DROUGHT ASSESSMENT REPORT

The Causes, Predictability, and Historical Context of the 2017 U.S. Northern Great Plains Drought

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Office of Oceanic and Atmospheric Research
Earth System Research Laboratory, Physical Sciences Division, Boulder, Colorado 80305

and

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Preface

This assessment is a National Oceanic and Atmospheric Administration (NOAA) response to a request by the National Integrated Drought Information System (NIDIS) for an evaluation of the causes, predictability, and historical context of the 2017 United States Northern Great Plains drought. This assessment was led by a team of weather and climate experts from NOAA's Earth System Research Laboratory's Physical Sciences Division and its Cooperative Institute located at the University of Colorado Boulder.

This assessment spans a Northern Great Plains region of North Dakota, South Dakota and eastern Montana. It begins with an examination of the observed hydroclimatic conditions that led to the 2017 spring and summertime drought and places those conditions into historical context of 1895-present. Next, the role of anthropogenic climate change is assessed through its possible impact on 2017 precipitation, temperature, and soil moisture. Finally, the report examines whether the record-low summertime precipitation that led to the 2017 drought was predicted by modern initialized forecast systems used by drought forecasters.

Executive Summary

The 2017 spring and summer drought over Montana, North Dakota and South Dakota sparked wildfires and reduced agricultural production, resulting in economic losses that exceeded one billion dollars. Neither the drought's swift onset nor its severity were forecast. This assessment explores the causes, predictability and historical context of the 2017 drought over a Northern Great Plains region.

The rapid onset of drought in spring and summer of 2017 was mainly due to the failure of rains. Rains failed as a result of persistent high pressure that deflected moisture-bearing storms away from the region during what is normally the wettest time of the year. Periods of hot temperatures, high winds and low cloud cover also contributed in the drought's rapid onset.

Two main characteristics of the 2017 drought were record low precipitation and near-record rapidity of the soil moisture decline. Observed May-July precipitation over eastern Montana was the lowest on record and precipitation averaged over Montana, North Dakota and South Dakota was the third lowest on record dating back to at least 1895. Between mid-May and early June, eastern Montana estimates of soil moisture declined from the 80th to the 17th percentile, the third largest such decline for any three-week period over that area since at least 1916.

The longevity of the 2017 drought paled in comparison to many prior droughts over the Northern Great Plains. The 2017 drought ended just three months after it began, and was thus considerably shorter than other standout droughts that include the 'Dust Bowl' of the 1930s and epochs during the early 1920s, 1950s, early 1960s, late 1970s, and late 1980s.

Climate model simulations reveal that anthropogenic forcing made the occurrence of the observed 2017 drought intensity up to 20% more likely. The increase in drought likelihood during July from a past to the current climate in model simulations is due to long-term reductions in soil moisture, also referred to as aridification. Aridification is forced by increases in evapotranspiration associated with rising temperatures.

Below average May-July 2017 precipitation was not predicted in advance of the season. State-of-the-art seasonal prediction systems initialized in April 2017 forecast that the observed low Northern Great Plains precipitation was an unlikely occurrence.

Cumulative precipitation deficits were only predictable through sequences of up to three day forecasts. Sequences of longer than five day forecasts provided no indication that the seasonal evolution of precipitation would be different from average.

1. Background

The 2017 spring and summer drought over Montana, North Dakota and South Dakota has been judged to be the most devastating in recent memory[1] in this region. The drought sparked wildfires and compromised water resources, which led to reduced agricultural production, the destruction of property, and livestock selloffs[2]. According to NOAA's National Centers for Environmental Information, economic losses resulting from the 2017 Northern Great Plains drought exceeded one billion dollars (Fig. 1).

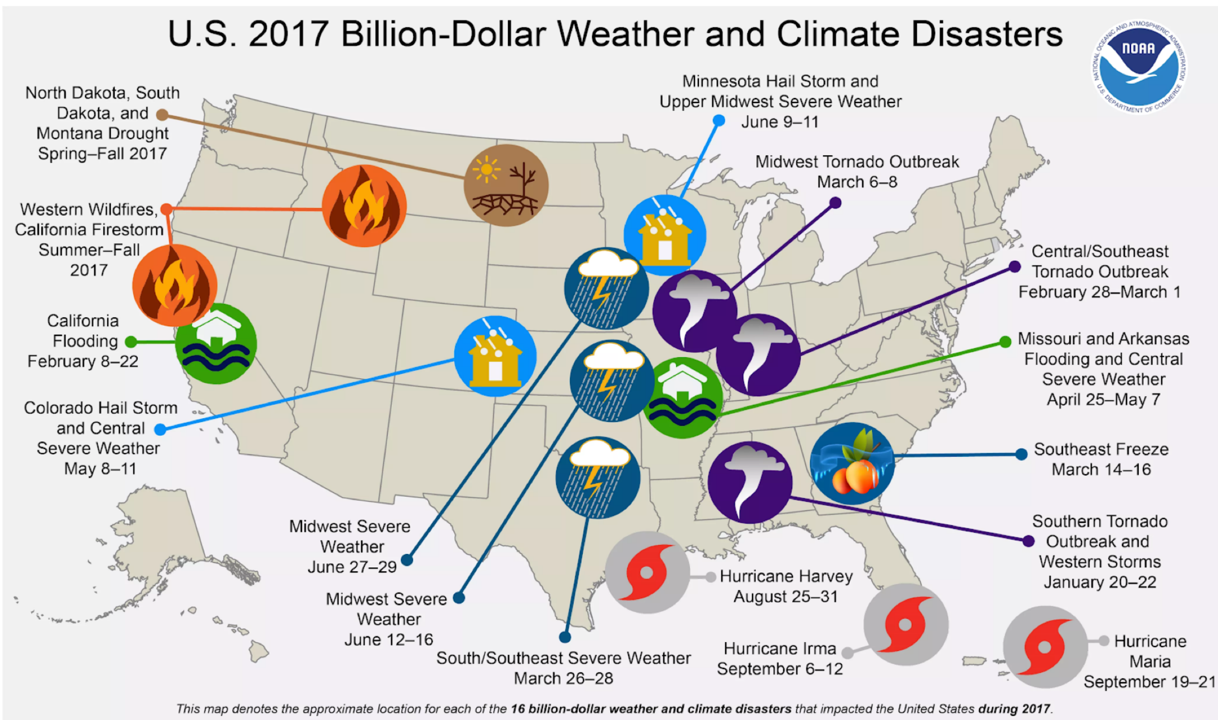

Figure 1: 2017 Billion Dollar Weather and Climate Disasters. Image courtesy of NOAA National Centers for Environmental Information. https://www.ncdc.noaa.gov/billions/

Within a Northern Great Plains region, defined herein as South Dakota, North Dakota, and Montana east of 109˚W longitude (Figs. 2a,b), resides a complex reservoir system and agriculture industry upon which the local and national economies rely. The reservoir system captures water for consumption, generates hydroelectric power, sustains ecosystems, and supports navigation to promote commerce. Agriculture is prolific throughout the Northern Great Plains, as staple crops such as spring wheat, winter wheat, corn, and barley are grown in abundance. Droughts are not uncommon stressors of the region's agricultural productivity. Though being irregular, infrequent and of various severity and duration, droughts share the attribute of deficient precipitation.

1 https://www.nytimes.com/2017/09/07/us/montana-wildfire-drought.html
2 https://www.usda.gov/media/blog/2017/10/03/million-acres-scorched-montana-wildfires

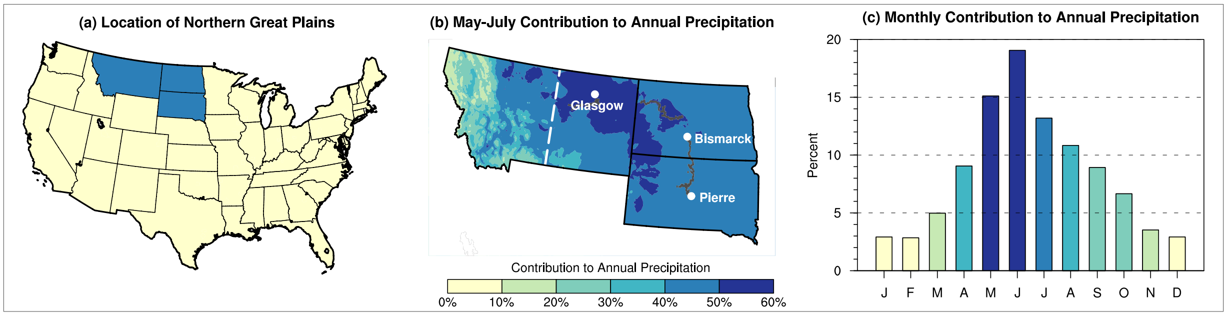

Figure 2: (a) Location of the three states – Montana, North Dakota, and South Dakota - that make up a Northern Great Plains region in this assessment. (b) Contribution of May-July precipitation to annual average precipitation. The area east of the 109˚W meridian (white dashed line) is taken here to be the Northern Great Plains region. (c) Monthly percent contribution to the annual average precipitation over the Northern Great Plains region.

The 2017 drought arrived suddenly during the rainy season (Otkin et al. 2018), which on average begins in spring, peaks during May-July, and ends during autumn (Figs. 2b,c). According to the U.S. Drought Monitor, the region was free of drought on May 16, 2017, with an isolated area of abnormal dryness straddling the border of North Dakota and South Dakota (Fig. 3). During the eight weeks leading up to July 25, moderate to exceptional drought conditions swiftly overspread the Northern Great Plains, with the most rapid drought intensification occurring over northeastern Montana and western North Dakota during June.

