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Predictions and Predictability of the Northern Great Plains Record Low 2017 Summertime Precipitation

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1. Introduction

Within a Northern Great Plains region, defined herein as South Dakota, North Dakota, and Montana east of 109˚W longitude (Figs. 1a, 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 (Bureau of Reclamation 2011). Agriculture is prolific throughout the Northern Great Plains, as staple crops such as spring wheat, winter wheat, corn, and barley are grown in abundance (U.S. Department of Agriculture 2019). 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.

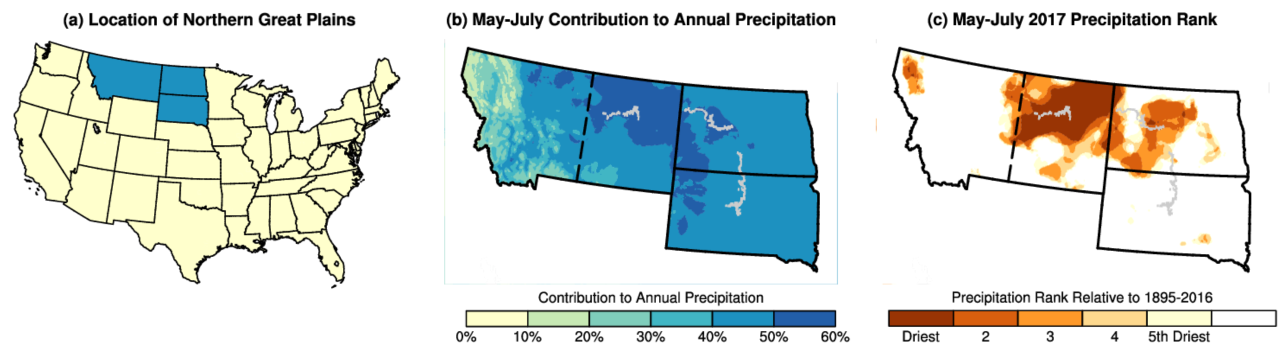

Fig. 1 (a) Location of the three states that constitute a Northern Great Plains region. (b) May-July contribution to the annual precipitation in percent. (c) May-July 2017 precipitation rank relative to 1895-2016. The 109˚W meridian is denoted by the dashed line in (b) and (c).

The 2017 spring and summer drought over Montana, North Dakota and South Dakota has been judged to be the most devastating in recent memory in this region (Fortin 2017). Economic losses resulting from the 2017 Northern Great Plains drought exceeded one billion dollars (NOAA/National Centers for Environmental Information 2018). The drought sparked wildfires and compromised water resources, which led to reduced agricultural production, the destruction of property, and livestock selloffs (U.S. Department of Agriculture 2017).

The 2017 drought arrived suddenly during the rainy season (Otkin *et al.* 2018, Hoell *et al.* 2019, Wang *et al.* 2019), which on average begins in spring, peaks during May-July (Figs. 2b), and ends during autumn. May-July precipitation ranked among the lowest on record over eastern Montana and portions of North Dakota and South Dakota dating back to at least 1895 (Fig. 2c).

Neither the drought's onset nor its severity was forecasted. Even as drought conditions emerged during mid-to-late May 2017 over Montana, North Dakota, and South Dakota (U.S. Drought Monitor 2017), further drought development was not anticipated within the following three months in NOAA's Seasonal Drought Outlook issued on May 18, 2017 (NOAA/Climate Prediction Center 2017a). Drought development was not anticipated because a failed rainy season was not expected. Instead, the NOAA forecast for May-July and June-

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August 2017 called for above-average precipitation over the Northern Great Plains (NOAA/Climate Prediction Center 2017b).

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 threefold: 1) to understand why drought was not forecast in advance of the season, 2) to identify at what lead times the cumulative precipitation deficits could be forecast with skill and 3) to provide insights into the prospects of early warning of future droughts.

2. Tools

a) Observed estimates

May-July 2017 precipitation ranks and the areally averaged May-July Northern Great Plains precipitation anomaly time series are based on the gridded National Centers for Environmental Information Precipitation Dataset version 1 (Vose *et al.* 2014). The Northern Great Plains is defined as Montana, North Dakota and South Dakota east of the 109˚W meridian. Anomalies are calculated relative to the 1982-2017 mean to align with the seasonal forecasts described in the following.

