Yes	1883
Fort Wayne	IN	14 July	73	-145	33.5	0.7	Yes	1897
West Lafayette*	IN	18 July	**30**	-187	14.0	2.9	Yes	1901
Lexington*	KY	12 July	**55**	-181	23.4	1.8	Yes	1872
Louisville	KY	2 July	**29**	-194	13.0	0.7	Yes	1872
Baltimore	MD	18 July	88	-100	47.0	0.9	Yes	1871
Lincoln	NE	16 July	**29**	-177	14.3	3.0	Yes	1887
Trenton	NJ	16 July	87	-153	36.3	0.3	No	1865
Albany	NY	22 July	90	-106	45.8	1.3	Yes	1874
Buffalo	NY	20 July	*38*	-137	21.9	-0.5	No	1871
Rochester*	NY	22 July	64	-99	39.0	0.9	Yes	1871
Syracuse*	NY	20 July	**21**	-153	12.0	0.9	Yes	1902
Columbus	OH	20 July	*66*	-152	30.2	1.4	Yes	1878
Pittsburgh	PA	20 July	**59**	-149	28.4	0.9	Yes	1871
Willamsport	PA	20 July	111	-90	55.1	0.4	No	1895
Pierre*	SD	22 July	**15**	-146	9.3	6.0	Yes	1893

lake. Prior research (Lebassi et al., 2009; Lebassi-Habtezion et al., 2011) has shown this effect in coastal California in recent decades as the inland areas have warmed quickly and coastal sites have shown marginal cooling. Supporting evidence of the onshore breeze hypothesis is shown in Fig. 2, which compares the difference in maximum temperature anomalies between Milwaukee, WI, located on Lake Michigan, and Madison, WI, located ~ 125 km west. During the period of flash drought development, the median maximum temperature anomaly was 5.6°C higher in Madison than in Milwaukee. This effect was particularly pronounced immediately preceding and after the core of the heat wave over the Midwest in mid-July.

b. Heat Waves

By the first week of July, we estimate that roughly 3 million km2 of the U.S. from the Front Range of the Rocky Mountains to the eastern Great Lakes and from the mid-South to the Canadian border were in drought or rapidly cascading into drought. Neither observations nor model state estimates of soil moisture are available for 1936 but it is likely that root zone soil moisture would either have been severely depleted or were rapidly declining over this entire area. This would have led to a significant reduction in the amount of available energy partitioned to latent heat flux, a reduced evaporative fraction, and a positive feedback cycle between an increasingly desiccated land surface and a warmer/drier boundary layer. The presumed wilting crops and grasses in early July likely accelerated this feedback and helped build and maintain the worst heat wave on record for many locations in the U.S. and southern Canada.

As such, the months of July and/or August in 1936 were the hottest on record in several central U.S. states according to data from the National Center for Environmental Intelligence (NCEI; Vose et al., 2014). The human mortality associated with the extreme surface temperatures resulted in the largest weather-related loss of life in the continental U.S. since 1900 (Laiker 2013). There were two main heat waves of significant duration in the summer of 1936 that followed an abnormally warm spell in the intermountain West in the latter half of June. The first was centered over the Midwest and peaked in the middle of July and the second was centered over the central and southern Great Plains and peaked in the middle of August. The closest comparisons to the main heat waves since 1936 occurred during the droughts of 1988 (Kunkel and Angel, 1989) and 2012 (Rippey 2015) in the Midwest and 2011 in Kansas, Oklahoma, western Arkansas, and the southern two-thirds of Missouri (Hoerling et al., 2013; Seager et al., 2013; Wakefield et al., 2019).

The first heat wave commenced just after the 1st of July from the northern High Plains down into the western Corn Belt and then expanded east of the Mississippi River after the 4th of July (Fig. 3).

While the northeastern and southeastern U.S. were mostly spared from this initial heat wave, a brief eastward and

Table 2d. Period 4 locations, depicted by dark red circles on Figure 1.Refer to the caption from Table 2a for further detail.