Neither the drought's onset nor its severity were forecast. Even as drought conditions emerged during mid-to-late May 2017 over Montana, North Dakota, and South Dakota (Fig. 3), further drought development was not anticipated within the following three months in NOAA's Seasonal

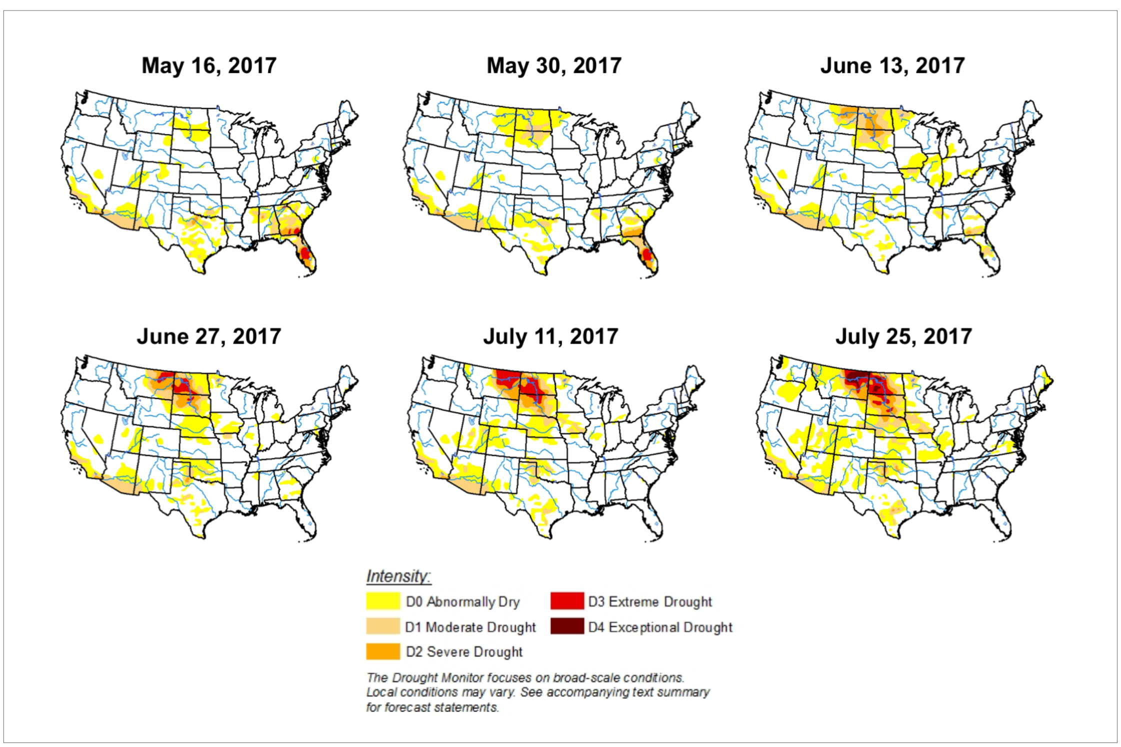

Figure 3: U.S. Drought Monitor. Images courtesy of the National Drought Mitigation Center, https://droughtmonitor.unl.edu/

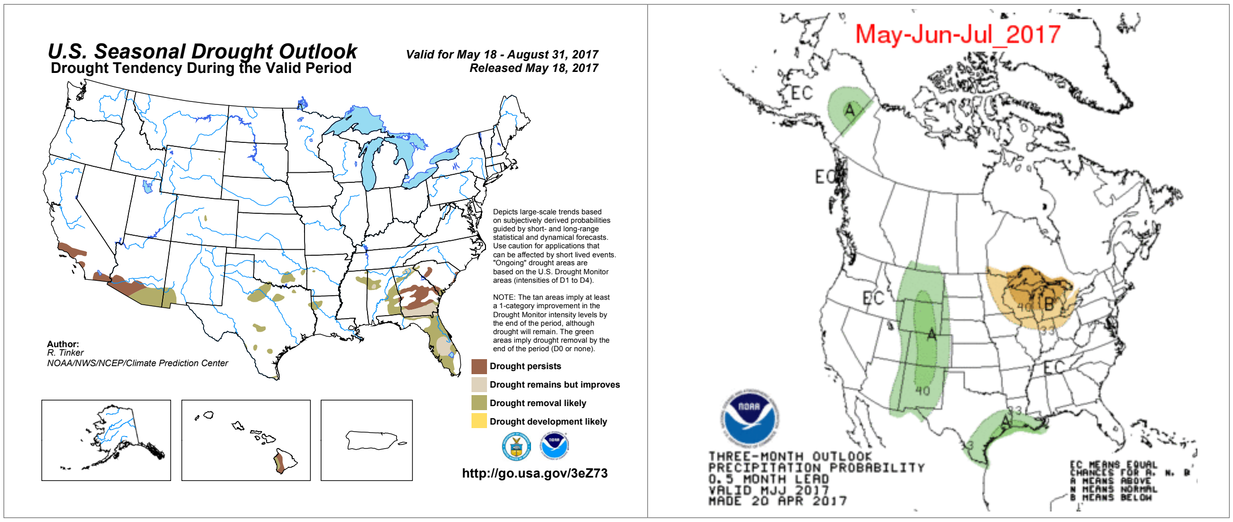

Figure 4: (left) NOAA's Seasonal Drought Outlook issued on May 18, 2017 for the period of May 18, 2017 to August 31, 2017. (right) NOAA's May-July precipitation forecast issued in April. Images courtesy of the Climate Prediction Center.

Drought Outlook issued on May 18, 2017 (Fig. 4 left). Drought development was not anticipated because a failed rainy season was not expected. Instead, the official NOAA forecast for May-July 2017 called for above-average precipitation in Montana and equal chances of below- or above-average precipitation elsewhere over the Northern Great Plains (Fig. 4 right).

2. Purpose of Assessment Report

The 2017 Northern Great Plains drought was costly and not well-forecast, prompting NIDIS to seek a better understanding of the characteristics and predictability of drought over this region. The NIDIS Reauthorization Act of 2014[3] mandates that NIDIS shall "provide an effective drought early warning system that – (A) collects and integrates information on the key indicators of drought and drought impacts in order to make usable, reliable, and timely forecasts of drought, including assessments of the severity of drought conditions and impacts; and (B) provides such information, forecasts, and assessments on both national and regional levels". To that end, the purposes of this scientific assessment of the 2017 Northern Great Plains drought are as follows:

1. Illustrate the evolution of the drought and determine its proximate causes
2. Place characteristics of the drought into historical context
3. Assess how anthropogenic influences contributed to the drought
4. Examine the drought's predictability characteristics by diagnosing the performance of prediction systems

3 https://www.gpo.gov/fdsys/pkg/PLAW-113publ86/pdf/PLAW-113publ86.pdf

This assessment of the 2017 Northern Great Plains drought is intended to aid policy makers and planners by better defining drought risk, assessing capabilities to predict drought, and quantifying how drought is changing in a warming world. A separate examination of the state, tribal, and federal response to the 2017 Northern Great Plains drought impacts appears in a companion assessment.

3. Chronology of the 2017 Drought

The lifecycle of the 2017 Northern Great Plains drought is illustrated in an effort to strengthen predictive understanding of droughts that rapidly emerge during spring and summer over the region. This chronology focuses on eastern Montana (Fig. A1), given the intensity (Fig. 2), rapid onset, and impacts[4] of the 2017 drought in that area, during the rainy season that extends from spring through autumn (Fig. 1). This drought chronology is described in terms of daily soil moisture, the key indicator of agricultural drought, and variables that help to control soil moisture: precipitation, maximum temperature, 10-m wind speed, and cloud cover (Fig. 5).

Given the favorable land surface state in April 2017, the sudden and severe drought onset over eastern Montana was all the more remarkable. Eastern Montana soil moisture ranked in the 90th percentile in April 2017, and frequent precipitation events during April 2017 sustained the moist land surface state throughout the month. Between May 18 and June 8, soil moisture decreased from the 80th to the 17th percentile due mainly to the failure of rains. During May and June of 2017, the typical storms that account for the normal wet season onset were deflected away from the region as persistent high pressure disrupted the normal weather patterns (Fig. 2).

Limited precipitation from May-July was the principal driver of the drought, though there were fluctuations in daily weather that was manifest in temperature, wind and cloud cover. The initial soil moisture decrease from the 80th to 40th percentile in late May occurred in the presence of below-average maximum temperatures, while the remaining decrease in soil moisture from the 40th to 20th percentile during the first week of June was associated with above-average maximum daily temperatures. Weather conditions during the latter half of June when soil moisture declined from the 20th to 10th percentile were windy with near-average maximum temperatures and cloudiness. By contrast, conditions during early July were warm with below-average winds and cloud cover.

The end of July and early August brought false hopes for drought recovery. The first signs of false hope occurred on July 11 and 12, when precipitation increased soil moisture into the 20th percentile. The second, and more significant, sign of false hope occurred during the first 11 days of August when three separate precipitation events increased soil moisture to, and sustained it in, the 40th percentile. Eastern Montana slipped back into intense drought during the latter half of August and the