Eastern Montana precipitation is derived from the average of 16 stations (Table 1) 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 over the region. Anomalies for a given day are calculated relative to the 1950-2017 mean.

Table 1 GHCN stations that make up the observed eastern Montana precipitation time series.

Map Identifier	GHCN Station Identifier	Station Name	Latitude (°N)	Longitude (°W)
1	USC00241088	Bredette	48.15	105.30
2	USC00241231	Brusett 3N	47.46	107.31
3	USC00243013	Flatwillow 4 ENE	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 4 NNW	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

Table 2 Models that make up the NMME ensemble.

Model	Ensemble Size	Reference
EMC: CFSv2	24	Saha *et al.* (2014)
CanCM4	10	Merryfield *et al.* (2013)
CanCM3	10	Merryfield *et al.* (2013)
GFDL: FLORa06	12	Vecchi *et al.* (2012)
GFDL: FLORb01	12	Vecchi *et al.* (2012)
GFDL: CM2.1	10	Zhang *et al.* (2007)
NASA: GEOS5	11	Vernieres *et al.* (2012)
RSMAS: CCSM4	10	Gent *et al.* (2011)

b) Seasonal forecasts

The ability of forecast models to predict areally averaged May-July Northern Great Plains precipitation in advance of the season is evaluated using April forecasts from the North American Multimodel Ensemble (NMME; Kirtman *et al.* 2014) and the European Centre for Medium-Range Weather Forecasts (ECMWF) SEAS5. In this analysis, NMME is a collection of 99 forecasts from eight different models listed in Table 2 that span 1982-2017. ECMWF SEAS5 is a collection of 50 forecasts from a single model that span 1993-2017 (Stockdale 2018). Anomalies are calculated relative to the period mean of each model.

c) Sub-seasonal forecasts

The ability of forecast models to predict the temporal evolution of eastern Montana areally averaged precipitation anomalies is evaluated using forecasts from daily initializations of the Global Ensemble Forecast System (GEFS; Hamill *et al.* 2013), daily initializations of the Climate Forecast System Version 2 (CFSv2, Saha *et al.* 2013) and twice weekly initializations of the ECMWF model. Eastern Montana is defined as the area east of the 109˚W meridian. Anomalies are calculated relative to the period of mean of each model.

3. Results

a) Seasonal forecasts

NMME and ECMWF forecast an increase in the likelihood of above average Northern Great Plains precipitation during May-July 2017, as evidenced by a slight shift in the distributions of forecast precipitation to anomalously wet conditions (Fig. 2). 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 May-July 2017 precipitation forecast also made by NOAA. While the prediction systems forecast an increased likelihood of above average precipitation, each system still forecast non-zero odds of dry conditions during May-July 2017, as the interquartile range of May-July forecast precipitation in both prediction systems was below average.

Given the poor precipitation forecast skill during 2017 over the Northern Great Plains, it is natural to probe the overall predictability in NMME and ECMWF during May-July over the region. This examination is performed by noting the magnitude of the shift in the distributions of forecast precipitation anomalies from zero relative to the magnitude of the spread of the forecast precipitation distributions. Larger shifts in the distribution of forecast precipitation anomalies from zero suggest greater levels of potential predictability.

The magnitude of the shifts in Northern Great Plains forecast precipitation anomaly distributions to wet or dry conditions are small relative to their spread (Fig. 2), suggesting low predictability of May-July precipitation in NMME and ECMWF. Note that the magnitude of ensemble mean anomalies are always smaller than observed anomalies for the more extreme summers. The spread, as estimated by the interquartile range, of the individual forecasts during a given year are consistently large and helps to explain why precipitation over the region is difficult to predict with skill. The mean forecast, as estimated by the median, hardly deviates from 0 in NMME and only begins to approach the magnitude of the spread 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.