City/Town	State	Peak Date	Total Prec	Prec Deficit	% of Normal	Temp Anomaly	Flash Drought	Start
Burlington*	IA	24 July	46	-176	20.6	2.7	Yes	1897
Des Moines	IA	9 August	71	-157	31.2	2.9	Yes	1878
Moline	IL	31 July	39	-180	17.8	2.7	Yes	1871
Indianapolis	IN	2 August	*26*	-193	11.8	2.0	Yes	1871
Goodland*	KS	28 July	**13**	-155	8.0	3.5	Yes	1895
Topeka	KS	26 July	**23**	-213	9.9	3.9	Yes	1887
Wichita	KS	4 August	**13**	-192	6.5	3.0	Yes	1888
Detroit	MI	5 August	78	-93	45.6	-0.5	No	1874
Hannibal*	MO	27 July	**41**	-178	18.7	3.3	Yes	1902
Kansas City	MO	27 July	**22**	-228	8.9	3.7	Yes	1888
Maryville*	MO	4 August	**25**	-221	10.2	3.3	Yes	1894
Springfield	MO	5 August	57	-148	27.6	2.8	Yes	1888
Glasgow*	MT	31 July	**21**	-80	21.1	4.1	Yes	1894
Fargo	ND	5 August	**16**	-144	10.0	3.0	Yes	1881
Grand Island	NE	4 August	***34***	-153	18.0	4.1	Yes	1895
Youngstown	OH	28 July	123	-82	59.9	1.7	No	1896
Hobart*	OK	4 August	**1**	-147	0.5	2.4	Yes	1910
Oklahoma City	OK	3 August	**2**	-186	1.1	1.8	Yes	1890
Tulsa	OK	6 August	**20**	-167	10.5	3.0	Yes	1893
Dallas	TX	1 August	60	-86	41.3	0.5	Yes	1898
Lubbock	TX	28 July	50	-76	39.6	0.1	No	1911
Wichita Falls	TX	6 August	21	-105	16.5	1.1	Yes	1897
Sheridan	WY	1 August	37	-43	45.7	4.0	Yes	1907

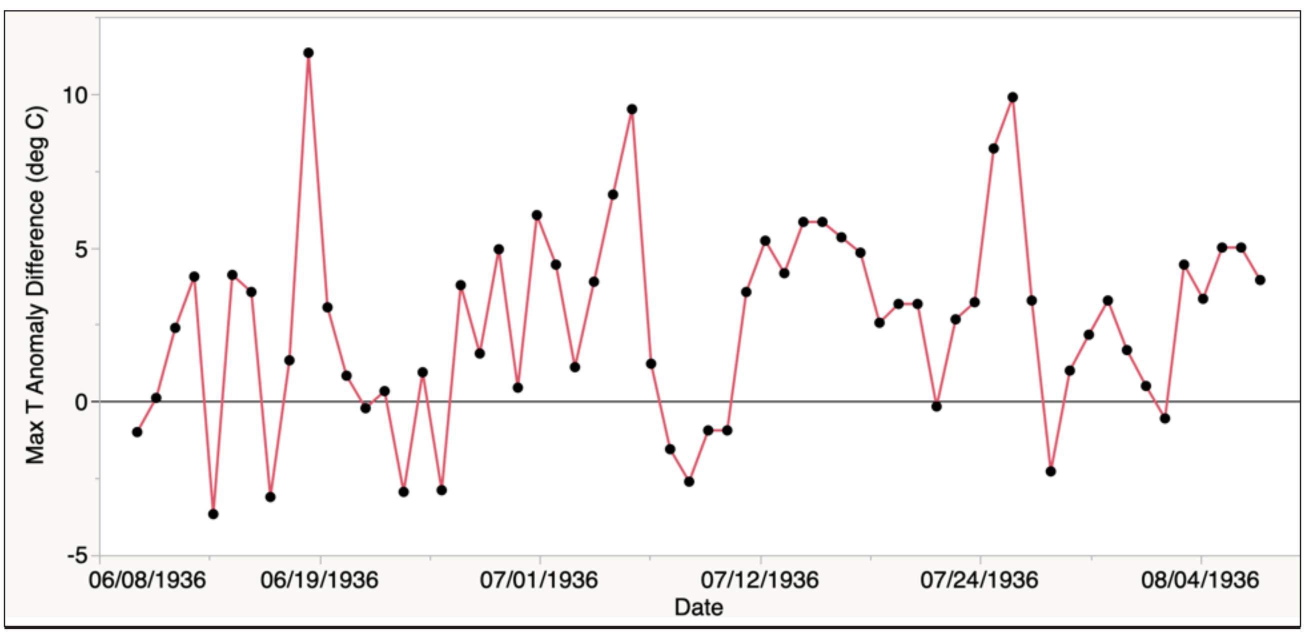

Figure 2. Difference in maximum temperature anomaly (°C) between Madison, WI and Milwaukee, WI during the period of drought development and intensification.

Table 2e. Period 5 locations, depicted by black circles. Refer to the caption from Table 2a for further detail.