4 https://www.nytimes.com/2017/09/07/us/montana-wildfire-drought.html

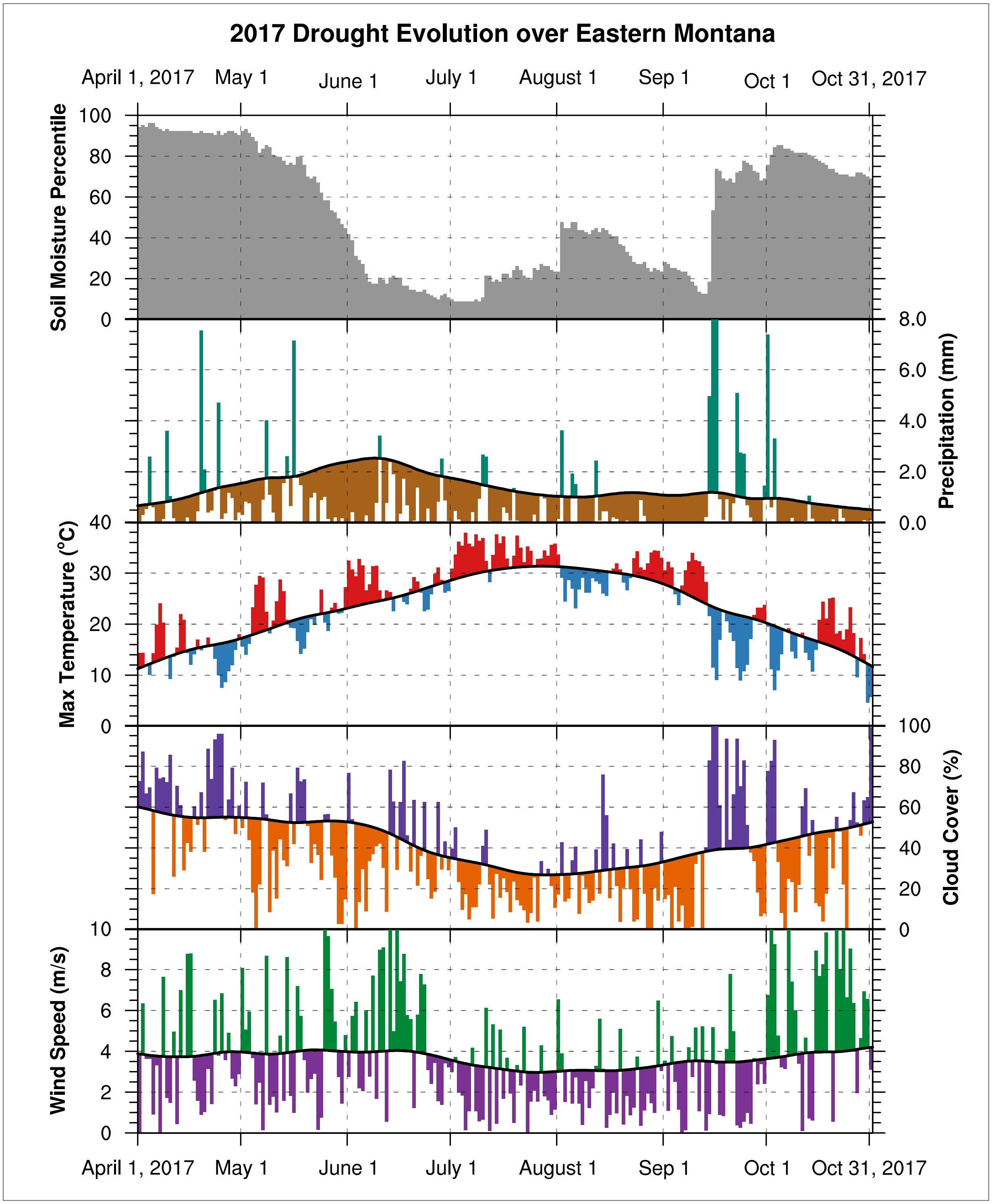

Figure 5: Eastern Montana daily soil moisture percentile and departures from average of precipitation (mm), maximum temperature (˚C), cloud cover (%), and wind speed (m/s) from April 1, 2017 to October 31, 2017.

first half of September 2017, as soil moisture decreased from the 40th percentile to the 10th percentile for the second time that summer. Precipitation was once again did not exceed the daily average during this four-week period. Anomalously clear skies, which increase incoming solar radiation, and above-average daytime maximum temperatures were also associated with drought intensification during that time.

Almost as suddenly as it developed, the 2017 drought over eastern Montana all but ended over the course of three days in mid-September. Soil moisture increased from the 20th to 70th percentile between September 14 and 16 due to soaking rains produced by a slow, southward-moving, low-pressure system from Alberta, Canada. The soaking rains fell primarily on September 15 and 16, the two wettest days during all of 2017. For the remainder of September 2017, storms continued to move through the region, resulting in well-above-average precipitation for the latter half of the month. The above-average precipitation over this three-week stretch increased soil moisture into the 80th percentile by early October.

4. The 2017 Drought in Historical Context

A more complete understanding the 2017 Northern Great Plains drought includes an awareness of how it compares against past droughts over the region. Notable aspects of the 2017 drought that are placed into historical context include: 1) the rapidity of the May and June soil moisture declines over eastern Montana, 2) the ranks of low precipitation and hot daily maximum temperatures in May-July, and 3) the expanse and longevity of low soil moisture over the Northern Great Plains.

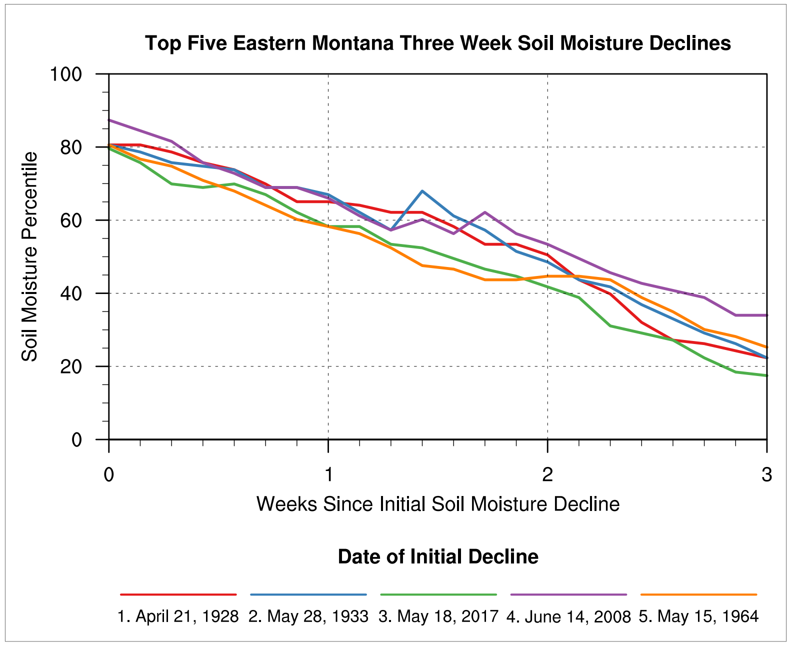

Figure 6: Top five eastern Montana three week soil moisture declines.

The rapidity of land surface drying in May and June 2017 was severe, but not unprecedented. Based on the land surface simulation, eastern Montana soil moisture between May 18 and June 8 of 2017 decreased from the 80th to the 17th percentile, the third largest such decline for any three-week period over the region since at least 1916 (Fig. 6). Within the last century alone, four other similar droughts developed suddenly during Spring: 1928, 1933, 1964 and 2008. These rapid soil moisture declines also appear to have a distinct seasonality - the top five events and the remaining events that fill out the top 10 all occur during April, May, and June. The seasonality of the rapid declines aligns with the rainy season, which if it fails, leads to rapid land surface drying.

For the May-July average as a whole, precipitation and daily maximum temperatures rank as among the driest and hottest over portions of Montana dating back to at least 1895 (Fig. 7). The historically dry and hot conditions were not confined to eastern Montana, however. Precipitation over much of western North Dakota and areas of South Dakota ranked within the driest five May-July seasons. Daily maximum temperatures during May-July were in the 90th percentile over western North Dakota and South Dakota, although temperatures failed to reach top-five status over a large portion of this area.

While of record proportions over eastern Montana, the spatial reach of the 2017 drought paled in comparison to other noteworthy droughts, for example 1936 (Fig. 8). Here, intensity is determined by the percent of the Northern Great Plains covered by soil moisture percentile ranges of 0-2, 3-5, 6-10, 11-20, and 21-30, which approximately align with drought categories of of the U.S. Drought Monitor[5]. At the height of the 2017 drought in July, soil moisture across 65% of the region was in

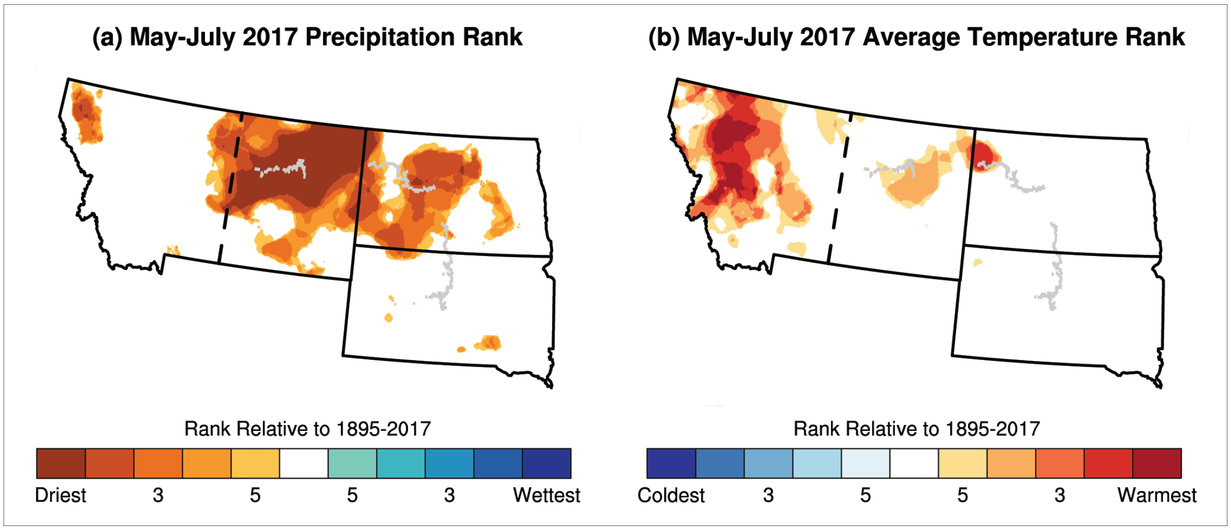

Figure 7: May-July 2017 precipitation and maximum daily temperature ranks.

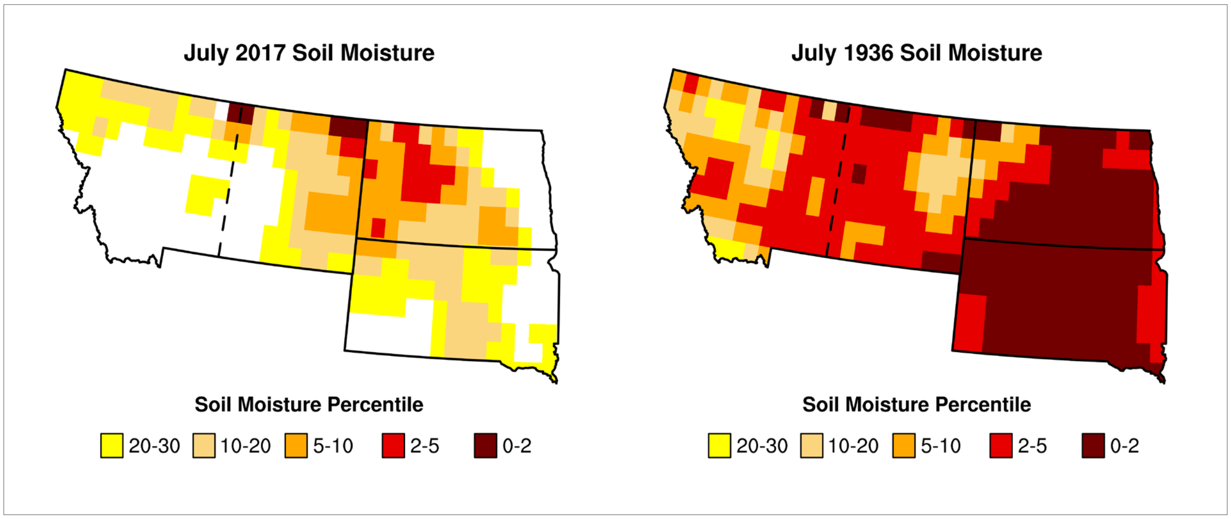

Figure 8: Soil moisture percentiles for July 2017 and July 1936.