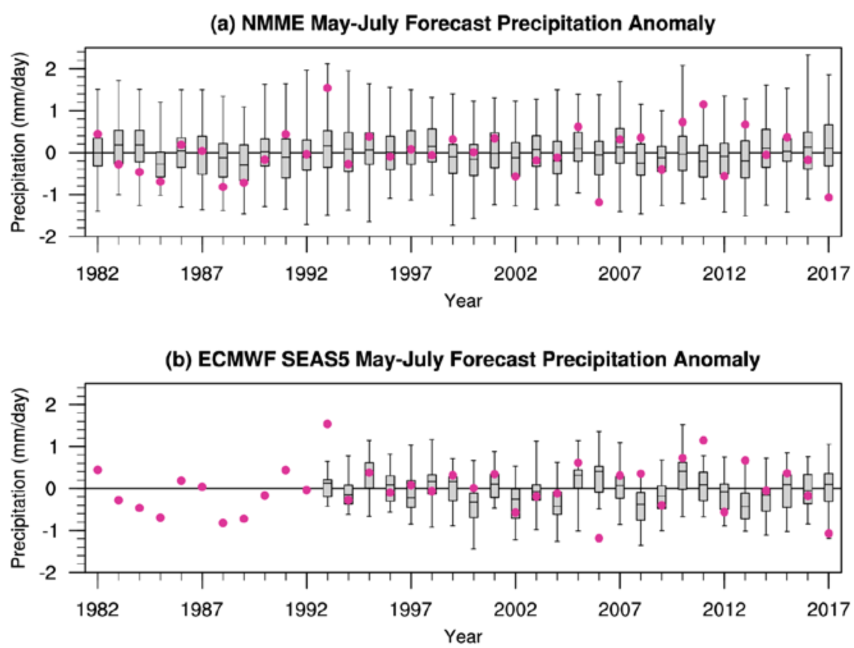

Fig. 2 For May-July averaged over the Northern Great Plains, precipitation anomaly (dot) and forecast precipitation anomaly in (a) NMME and (b) ECMWF made the preceding April (box and whisker). Boxes denote the interquartile range and whiskers the maximum and minimum.

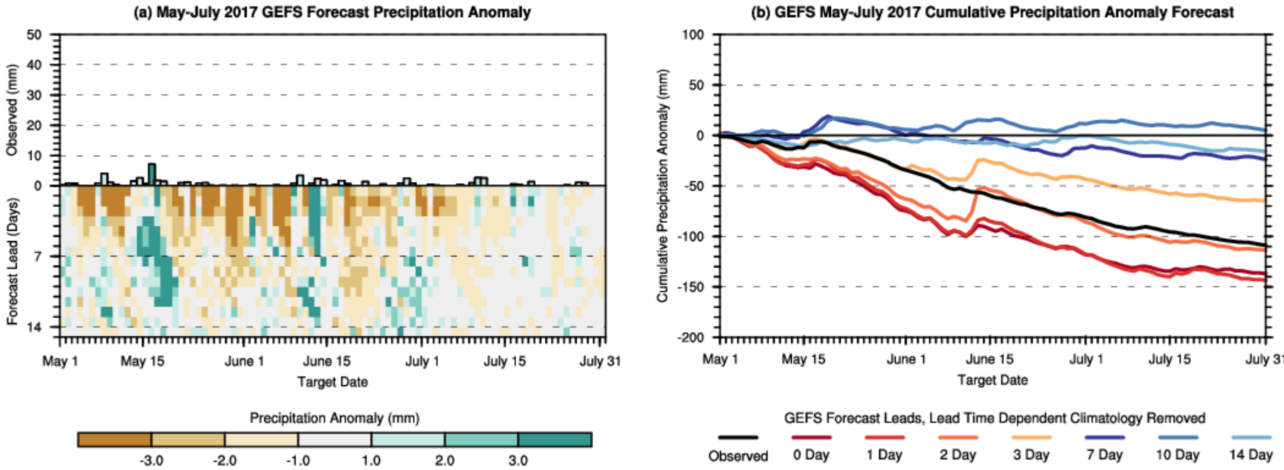

Fig. 3 (a) Observed daily precipitation (mm) and ensemble mean forecast daily precipitation anomaly (mm) as a function of lead time in GEFS averaged over eastern Montana. (b) Ensemble mean lead time dependent forecast of cumulative precipitation anomaly in GEFS averaged over eastern Montana.