City/Town	State	Peak Date	Total Prec	Prec Deficit	% of Normal	Temp Anomaly	Flash Drought	Start
Dubuque	IA	8 August	**34**	-181	15.9	3.1	Yes	1873
Sioux City	IA	4 August	**38**	-141	21.3	4.6	Yes	1889
Waterloo	IA	9 August	**28**	-215	11.7	2.8	Yes	1895
Chicago	IL	9 August	**24**	-162	13.0	-0.3	No	1871
Rockford*	IL	9 August	**24**	-187	11.2	1.4	Yes	1893
Alpeena	MI	8 August	46	-98	32.0	0.0	No	1916
Grand Rapids	MI	7 August	**28**	-158	15.3	1.2	Yes	1892
Marquette	MI	11 August	44	-97	31.4	0.9	Yes	1871
Saginaw	MI	19 July	55	-89	38.1	1.4	Yes	1912
Duluth	MN	10 August	**35**	-164	17.8	1.6	Yes	1871
Fairmont*	MN	10 August	**19**	-202	8.4	2.3	Yes	1887
Minneapolis	MN	10 August	**18**	-193	8.7	2.4	Yes	1871
Rochester*	MN	8 August	58	-171	25.4	1.3	Yes	1886
Norfolk	NE	8 August	**16**	-166	8.5	4.2	Yes	1893
North Platte	NE	8 August	31	-124	20.2	3.7	Yes	1874
Scottsbluff	NE	8 August	42	-62	40.0	2.9	Yes	1893
Allentown	PA	13 August	126	-102	55.4	0.6	No	1912
Sioux Falls*	SD	8 August	**39**	-130	23.2	4.4	Yes	1893
Eau Claire*	WI	10 August	**35**	-169	16.9	3.0	Yes	1893
Green Bay	WI	8 August	**37**	-143	20.7	1.5	Yes	1886
Madison	WI	8 August	**42**	-173	19.6	2.2	Yes	1869
Milwaukee	WI	8 August	***16***	-173	8.4	0.0	No	1871

southeastward expansion of intense heat occurred. On the 10th of July when the first heat wave was at its spatial peak, maximum temperatures exceeded 38°C (100°F) in at least 30 states east of the Rocky Mountains. This temperature threshold was reached almost everywhere from eastern Montana to upstate New York and Connecticut in the northern section of the U.S., down along the eastern seaboard from New York, NY to Richmond, VA, and into deep south cities like Atlanta, GA, Birmingham, AL, and Tupelo, MS. Many eastern U.S. locations set their all-time record high on or near 10 July 1936. This list includes: Avoca, PA (39°C), Baltimore, MD (42°C), Dover, DE (40°C), Lexington, KY (42°C), Martinsburg, WV (44°C), New York, NY (41°C), Rochester, NY (39°C), Syracuse, NY (39°C), Trenton, NJ (41°C), and Williamsport, PA (41°C). With the exception of the locations in purple, black, and gray dots shown in Fig. 3 (e.g., Nashville, TN, Dallas, TX, Memphis, TN) and Wichita Falls, TX, Marquette, MI, and Duluth, MN every one of these cities was at or in excess of 38°C on 10 July 1936.

At the peak of the first heat wave, most locations in the Midwest set their all-time records for maximum temperature with several cities recording temperatures in excess of 43°C (110°F) and in most cases were 6-8°C above the typical hottest temperature experienced in a given year. Figure 4 further shows that most Midwestern cities had at least 7 consecutive days with temperatures over 38°C, with a maximum of 14 to 15 consecutive days occurring from a large area from central Iowa into central Illinois. Perhaps the most impressive point with the area of maximum duration in the Midwest is that none of those locations average 38°C for their warmest temperature in a year.

Most locations in the Midwest also had their record number of days over 40°C and their hottest 5-day period on record, the latter of which was in the range of 8 to 10°C above the typical warmest 5-day period in a year. In Duluth, it was the only time over the climatological period of record that the city reached 38°C, which occurred three times in a week and on the 13th of July, the city had its all-time record high of 41°C. Eau Claire, WI had never had a maximum temperature of 43°C prior to 1936 since records began in 1893 and hasn't had one since. During the first heat wave a temperature in excess of 43°C was achieved at that location on three consecutive days during a stretch of 11 consecutive days over 38°C. Detroit had as many consecutive days (7) of temperatures exceeding 38°C during the first heat wave