5 https://droughtmonitor.unl.edu/AboutUSDM/AbouttheData/DroughtClassification.aspx

the lower 20th percentile, with much smaller areas falling into the lower 10th and 5th percentiles. By contrast, near the height of the iconic 'Dust Bowl' in July 1936, 100% of the Northern Great Plains soil moisture was in the lower 20th percentile, with 60% of that area falling into the lower 2nd percentile. Other July months with greater low soil moisture coverage than 2017 over the Northern Great Plains include 1926, 1934, 1937, 1953, 1959, 1961, and 1988 (Fig. 9). Note that these cases are different from the rapid onset cases highlighted in Fig. 6.

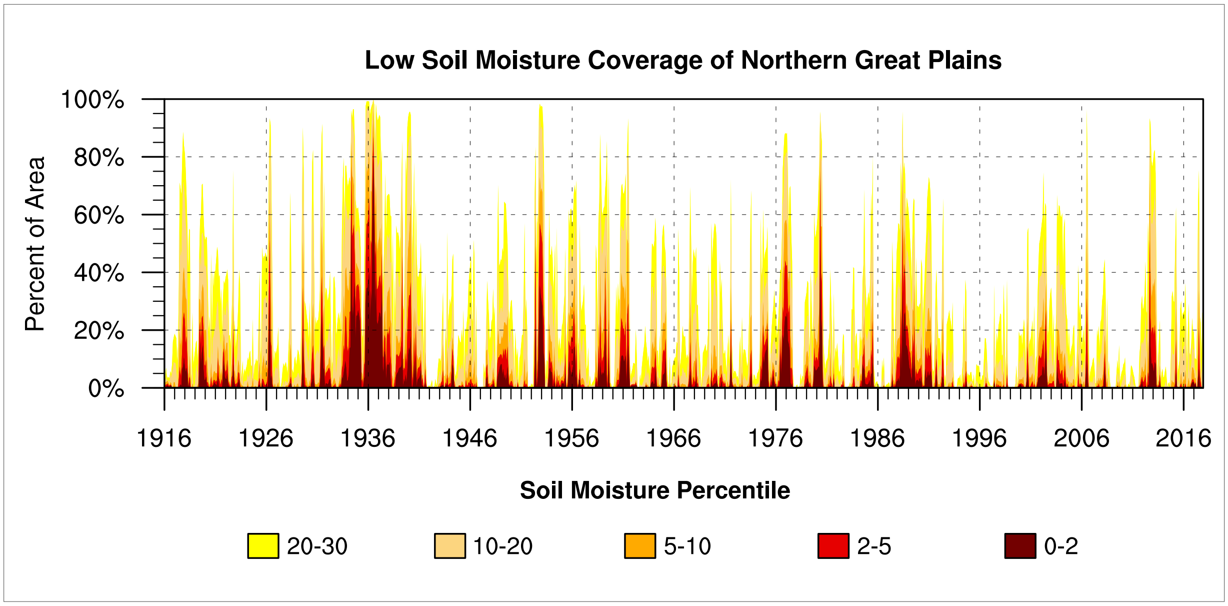

Figure 9: Monthly percent of Northern Great Plains covered by soil moisture percentiles.

The longevity of the 2017 drought also pales in comparison to many noteworthy droughts over the Northern Great Plains. The 2017 drought lasted just three months (Fig. 5), and is thus hardly noticeable on time series that graphs the percent of the region covered by low soil moisture (Fig. 9). By contrast, there were multiple instances during which the Northern Great Plains region was almost entirely covered by very low soil moisture percentiles for consecutive years. These standout droughts include the 'Dust Bowl' of the 1930s and epochs during the early 1920s, 1950s, early 1960s, late 1970s, and late 1980s.

From a perspective spanning the entire instrumental period, drought activity over the Northern Great Plains has been relatively quiescent since the last of the region's protracted droughts in the late 1980s (Fig. 9). Aside from the short droughts of 2000-2003, 2006, 2013, and 2017, the Northern Great Plains has been largely free of extended periods of widespread very low soil moisture percentiles.

The relatively quiescent drought activity since the late 1980s was caused by abundant precipitation, as the 30-year period ending in 2017 was the wettest such time span dating back to at least 1895 (Fig. 10a). Droughts that did occur were short-lived as adequate precipitation during the following

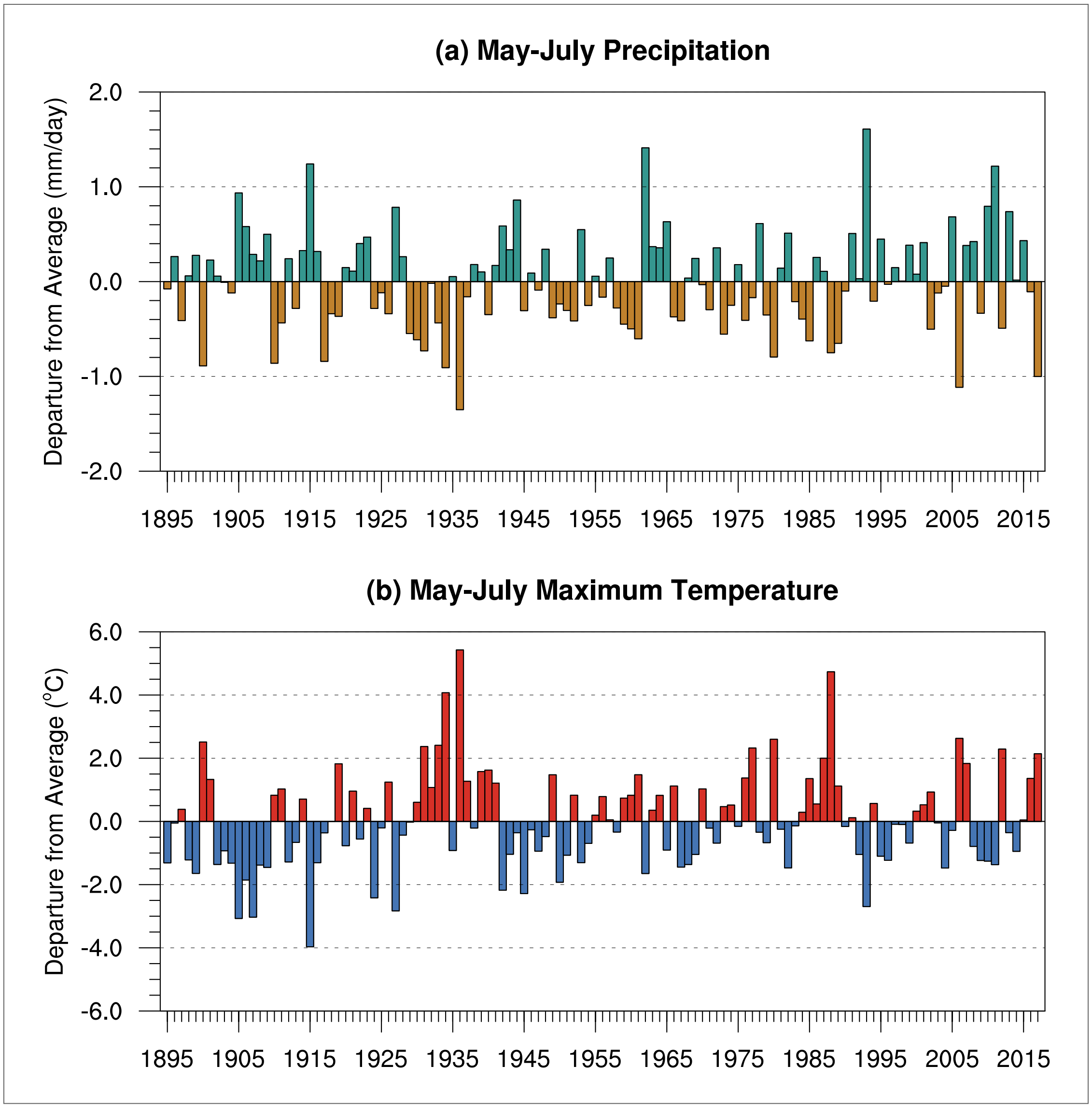

Figure 10: Northern Great Plains (a) precipitation and (b) maximum temperature time series for 1895-2017.

seasons and years quickly replenished low soil moisture. Those droughts include 2006 and 2017, which were two of the three driest May-July seasons over the Northern Great Plains dating back to at least 1895.

5. Climate Change Effects on the 2017 Drought

An outstanding feature of the Northern Great Plains drought time series is a decline in the intensity and the duration of low soil moisture (Fig. 9). Is this a symptom of climate change? Earth system model simulations spanning 1920-2016 are used to evaluate whether anthropogenically-forced changes to the climate alter the likelihood of Northern Great Plains droughts with intensity comparable to 2017.

This evaluation is performed by comparing characteristics of drought in a past climate to those in a current climate of a large (40 member) ensemble of climate model simulations. A comparison between drought characteristics in past versus climate climates, defined by the time periods of 1920-1949 and 1987-2016, respectively, is used to isolate the effect of changes brought about mostly by humans (Bindoff et al. 2013). Drought characteristics are described in terms changes to July soil moisture and May-July precipitation, evapotranspiration and 2-m air temperature over the region. The classes of drought intensity based on soil moisture percentiles relative to the past climate that are considered are 0-2, 3-5, 6-10, 11-20, and 21-30. This examination is based on Hoell et al. 2018.

The model simulations indicate that anthropogenic effects increase the likelihood of droughts with intensity comparable to 2017 (Fig. 11). Droughts over the Northern Great Plains with soil moisture in the 10-20th percentiles, such as during July 2017, are found to occur 20% more often in current than past climates. The likelihood of more intense droughts are also found to increase under anthropogenic forcing. July droughts over the Northern Great Plains in the 5-10th and 2-5th soil moisture percentiles occur 50% and 100% more often in the current than in the past climates, respectively.