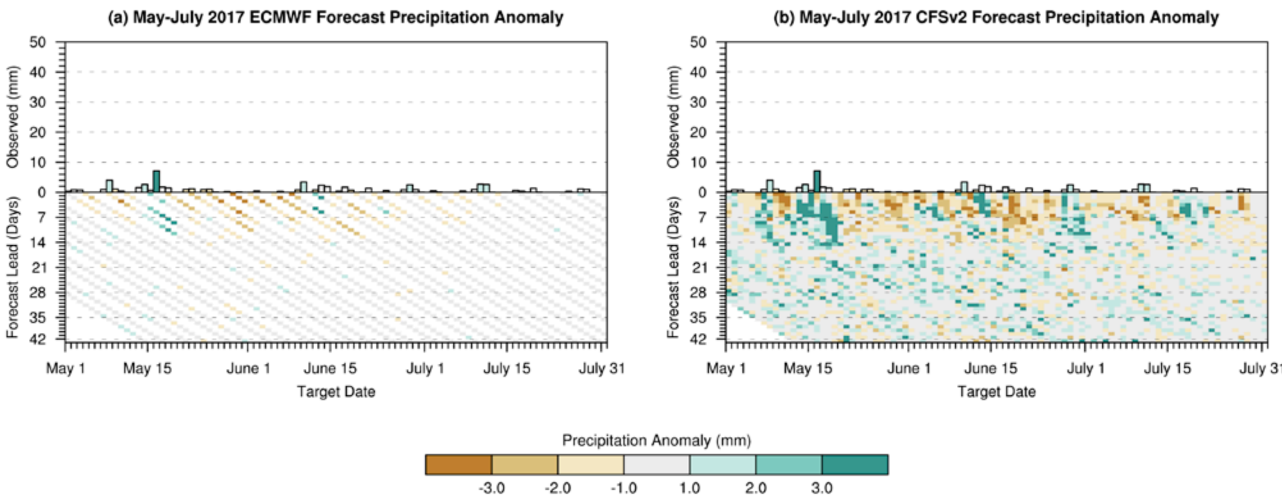

Fig. 4 Observed daily precipitation (mm) and ensemble mean forecast daily precipitation anomaly (mm) as a function of lead time in (a) ECMWF and (b) CFSv2 averaged over eastern Montana.

b) Sub-seasonal forecasts

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 over eastern Montana are probed. Eastern Montana is chosen because of record low May-July 2017 precipitation (Fig. 1a) and that its size is appropriate to analyze in the context of weather forecasts.

Anomalously wet and dry periods during May-July 2017 were foreseeable in GEFS approximately six to 12 days in advance of many events (Fig. 3a). Examples include the anomalously dry conditions during late May and early June and the anomalous wet conditions during mid-May. There was one notable period during which GEFS consistently called for above average precipitation up to two weeks in advance. This period, which occurred during the second week of June, did see precipitation over eastern Montana, but not the very heavy precipitation that was forecasted. The ECMWF and CFSv2 forecasts during May-July 2017 are similar to the GEFS forecasts (Fig. 4).

The GEFS prediction system captured the observed May-July 2017 cumulative precipitation deficits through sequences of up to three day forecasts (Fig. 3). By contrast, sequences of longer than five day GEFS forecasts (7, 10, 14 days are highlighted in Fig. 3b) provided no indication that the seasonal evolution of precipitation would be different from average, despite the fact that some precipitation events were foreseeable at 6-12 days lead time. These analyses help to explain the lack of drought development being forecast by NOAA's Seasonal Drought Outlook in mid-May 2017. In so far as weather variability was fundamentally its cause, the indications for which could not be skillfully foreseen beyond a week in advance.

4. Summary

The predictability of the May-July 2017 drought over the Northern Great Plains 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. Further, select anomalously wet and dry periods during May-July 2017 were foreseeable in GEFS, ECMWF and CFSv2 approximately six to 12 days in advance of the event.

Acknowledgements. This work is based on an assessment of the causes, predictability and historical context of the 2017 Northern Great Plains drought funded by the National Integrated Drought Information System. LINK TO ASSESSMENT HERE WHEN NIDIS POSTS IT TO THE WEB. THIS SHOULD HAPPEN BY THE END OF APRIL.

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