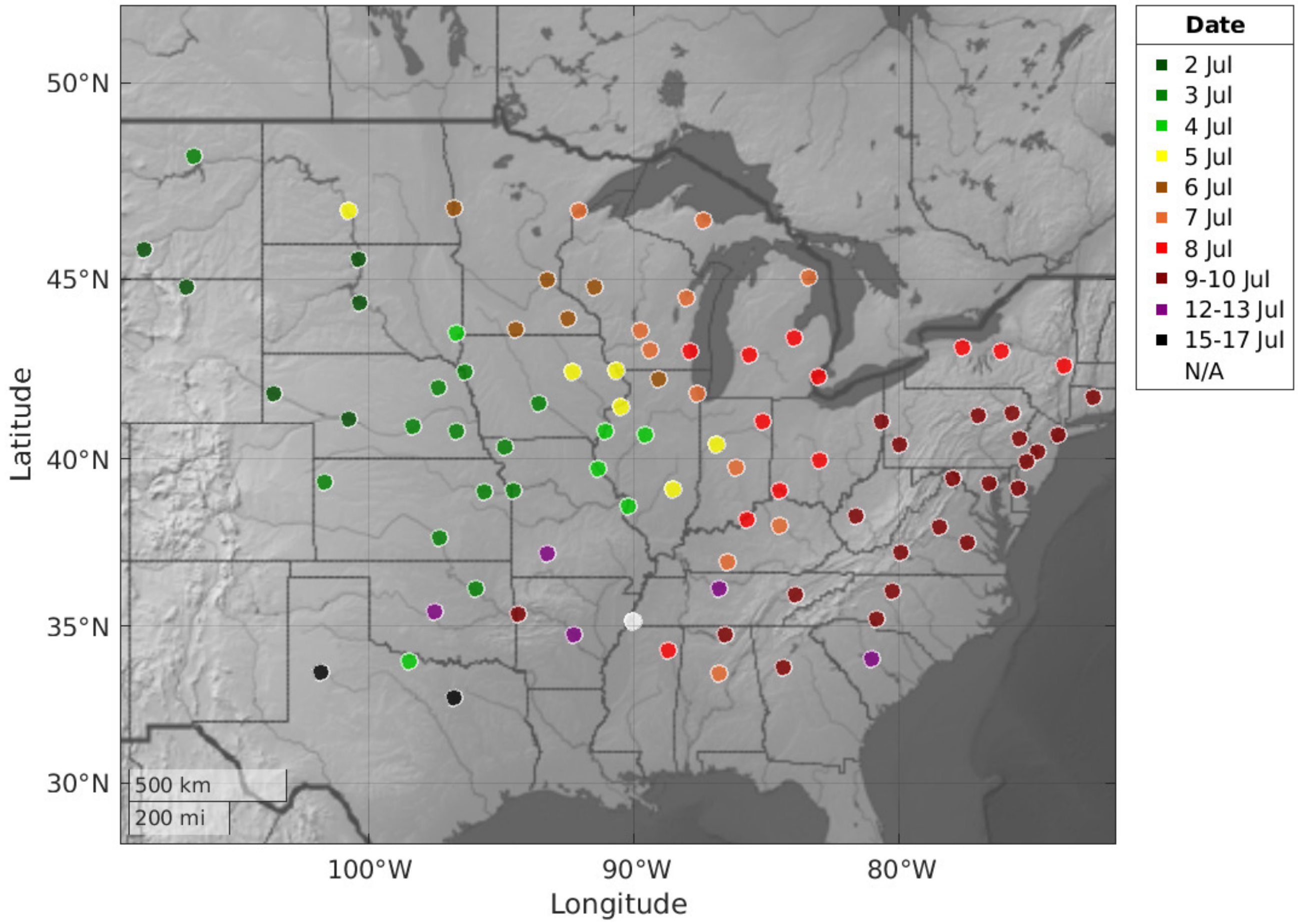

FIGURE 3. First date of temperatures at or in excess of 38°C after the 1st of July. Dates that correspond to the colored dots can be found in the legend on the upper right.

as their total number of days in recorded history (which began in 1874 in Detroit) at that temperature prior to the heat wave in 1936 (Root 1937). Not even in recent heat waves such as 1988 or 2012 (not shown) did Detroit have that many days of 38°C combined. Other highly impressive records set in the first heat wave include Minneapolis averaging nearly 35°C in a five-day stretch, Milwaukee not falling below 27°C for a week (including at night), and Green Bay having twice as many days over 38°C in a week (6 total) than they have recorded since.