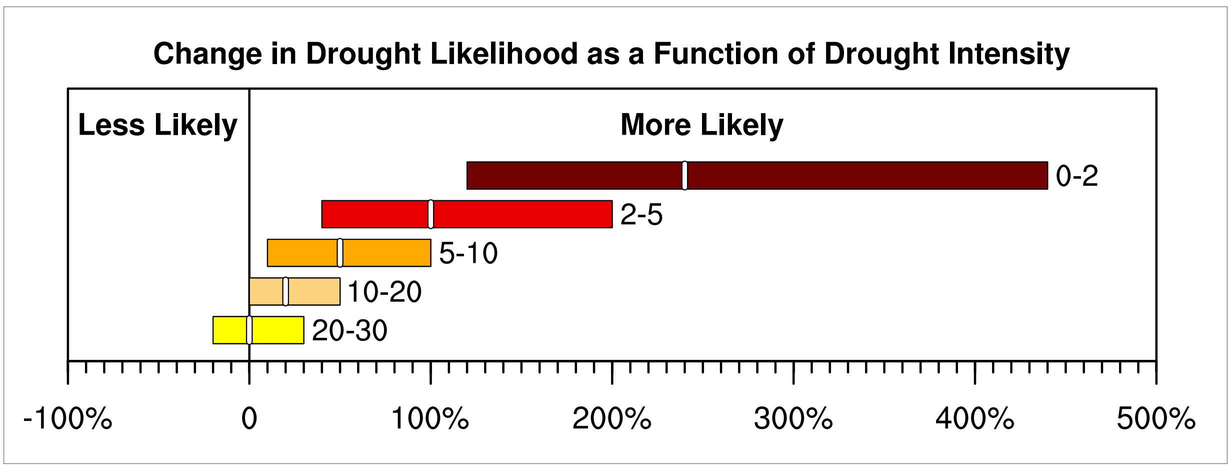

Figure 11: Change in the likelihood of July soil moisture percentiles (white line) and the 95% confidence interval (bar) between the current and past climates over the Northern Great Plains. Soil moisture percentiles are calculated relative to the past climate.

Over the Northern Great Plains, the increase in drought likelihood during July from past to current climates of the model simulations is due to long-term reductions in soil moisture, also referred to as aridification. The simulations exhibit statistically significant (p<0.001) declines in July soil moisture over the region, the magnitude of which corresponds to 0.5 standard deviations of the interannual variability (Fig. 12a).

The model simulations reveal a relationship between aridification of the Northern Great Plains during July and May-July increases in evapotranspiration (Fig. 12c) associated with rising temperatures (Fig. 12d). The model simulations indicate a slight, but significant, increase (at p<0.04) in the region's May-July precipitation (Fig. 12b). The overall declines in soil moisture in the ensemble model

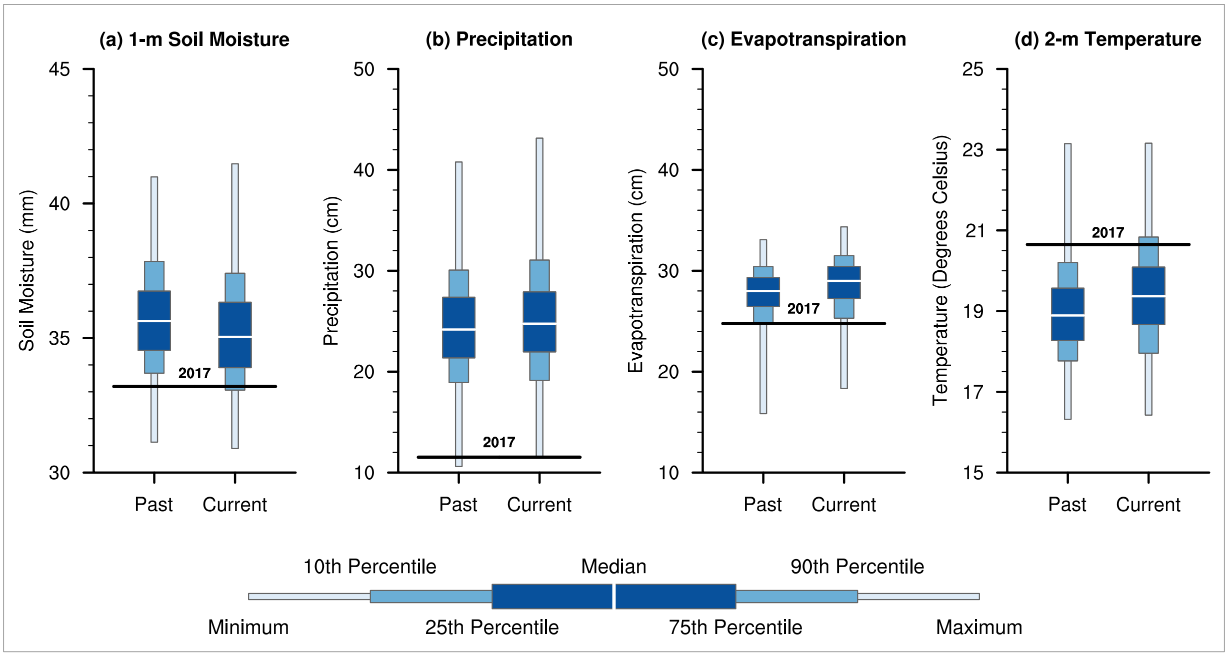

Figure 12: Boxplots of 1-m soil moisture during July and precipitation, evapotranspiration, 2-m air temperature during May-July averaged over the Northern Great Plains in the past and current climates. Box plots for each variable during past and current climates are constructed from 1200 samples, 30 years across the 40 ensemble members. Black lines denote the observed percentile rank from the observed land surface model simulation during 2017 at the value corresponding to the same percentile rank in the earth system model simulations of the current climate.

simulations thus indicate that anthropogenically-forced aridification is not caused by a decline in precipitation, but rather by 0.5-0.6˚C increases in May-July surface air temperature. Previous studies show that much of the observed rise in temperatures over North America during the last century is attributable to human influences (e.g. Knutson et al. 2013). These findings are thus consistent with a body of literature indicating anthropogenic forcing to decrease soil moisture and increase the risk of agricultural drought over much of North America (e.g. Hoerling et al. 2008, Sheffield and Wood 2011).

In this sense, human-induced warming intensified the severity of the 2017 Northern Great Plains drought; however, the drought's principal driver was an extreme deficit in rainfall, a feature not strongly related to human-induced change. As shown in Fig. 13, the likelihood of drought for various severities of rainfall increases as a consequence of gradual aridification. Note, however, that when May-July precipitation falls in the 0-2nd percentile, as was the case in 2017, the likelihood of July drought does not change appreciably between the current and past climates. A drought event having the meteorological properties of severe rainfall deficit such as occurred in 2017 was thus a rare event whose odds were not made appreciably greater by the effects of climate change.

Precipitation variability continues to be the principal driver of year-to-year variability in summertime soil moisture, and thus agricultural drought. The correlation and slopes of the linear regression between precipitation and soil moisture remain the same between the current and past climates (Fig. 14), meaning that the same increment of May-July precipitation is related with the same increment

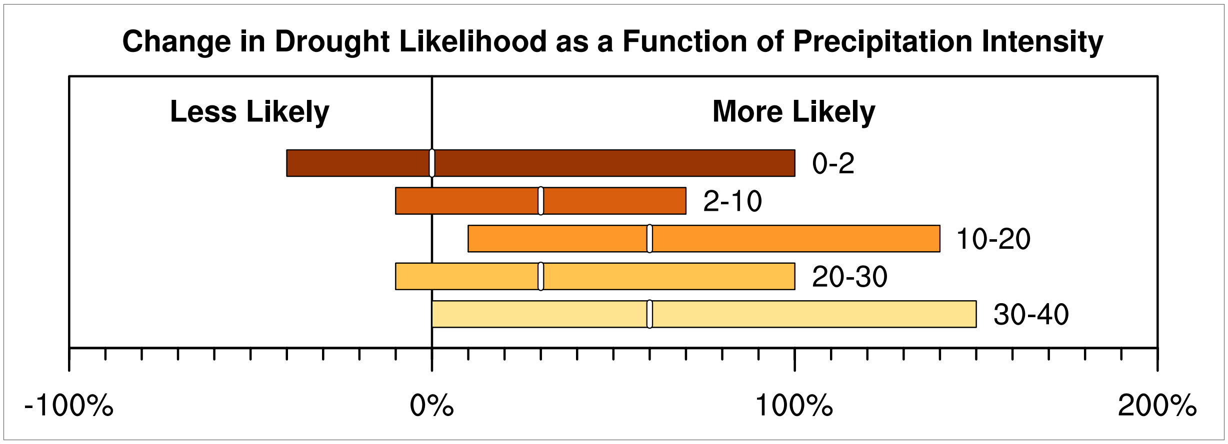

Figure 13: Change in the likelihood of July soil moisture falling below the 20th percentile between current and past climates as a function of May-July precipitation percentiles (white line) and the 95% confidence interval (bar). Precipitation and soil moisture percentiles are calculated relative to the past climate.

of July soil moisture. The effect of climate change is revealed by the change in the y-intercept of the regression line being less in the current climate than the past climate, consistent with aridification. Note that this increment of change (~1mm) is small compared to the magnitude of soil moisture variability driven by year-to-year rainfall variations.

