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Anatomy of an interrupted irrigation season: Micro-drought at the Wind River Indian Reservation

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ABSTRACT

Drought is a complex phenomenon manifested through interactions between biophysical and social factors. At the Wind River Indian Reservation (WRIR) in west-central Wyoming, water shortages have become increasingly common since the turn of the 21st century. Here we discuss the 2015 water year as an exemplar year, which was characterized by wetter-than-normal conditions across the reservation and, according to the U.S. Drought Monitor, remained drought-free throughout the year. Yet parts of the reservation experienced harmful water shortages, or "micro-drought" conditions, during the growing season in 2015. In this assessment of the 2015 water year at the WRIR we: (1) describe the hydroclimatic and social processes under way that contributed to the 2015 water year micro-drought in the Little Wind Basin; (2) compare water availability conditions within and between other basins at the WRIR to illustrate how micro-droughts can result from social and environmental features unique to local systems; and (3) describe how a collaborative project is supporting drought preparedness at the WRIR. We combine a social science assessment with an analysis of the hydroclimate to deconstruct how shortages manifest at the WRIR. We provide insights from this study to help guide drought assessments at local scales.

1. Introduction

The Wind River Indian Reservation (WRIR) in west-central Wyoming is home to the Eastern Shoshone and Northern Arapaho tribes, who depend on snowpack- and glacier-fed tributaries to the Wind River, near the headwaters of the Missouri Basin (Fig. 1). The local climate and the management of water resources are both important drivers for ensuring adequate supplies of high-quality water to meet human and environmental needs in the region. Although drought is part of natural variability in west-central Wyoming, the region has experienced several severe and long-lasting drought events in the last two decades—most notably during the early 2000s and 2012–2013—that caused significant water shortages and devastating impacts to social and ecological systems across the reservation. For example, during the extreme 2012–2013 drought, reduced spring runoff led to a management crisis and drastically reduced the summer irrigation season, which forced several local cattle producers to liquidate their herds and caused productive agricultural fields to die (Feemster, 2013). In comparison, the 2015 water year (defined as the period of October 1, 2014 –

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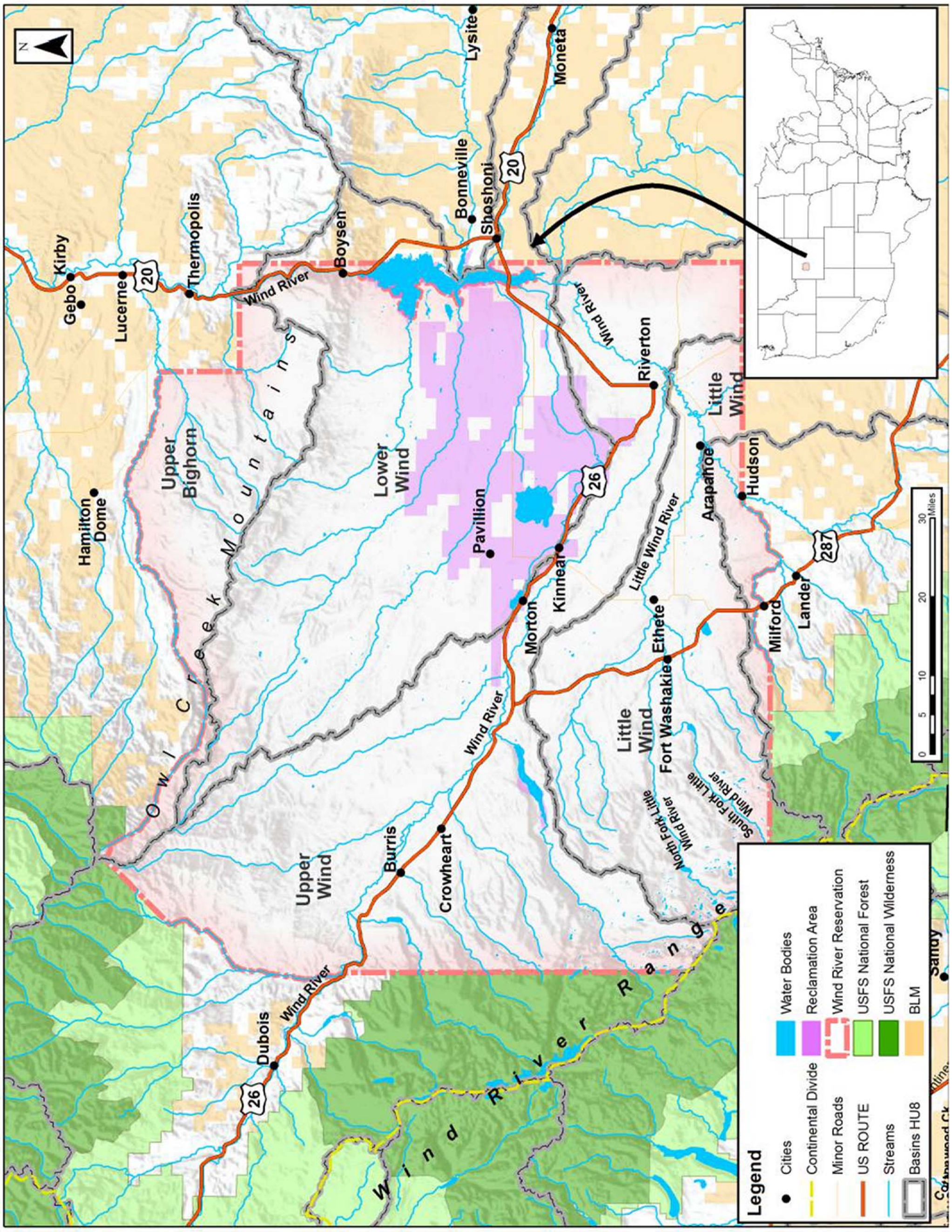

Fig. 1. Map of Wind River Indian Reservation and surrounding area.