The second main heat wave started in the first week of August and scorched the central and southern Plains and much of Missouri and western Arkansas before finally abating at the end of August. It should be noted that much of this area was on the periphery of the first heat wave and had multiple days of 38-40°C in July. From a climatological perspective, this heat wave was marginally less exceptional as temperatures in excess of 38°C in the south-central U.S. are not as unusual as in the upper and eastern Midwest during this period. Nevertheless, the duration and intensity of the August 1936 heat wave was impressive and only the heat waves of 1954 (Westcott 2011), 1980 (Karl and Quayle 1981), 2011 (Luo and Zhang 2012), and 2012 (Basara et al., 2019) are comparable in that region. The second heat wave did extend into northern Texas but most of the state of Texas was spared, even though it was seasonally hot and dry in August. Occasional northward expansions of extreme heat into Nebraska, northern Missouri, southern Iowa, and western Illinois also occurred during this second heat wave but the epicenter was considerably further south and west compared to the first heat wave.

c. Human, agricultural, and forest impacts

The heat waves in the summer in 1936 that followed the flash drought were the most lethal on record in the U.S., with over 5,000 direct heat-related deaths in the U.S. (Laiker 2013). Newspapers such as the St. Paul Daily News and the Detroit Free Press indicate that local hospitals received a sudden surge of people with heat related illnesses about three days into the heat wave. As expected with most heat waves, many of the deaths were attributed to the elderly, poor, and infirm (Hutchinson 2008). This sudden surge of heat related illnesses overwhelmed the ability of hospitals to effectively treat all patients, as the total number of deaths for July and August were 65% higher than 1935 (Hutchinson 2008). The Detroit Times reported that a "great

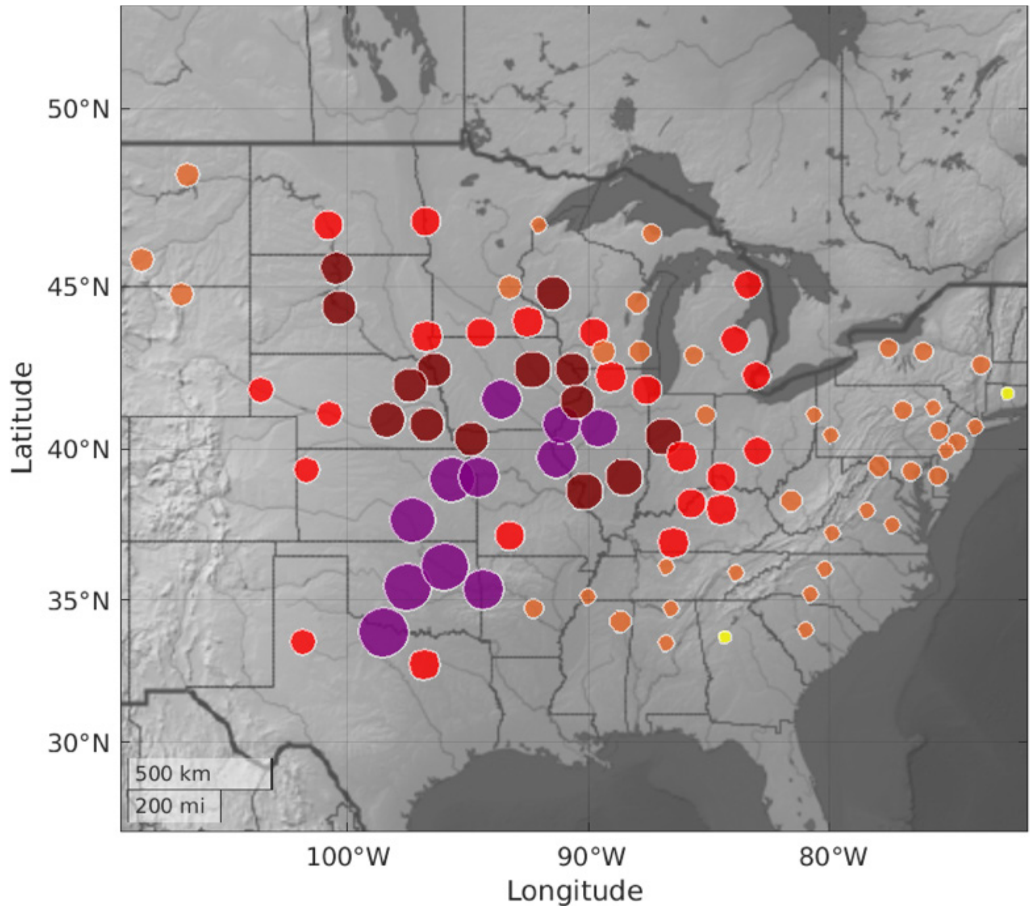

Figure 4. Consecutive days with maximum temperatures ≥ 38°C for various U.S. cities in the summer of 1936. The larger circles represent a larger number of consecutive days. Color coding as follows: Yellow (1 day), Orange (2 to 6 consecutive days), Red (7 to 9 consecutive days), Dark red (10 to 13 consecutive days), Purple (≥ 14 consecutive days).

city is dying of heat" and that the medical examiners ran out of white sheets to cover the bodies. Finally, there were also deaths in northern Minnesota when forest fires broke out in late July and August. The accumulated total of over 5,000 deaths from the heat waves is the largest weather-related mortality event since the Galveston hurricane in 1900 in the United States.