Given the paramount effect of precipitation on Northern Great Plains drought, it is no surprise that the pluvial conditions during the 30-year period ending in 2017 have staved off sustained drought

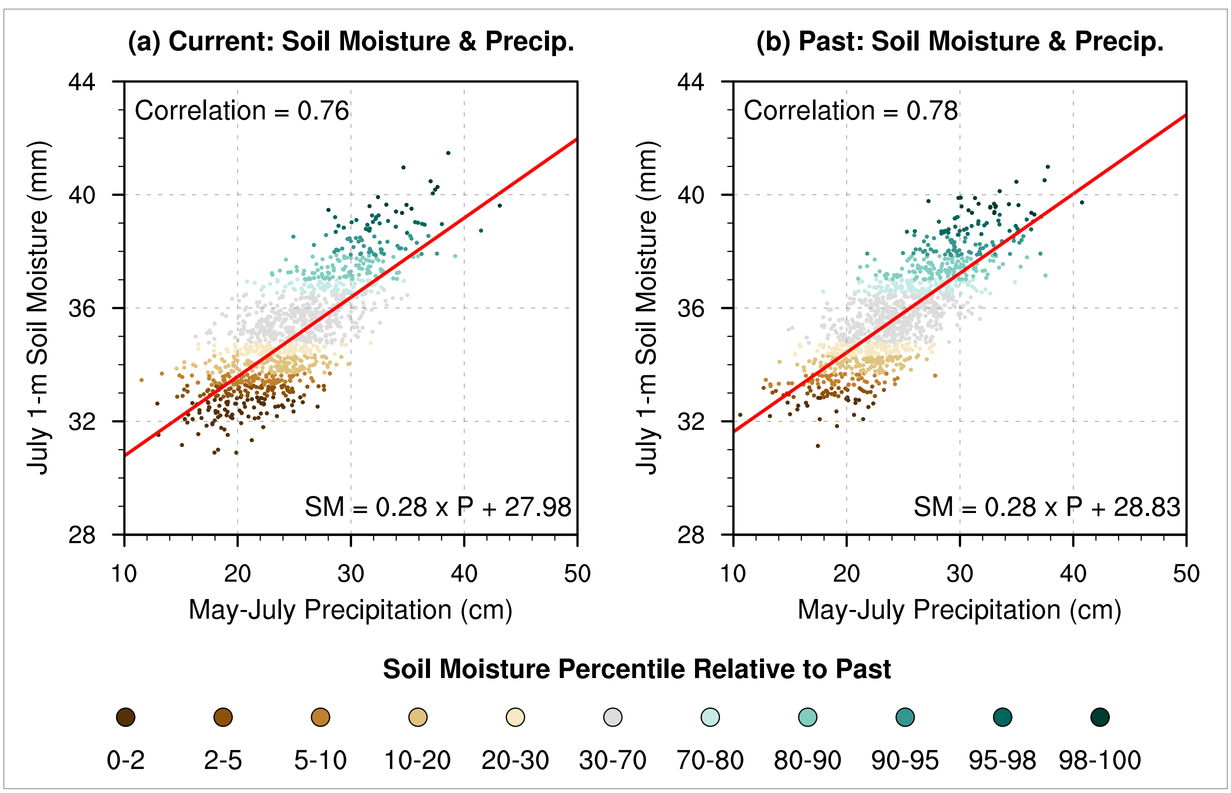

Figure 14: Scatter diagrams of July 1-m soil moisture and May-July precipitation for the past and current climates averaged over the Northern Great Plains. The linear regression of the scatter is shown by the red line. Soil moisture percentiles are calculated relative to the past climate.

despite human-caused increases in temperature. The model simulations reveal a wide range of possible precipitation possibilities for the Northern Great Plains, so although not of a high probability, drought-preventing pluvial conditions since the late 1980s fall within the range of possible outcomes as indicated by Figs. 12 and 14.

6. Predictability of the 2017 Drought

The lead times at which initialized prediction systems forecast the record-low May-July precipitation that principally caused the 2017 Northern Great Plains drought are examined. The purposes of this examination are twofold: 1) to understand why the drought was not forecast during 2017 and 2) to provide insights into the prospects of early warning of future droughts during May-July.

The ability of models to forecast low May-July 2017 Northern Great Plains precipitation in advance of the season is evaluated using predictions from the North American Multimodel Ensemble (NMME) and the European Centre for Medium-Range Weather Forecasts (ECMWF) SEAS5 system. Those same forecast models are also used to evaluate the regional May-July precipitation predictability dating back to the 1980s. The ability of models to forecast the temporal evolution of the regional precipitation during May-July 2017 is examined using the Global Ensemble Forecast System (GEFS), 11 daily predictions from the Global Forecast System (GFS).

Both the NMME and ECMWF prediction systems forecast that May-July 2017 precipitation would more likely be above average (Fig. 15). These predictions help to explain the lack of drought development forecast by NOAA's Seasonal Drought Outlook issued in May 2017 and the above-average

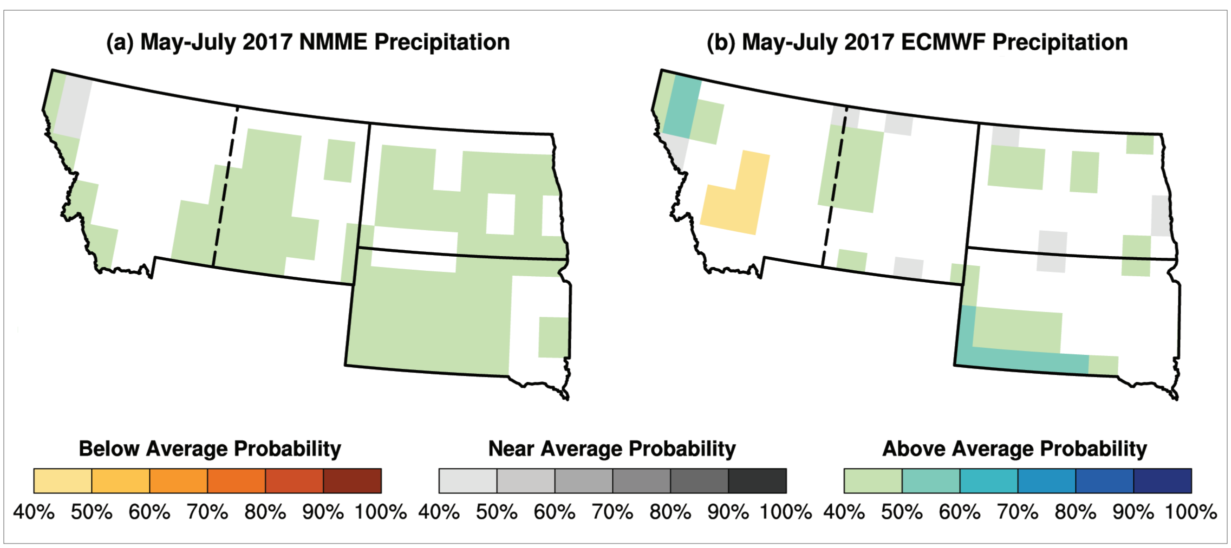

Figure 15: Probability of below, near, and above-average May-July 2017 precipitation from NMME and ECMWF forecast systems made in April 2017. White shading indicates that neither below, near or above-average precipitation probability exceeds 40%.

May-July 2017 precipitation forecast also made by NOAA.[6] It is important to note that while the prediction systems forecast an increased likelihood of above average precipitation, each system still forecast non-zero odds of the below average rainfall.

Given the poor precipitation forecast skill during May-July 2017 over the Northern Great Plains, it is natural to probe the overall predictability during May-July over the region. This examination is performed using the signal-to-noise ratio of retrospective forecasts in the NMME and ECMWF prediction systems (Fig. 16). The signal is defined as the average precipitation across the ensemble of forecasts and represents the "expected" precipitation (Fig. 16 black line). The noise is defined as the standard deviation across the individual forecasts and represents the range of possible outcomes (Fig. 16 dark blue shading). Larger signal-to-noise ratios suggest greater levels of potential predictability.

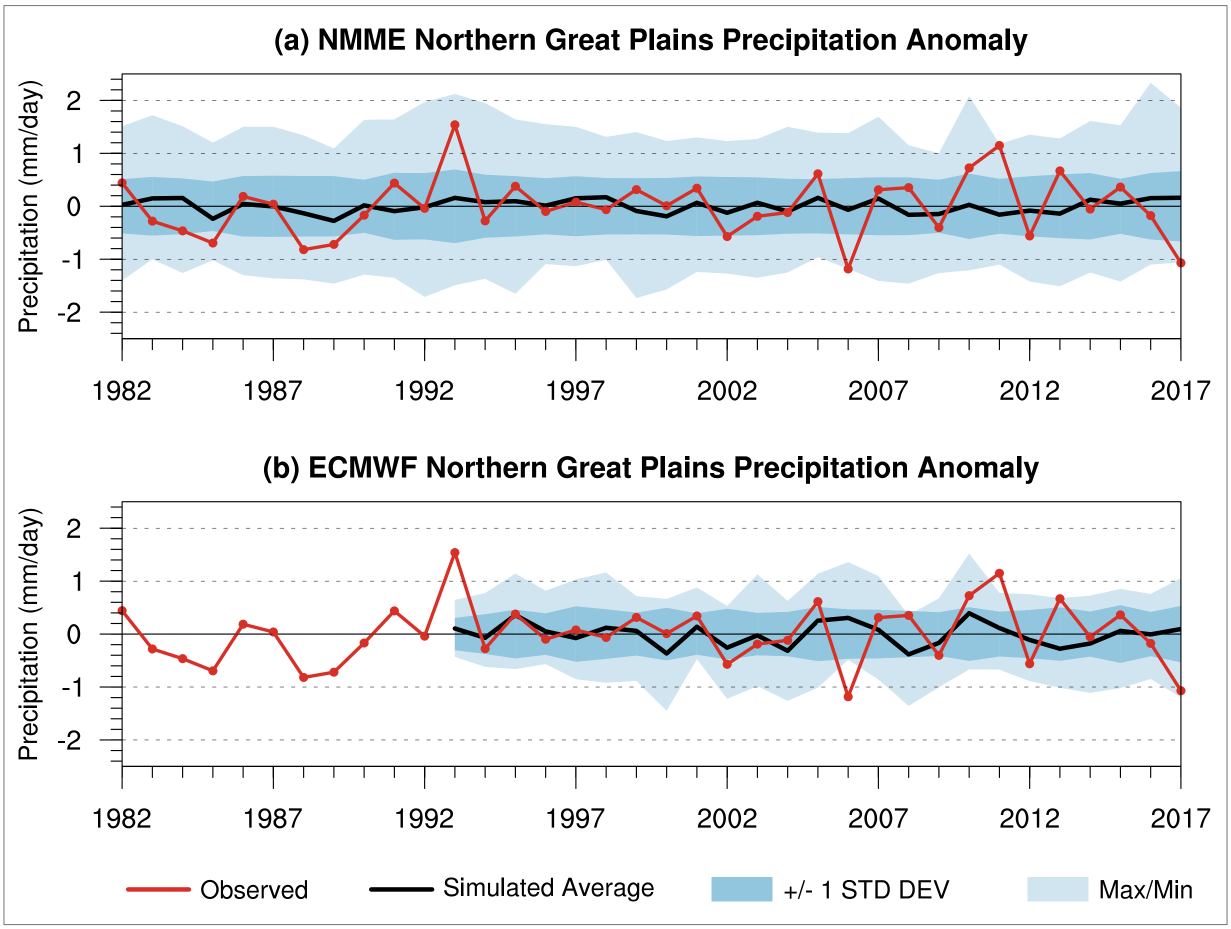

Figure 16: May-July precipitation forecasts from NMME and ECMWF over the Northern Great Plains made in April of that year in units of mm/day. The average precipitation forecast for each prediction system (also known as the signal) is shown in black. The standard deviation of all forecasts from each system (also known as the noise) is shown in dark blue shading. The maximum and minimum forecast from each system is shown in light blue shading. Observed precipitation is shown in red.