The flash drought and subsequent heat waves also had a devastating impact on crops, with the biggest impact being to corn and spring wheat in the north central U.S. (Fig. 5). Across the Dakotas and western Minnesota, the onset of the flash drought early in the season and the intense heat wave in July led to most crop reporting districts having yields that were between 30 and 80 percent below trend. The corn crop across the Corn Belt fared little better as the timing of the onset of the flash drought in May to early June severely limited the amount of root zone soil moisture available during the heat wave and the important reproductive stage. The values of 70 to 90 percentage points below trend were found over northern Missouri, western Iowa and eastern Nebraska where several additional days of extreme heat occurred after the first heat wave. Furthermore, according to NASS over half of the spring wheat and over a third of the corn crop was not even harvested in 1936, which likely led to further degradation of the agricultural landscape in the western Corn Belt (Peters et al., 2020). Soybean was not a major crop in this region at the time, so it was not analyzed for this study.

There were also numerous forest fires that summer. Wolff (1958) described the summer of 1936 as the worst in the heavily forested region of northeastern Minnesota. Between mid-July and late August, there were dozens of small fires and a few significant fires that burned thousands of acres and heavily affected the local timber industry and the Superior National Forest. The worst fire occurred in mid-August at Frost Lake when firefighters briefly lost control over it due to persistent high winds and communication failures.

Discussion

The flash drought began in the spring of 1936 in the southeastern U.S. Shortly thereafter a secondary area of flash drought developed in the northern Plains of the U.S. Over the course of the late spring and summer, flash drought spread from those areas into the entire Midwest, throughout most of the central and southern Great Plains, and into parts

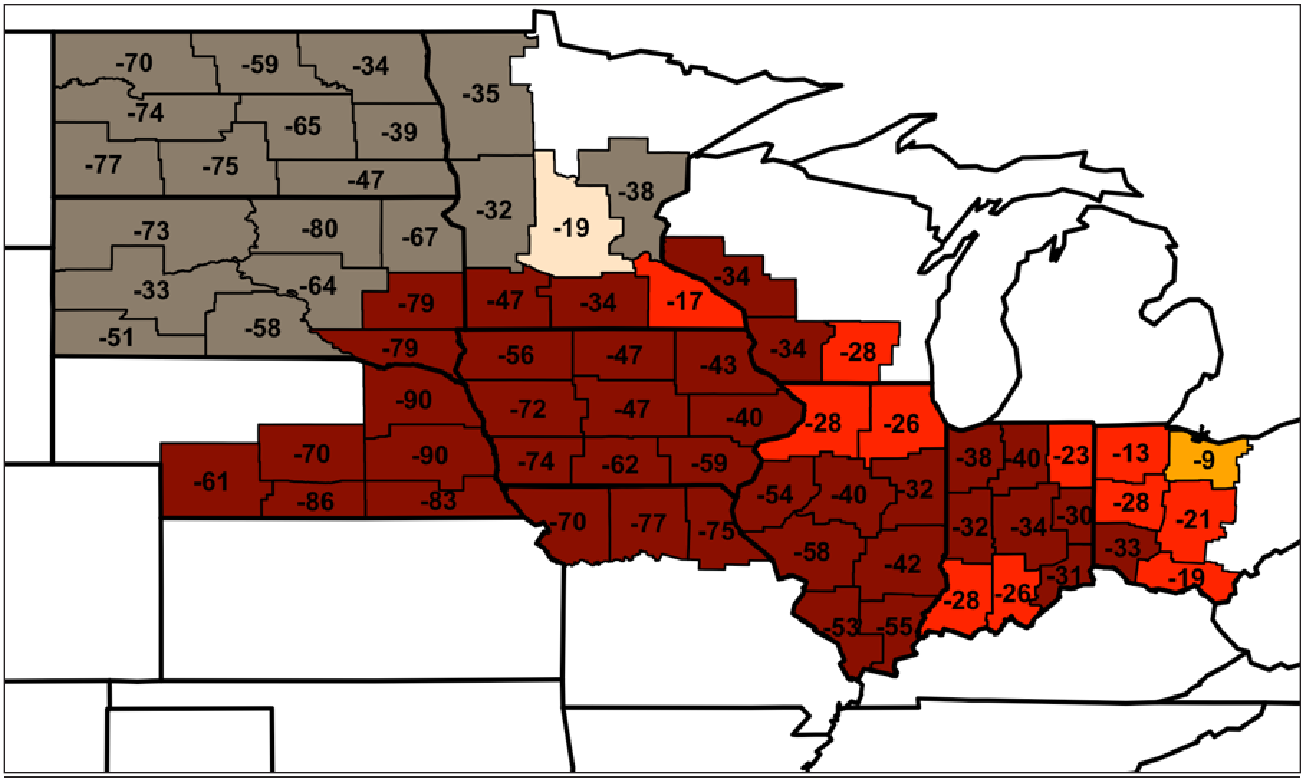

FIGURE 5. Percentage point deviation from trend for corn (shown in orange and red) and spring wheat (shown in gray) in 1936 based on a linear trend for the period 1931-1960.

of the eastern Great Lakes region (Fig. 1). The timing of the onset of this event was such that most locations were at or entering their climatological peak for precipitation. This led to 60-day precipitation deficits that generally exceeded 150 mm and in the most extreme cases, exceeded 200 mm. Most locations easily exceeded the precipitation and temperature criteria used to identify flash drought in this study (Tables 2a-e), with most locations receiving less than 25 percent of normal precipitation and temperatures more than 1.5°C above average over the 60-day period of peak accumulation deficits. Records for minimum precipitation over a 60-day period were set at locations in 25 U.S. states and 28 U.S. states had at least one station verify as having flash drought during this event. Our estimate is around 3 million square kilometers of the U.S. were affected by drought conditions at some point in the spring and summer of 1936.

Over 80 percent of the 90 locations used in the analysis had a flash drought based on the criteria set forth in the methodology. The ones that did not qualify as a flash drought were split between being too wet and too cool, albeit a few failed on both. Of the locations that did not verify as a flash drought because of 60-day temperatures that were below the threshold of 0.5°C above average, several are near the Great Lakes. This would possibly indicate onshore flow from the relatively cool Great Lakes that may be fairly dominant at times and act to moderate surface temperatures to limit flash drought development and excessive heat during the heatwave.

Perhaps the greatest consequence of the timing of the onset of the flash drought was the increased stress or desiccation of vegetation and depleted soil moisture over a very large area of the U.S. preceding the climatologically hottest time of the year. The extremely dry land surface likely helped maintain and possibly further build an intense mid-to-upper level anticyclone that further suppressed precipitation and allowed for prolonged stretches of extreme heat, first in the Midwest and then further south and west in Kansas, Oklahoma, and Missouri. The combination of the flash drought and heat wave led to an agricultural disaster in the north-central U.S., and the heat wave in the Midwest was the one of the deadliest weather-related events in U.S. history. A total of 13 U.S. states established all-time maximum temperature records during the summer of 1936 that still stand today (NOAA) and many central and eastern U.S. cities set records for duration of temperatures of 38°C or greater.

It is likely that teleconnections and land-atmosphere interactions were very important in driving this event, including the relative lack of vegetation during that era in the southern High Plains (Cook et al., 2009). Past studies noted that quasi-stationary Rossby wave trains that originate in the western Pacific can induce extreme anomalies over several weeks (Chen and Newman 1998; Moon et al., 2013; Lopez et al., 2019) and land-atmosphere feedbacks are critical in the propagation of flash drought (Basara et al., 2019). Flash drought development due to an upper-level ridge and land-atmosphere interactions were similarly seen in the 1988 flash drought in the central U.S. (Basara et al. 2020) and the 2010 flash drought in Russia (Christian et al., 2019).

Trenberth et al. (1988) showed that cold anomalies in the equatorial Pacific combined with warm anomalies between 10-20°N in the Pacific led to a northward displacement of the intertropical convergence zone, which in turn led to an anomalous Rossby wave train and the upper air circulation anomalies over the central and eastern U.S. partly responsible for the 1988 drought. But perhaps the most important similarity between 1936 and 1988 is the timing. In both years, there is evidence of flash drought beginning in April to early May, which may be crucial for allowing sufficient time for the land surface to reach a desiccated state over a large area entering the climatologically hottest part of summer.