6 Probabilistic precipitation forecasts are obtained by calculating the percentage of individual forecasts from NMME and ECMWF that fall below, near, or above average, following the convention of operational centers like NOAA's Climate Prediction Center (e.g. Fig. 3). Below, near, and above average are defined by the lower, middle, and upper thirds of a historical precipitation distribution, respectively.

The magnitude of the Northern Great Plains May-July precipitation forecast signal does not exceed that of the noise in either NMME or ECMWF forecast systems dating back to the 1980s (Fig. 16), which suggest low May-July precipitation predictability over the region. Note that the magnitude of ensemble mean anomalies is always smaller than observed anomalies for the more extreme summers. The spread (noise) of the individual forecasts during a given year in each ensemble is constantly high and helps to explain why precipitation over the region is difficult to predict with skill. By contrast, the mean forecast (signal) hardly deviates from 0 in NMME and only begins to approach the magnitude of the noise in ECMWF during a handful of years since 1993. Slight differences between NMME and ECMWF forecasts, likely rooted in the way each ensemble is constructed, do not alter the interpretation of the results. These differences include the magnitude of the signal, where ECMWF is usually greater, and the magnitude of the noise, where NMME is usually greater. NMME is constructed using 99 forecasts from many different models while ECMWF is constructed from 50 forecasts from the same model.

Given that low May-July 2017 precipitation over the Northern Great Plains was not well forecast in advance of the season, the time scales at which precipitation deficits could be forecast are probed. GEFS is used to examine whether the evolution of the seasonal precipitation deficits could be

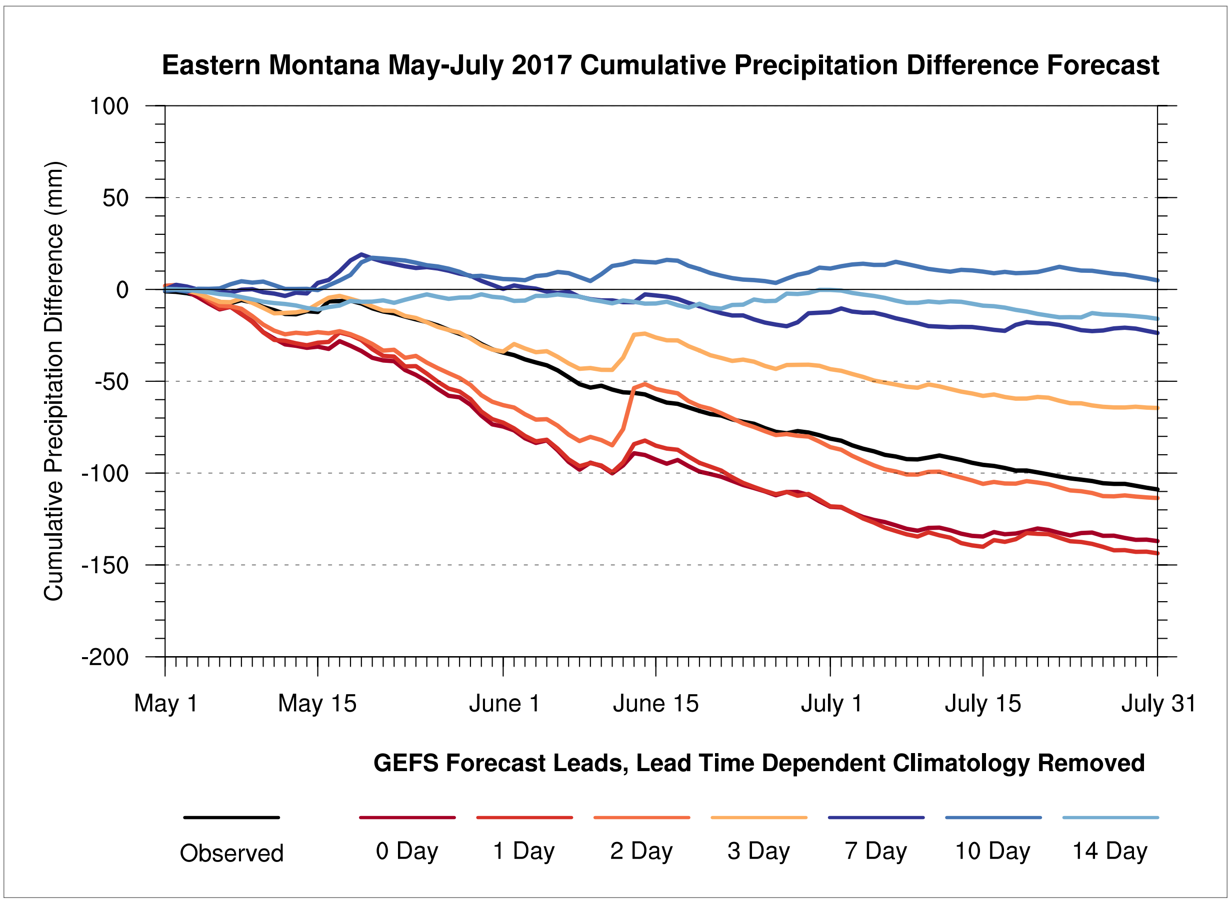

Figure 17: Eastern Montana May-July 2017 cumulative precipitation difference from average. Observed precipitation derived from 16 monitoring stations is shown in black while GEFS forecasts for given lead times are shown in red and blue.

predicted through a sequence of shorter range weather forecasts. This analysis is performed by comparing the observed cumulative precipitation difference from average (Fig. 17 black line) to the forecast cumulative precipitation difference from average for sequences of 0, 1, 2, 3, 7, 10 and 14 day forecasts of the GEFS (Fig. 17 red and blue lines). This analysis focuses on eastern Montana, the sub-region of the Northern Great Plains over which May-July 2017 precipitation deficits were most intense (Fig. 7a, Fig. 5, Fig. A1).

The GEFS ensemble prediction system captured the observed May-July 2017 cumulative precipitation deficits through sequences of up to three day forecasts (Fig. 17). By contrast, sequences of longer than five day GEFS forecasts (7, 10, 14 days are highlighted in Fig. 17) provided no indication that the seasonal evolution of precipitation would be different from average. These analyses help to explain the lack of drought development being forecast by NOAA's Seasonal Drought Outlook in mid-May 2017 (Fig. 3). In so far as weather variability was fundamentally its cause, the indications for which could not be skillfully foreseen beyond a week in advance.

7. Concluding Remarks

Summary

This assessment is a NOAA response to a request by NIDIS for an evaluation of the causes, predictability and historical context of the 2017 Northern Great Plains drought. The purposes of this assessment are to inform forecasters on current drought prediction capabilities, to quantify how drought risk changes in a warming world and aid to policy makers better define drought risk.

The onset and demise of the 2017 drought were rapid. Between May 18 and June 8, soil moisture decreased from the 80^{th} to the 17^{th} percentile. Failed rains during May-July, on average the wettest time of the year, was the principal driver of the drought, though periods of warm temperatures, high winds and low cloud cover likely contributed to the drought's rapid onset and ultimate intensity. The drought ended suddenly over the course of three days in mid-September, as soaking rains from a slow-moving low-pressure area increased soil moisture from the 20^{th} to 70^{th} percentile.

Several physical characteristics of the 2017 drought rank among the most severe on record. The rapidity of the land surface drying in May and June ranked as the third largest such decline for any three-week period since at least 1916. May-July precipitation and maximum daily temperatures also ranked among the driest and hottest, respectively, over the region dating back to at least 1895. However, the maximum intensity and longevity of the drought pale in comparison to other noteworthy droughts over the region. Lasting just three months, the 2017 drought lags behind standout droughts that lasted many years, include the 'Dust Bowl' of the 1930s and epochs during the early 1920s, 1950s, early 1960s, late 1970s, and late 1980s.

Anthropogenic effects increase the likelihood of droughts with intensity comparable to 2017. Droughts over the Northern Great Plains with soil moisture in the 10-20th percentiles, such as during July 2017, are found to occur 20% more often in current than the past climate. The increase in drought likelihood is due to long-term reductions in soil moisture, also referred to as aridification. Aridification is caused by increases in evapotranspiration associated with rising temperatures.

The predictability of the 2017 drought was limited. The NMME and ECMWF prediction systems did not forecast below average May-July 2017 precipitation in advance of the season. Rather, both systems forecast an elevated probability of above average precipitation, which help to explain the lack of drought development forecast by NOAA in May 2017 during the three subsequent months. A sequence of shorter range weather forecasts from the GEFS indicate that cumulative precipitation deficits during May-July 2017 were only predictable through sequences of up to three day forecasts.

Limitations

There are limitations to this assessment that may affect the conclusions on the causes and predictability of the 2017 Northern Great Plains drought, including:

Model outputs are used to proxy observed conditions. Given the scarcity of observed conditions in space and time, complete spatial representations of key variables during the 20th century are derived from models constrained by a limited network of observations. These variables include soil moisture from a single land surface model, and incoming solar radiation and wind speed from a single atmospheric reanalysis. The fidelity of the observed proxies are therefore dependent upon how well models are able to capture key processes and how well the day-to-day weather is represented by the scarce observations used to constrain the models. The analyses herein could be repeated with other land surface models and atmospheric reanalysis to test the robustness of the results.

A single model framework is used to investigate anthropogenic effects on drought risk. Increased drought risk in CESM due to aridification is supported by previous works (e.g. Hoerling et al. 2008, Sheffield and Wood 2011). However, the analysis could be repeated with additional coupled climate models to test the robustness of the result.

The precipitation prediction skill of just a few operational forecast systems were evaluated. NMME, ECMWF and GEFS analyzed herein are widely used, but they are not the only prediction systems used by drought forecasters. Evaluations of the precipitation prediction skill of more forecast systems would provide greater benefit to the drought community. Moreover, the ensemble sizes of these prediction systems are not adequate to diagnose the probability of extreme wet or dry seasons similar to observed conditions in 2017.

Outstanding Research

There are gaps in our physical understanding and potential predictability of Northern Great Plains drought, including:

A suitable predictive understanding of quick onset, or *flash*, drought has yet to be established. The interplay and importance of key physical processes responsible for flash drought development are currently unknown. At the local scale, how do the supply (i.e. precipitation) and demand (i.e. potential evapotranspiration) of water from the land surface drive flash drought? How does the large-scale atmospheric circulation condition local scale processes during flash drought? Do increases in potential evapotranspiration as a result of climate change alter the likelihood of flash drought occurrence?

The causes of limited Northern Great Plains precipitation prediction skill are not yet fully understood. It is unclear at this time whether droughts are truly unpredictable beyond one week or whether forecast model prediction skill is compromised by the poor simulation of key processes.

The likelihoods of key drought characteristics have yet to be quantified. How common are long duration droughts like the 'Dust Bowl' during the 1930s? How uncommon are periods like 1990-2015 during which there was little drought activity? How common are flash droughts and how long do they tend to last?

Appendix

a) 2017 Drought Chronology

The chronology of the 2017 Northern Great Plains drought is illustrated in terms of soil moisture, precipitation, maximum temperature, 10-m wind speed, and cloud cover (Fig. 5). The chronology focuses on eastern Montana, defined here as the region bounded by 46˚N-49˚N and 109˚W-104˚W (Fig. A1, red rectangle).

Eastern Montana precipitation and maximum temperature are derived from the average of 16 stations (Figure A1 and Table A1) drawn from the Global Historical Climatology Network (Menne et al 2012). These 16 stations have reported almost continuously - at greater than 90% of days during each year since 1950 - and therefore provide a robust estimate of daily precipitation and temperature over the region. Departures for a given day are calculated relative to a 1950-2017 mean.

Daily soil moisture is drawn from a simulation of the Variable Infiltration Capacity hydrologic model (Liang et al. 1994) forced by the observed time-varying meteorology. This simulation is provided by the University of Washington Surface Water Monitor (Wood et al. 2008). Soil moisture percentiles are calculated relative to a 1916-2017 baseline.

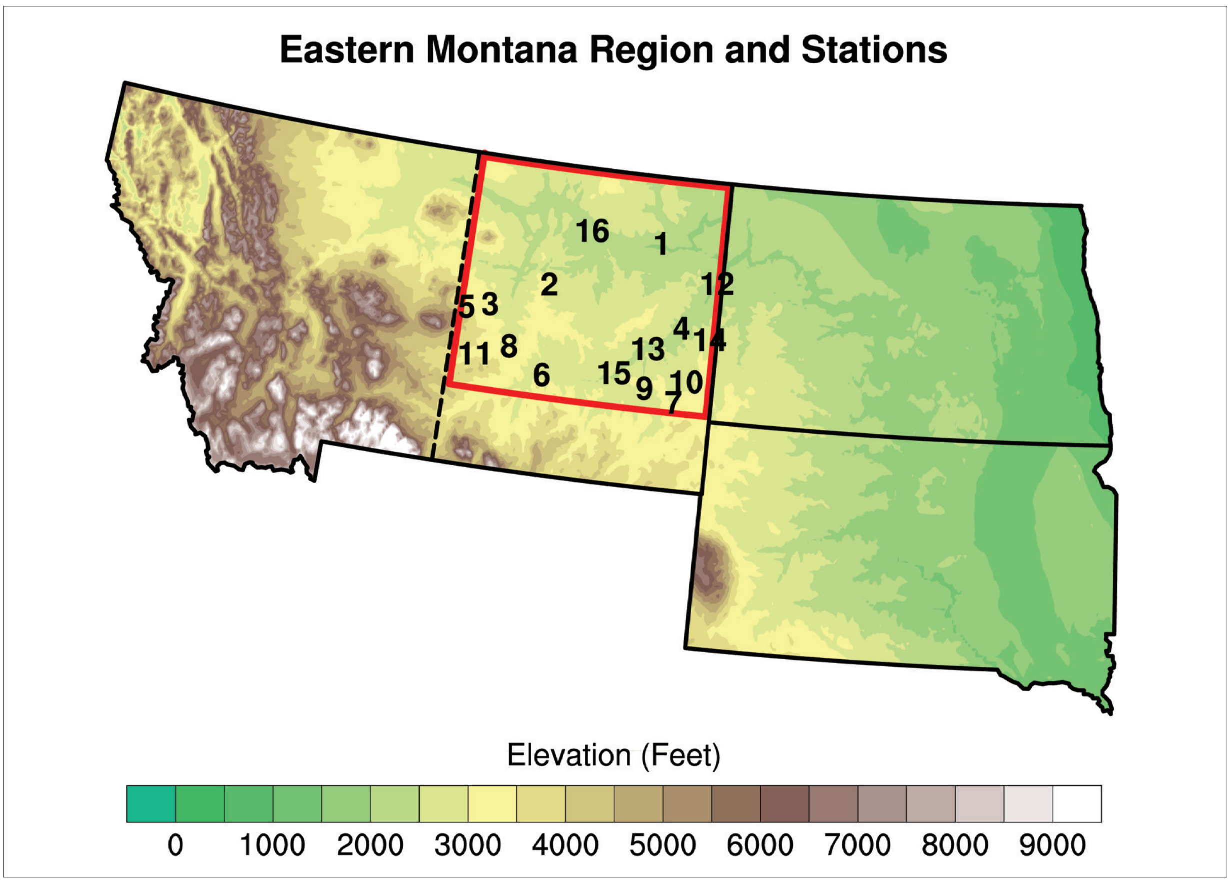

Figure A1: Eastern Montana (red rectangle) and location of stations overlaid on elevation in feet.

10-m wind speed and cloud cover are drawn from the ERA-Interim atmospheric reanalysis (Dee et al. 2011). Departures of the variables areally averaged over eastern Montana are calculated relative to a 1979-2017 mean.

Table A1: List of Eastern Montana Stations

Fig. 1M Location	Station ID	Station Name	Latitude (North)	Longitude (West)
1	USC00241088	Bredette	48.15˚	105.30˚
2	USC00241231	Brusett 3N	47.46˚	107.31˚
3	USC00243013	Flatwillow 4ENE	47.10˚	108.37˚
4	USC00243581	Glendive	47.10˚	104.72˚
5	USC00243727	Grass Range	47.02˚	108.80˚
6	USC00244358	Hysham	46.29˚	107.22˚
7	USC00245303	Mackenzie	46.14˚	104.72˚
8	USC00245596	Melstone	46.60˚	107.90˚
9	USC00245754	Mizpah 4NNW	46.28˚	105.29˚
10	USC00246601	Plevna	46.42˚	104.52˚
11	USC00247214	Roundup	46.44˚	108.54˚
12	USC00247560	Sidney	47.72˚	104.13˚
13	USC00248165	Terry	46.79˚	105.30˚
14	USC00248957	Wilbaux 2E	46.99˚	104.16˚
15	USW00024037	Miles City	46.43˚	105.88˚
16	USW00094008	Glasgow Intl AP	48.21˚	106.62˚

b) 2017 Drought in Historical Context

The rapidity of soil moisture declines over eastern Montana and the expanse and longevity of low soil moisture over the Northern Great Plains are derived from the VIC simulation described previously.

The May-July 2017 precipitation and daily maximum temperature ranks relative to 1895-2017 are derived from the gridded National Centers for Environmental Information Daily Temperature and Precipitation Dataset version 1 (Vose et al. 2014).

c) 2017 Drought and Climate Change

The evaluation of anthropogenic effects on Northern Great Plains drought likelihood and intensity is performed using 40 simulations of the Community Earth System Model (CESM) version 1 (Kay et al. 2015) during 1920-2016. All simulations are controlled by identical time-evolving external (e.g. greenhouse gases and aerosols) and natural (e.g. solar and volcanic) drivers. The weather and climate in each of the 40 simulations otherwise freely evolve. For example the timing of important phenomena like El Niño Southern Oscillation events is different in each simulation.

d) 2017 Drought Predictability

The ability of models to forecast low May-July 2017 Northern Great Plains precipitation in advance of the season is evaluated using April 2017 predictions from the North American Multimodel Ensemble (NMME; Kirtman et al. 2014) and the European Centre for Medium-Range Weather Forecasts (ECMWF) SEAS5. Those same forecast systems are also used to evaluate the regional May-July precipitation predictability dating back to the 1980s. In this analysis, NMME is a collection of 99 forecasts from eight different models listed in Table A2 that span 1982-2017. ECMWF SEAS5 is a collection of 50 forecasts from a single model that span 1993-2017 (ECMWF 2018).

Table A2: List of NMME Forecast Models

Model	Forecasts	Reference
Climate Forecast System Version 2	24	Saha et al. (2014)
Canadian Centre for Climate Modeling and Analysis Version 4	10	Merryfield et al. (2013)
Canadian Centre for Climate Modeling and Analysis Version 3	10	Merryfield et al. (2013)
Geophysical Fluid Dynamics Laboratory Forecast-oriented Low Ocean Resolution Version a06	12	Vecchi et al. (2012)
Geophysical Fluid Dynamics Laboratory Forecast-oriented Low Ocean Resolution Version b01	12	Vecchi et al. (2012)
Geophysical Fluid Dynamics Laboratory Forecast-oriented Low Ocean Resolution CM2.1	10	Zhang et al. (2007)
National Aeronautics and Space Administration GEOS5	11	Vernieres et al. (2012)
RSMAS Community Climate System Model version 4	10	Gent et al. (2011)

The ability of models to forecast the temporal evolution of the regional precipitation during May-July 2017 is examined using the Global Ensemble Forecast System (GEFS; Hamill et al. 2014), 11 daily predictions from the Global Forecast System (GFS).

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