The strongest possible similarity between 2010 in Russia and 1936 in the U.S. is that the heat waves from both cases were after a spring-onset flash drought and that there was a desiccated and spatially large agricultural landscape in the middle of a boreal summer that acted as a source region for sensible heat advection during the subsequent heat wave (Christian et al. 2020, Schumacher et al. 2019). The second possible similarity is that land-atmosphere feedbacks in the 1936 flash drought acted as described in Miralles et al. (2014) whereby heat generated during the day was stored in an abnormally deep atmospheric layer that in turn would re-enter the lower boundary layer during the day. This process would perpetuate a positive feedback cycle that led to record maximum temperatures over a very large area for days and weeks at a time.

Future Implications:

Perhaps the most important question from this study is the following: "Could a similarly extreme event happen again and what would be the associated impacts?" There are a few factors that might make an event with this extreme of impacts a bit less likely in the future. First, the flash drought occurred during the heart of the Dust Bowl era (Peters et al., 2020) and the dust aerosols likely further inhibited precipitation in the central U.S. (Cook et al., 2008; 2009). Second, crop genetics and the use of cover crops have enhanced plant water-use efficiency and soil water storage since the 1930's (Basche et al., 2016). Thus, it's possible a heat wave of that magnitude may not lead to proportionate losses. Third, irrigation in many parts of the Plains and Corn Belt would help offset some of the production losses and may also potentially reduce maximum temperatures in a future heat wave due to localized evaporative flux (Li et al., 2020). Fourth, there has been widespread adoption of air conditioning in the region which would limit human mortality.

However, with a changing climate enhancing natural variability, it appears plausible that a summer with more widespread extreme heat than in 1988, 2011, or 2012 will occur in the coming decades (Lau and Nath 2012, Russo et al., 2014; Chapman et al., 2019). It is possible that the lack of a widespread drought and heat wave of the magnitude of 1936 in the U.S. over recent decades is because the teleconnections and land-atmosphere interactions have not been fully aligned in space and time for a truly prolonged and spatially large event. While it is hoped that the impacts from a repeat of a 1936-like event would be less extreme, there are legitimate concerns about the cascading impacts in present day.

First, a repeat of the duration and spatial extent of temperatures 38-42°C would put a serious strain on the power grid because of persistent peak energy demand, so rolling blackouts would be a very real concern. Second, even with the adoption of air conditioning a long lasting and intense heat wave would still cause spikes in mortality, as in Chicago during a brief but very intense heat wave in 1995 (Kunkel et al., 1996; Kaiser et al., 2007) because not everyone has air conditioning or the ability to pay for it if available. Sailor et al. (2019) further adds over-reliance on air conditioning has led to a significant portion of the population being health compromised without it (as would happen in a blackout) and that upwards of 50 million people live in cities at high risk of a heat weather disaster.

Extreme flash drought will also impact the forest ecosystems present in this region of the U.S. Consequences of water and heat stress in forests include increased rates of tree mortality and regional forest die-off due to insect and disease outbreaks (Allen et al., 2010). Adaptive forest management strategies in the Great Lakes regions may help mitigate forest vulnerability to drought. For example, increasing the connectivity of forest reserves may facilitate tree species migration (Duveneck et al., 2014) while planting drought-tolerant species in managed forests could mitigate mortality rates during extreme drought (Muller et al., 2019). However, it remains uncertain as to how forests processes will be impacted by changing species compositions (Janowiak et al., 2011). Moreover, the widespread moisture deficits and increase temperatures are projected to increase the risk of wildfire in this region (Handler et al., 2014). Increased wildfire severity in the western U.S. has severely threatened water supplies and air quality in recent decades (Bladon et al., 2014). If high severity forest fires occur under extreme flash drought, there will likely be major threats to water for domestic use, agriculture, and industry in affected communities.

Finally, a flash drought and heat wave of that magnitude over the same area would affect the most productive locations for corn, soybean, and spring wheat. The significant reductions in crop yields could cause havoc in the commodity markets and cause real concern about supply, especially if the U.S. drought occurred in the same year as a drought in another major world breadbasket and/or the supply-to-use ratio was abnormally low going into the season. An example of the former is 1983 when the corn crop was affected by a drought in both the U.S. and South Africa (Anderson et al. 2019). Thus, even with the modernization and improvements since the flash drought of 1936, if this event were to repeat itself, there would still be large disruptions to daily lives and the economy. A humanitarian crisis would not be out of a question if many major cities had simultaneous blackouts on a day when temperatures were at record levels. Therefore, it is recommended that leaders in areas such as agriculture, business, government, and public health plan for potentially catastrophic impacts of flash drought on public and environmental health.

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