September 30, 2015 and hereafter referred to as "WY2015") was characterized by wetter-than-normal conditions across the reservation (HPRCC, 2016) and remained drought-free throughout the year, according to the U.S. Drought Monitor (NDMC, 2016). Given these conditions, it would seem that water availability would not be an issue in 2015, yet the reservation experienced water shortages in the Little Wind Basin.

There is, therefore, an urgent need to improve the understanding of the connections between climate and water resources management at the WRIR given the effects of past droughts and related water shortages, but also because of the implications of changing climatic conditions in the region. Rice et al. (2012) report that warming has already occurred in the region and is expected to continue and accelerate during the next century. Water resources are particularly vulnerable to this warming, and climate change is projected to reduce snowpack, increase evaporation, lengthen summer seasons, and start spring runoff earlier. Although there is uncertainty associated with the climate projections, changes are expected to continue to affect the amount, phase, and timing of precipitation and availability of the reservation's water resources (Ojima et al., 2015). These changes bring with them new water-management challenges. Increasing water managers' understanding of the nexus of climate and water resources management on the reservation will provide essential information to plan for, and adapt to, current climate variability and potential future climatic changes.

To assist in these efforts, we present an assessment of WY2015 at the WRIR. Specifically, we describe the hydroclimatic and social processes under way that contributed to the WY2015 "micro-drought" or "system drought" as it is referred to locally, in the Little Wind Basin (Hydrological Unit Code [HUC] 8). In the discussion section, we compare water availability conditions within and between other HUC8 basins at the WRIR to illustrate how micro-droughts, which we define as droughts that are highly localized, short in duration, and develop due to the unique social and environmental features of local systems. Here we argue that water availability at the WRIR is a function of hydroclimate, infrastructure (storage and delivery systems), legal availability (water rights), and management decisions (competing uses and allocation).

2. Materials and methods

2.1. Conceptual framework

Drought arises through complex interactions between physical climate, hydrology, environment, socio-economic, political, and cultural drivers (Kallis, 2008; Van Loon et al., 2016; Wilhite and Buchanan-Smith, 2005). Together, these drivers alter surface runoff, storage, and evapotranspiration, which can create cascading impacts to social and ecological systems (AghaKouchak et al., 2015; Kallis, 2008).

The factors that drive water availability can be framed in the context of four interacting factors: biophysical availability (Kallis, 2008; Van Loon et al., 2016; Wagener et al., 2010); legal availability (Barnes, 2017; Chief et al., 2016; Christian-Smith et al., 2015; Hill and Engle, 2013; McNeeley, 2014; Orlove and Caton, 2010); management behavior and use (AghaKouchak et al., 2015; Hill and Engle, 2013; Pahl-Wostl, 2007; Silva et al., 2015; Van Loon et al., 2016); and infrastructure to store and convey water (Barnes, 2017; Kallis, 2008; Pahl-Wostl, 2007; Plummer et al., 2013; Van Loon et al., 2016).

Biophysical availability includes factors related to moisture, especially with regard to the effectiveness of precipitation, its spatial distribution and runoff, timing and phase of precipitation, and storage components such as snowpack, soil, and vegetation (Kallis, 2008). Yet, water rights and management behavior are arguably as important as environmental conditions to ensuring adequate water availability. For instance, Van Loon and Lanen (2013) found that groundwater abstraction resulted in four times higher impact to the hydrological cycle when compared to drought in Spain's Upper-Guadiana watershed. Additionally, Haddeland et al. (2014) found that direct human impacts to the water cycle—due to infrastructure development and water withdrawals—in the western U.S. are comparable to projected climate change impacts.

Many tribal and indigenous communities are especially vulnerable to drought and climate change, due to their natural resource-based livelihoods, deep cultural and spiritual connections to land and water resources, and the marginalized environments in which many indigenous groups live (Chief et al., 2016; Cozzetto et al., 2013; Wildcat, 2013). For instance, many reservations suffer from high rates of poverty and unemployment (Cozzetto et al., 2013; Maynard, 2014). These poor economic conditions, combined with deferred maintenance of Bureau of Indian Affairs (BIA)-managed irrigation projects, are responsible for the dilapidated infrastructure for water management (Chief et al., 2016; Cozzetto et al., 2013). The U.S. Government Accountability Office (2015) estimated that the deferred maintenance and replacement costs of 17 BIA-operated irrigation projects on tribal land at half a billion and four billion dollars, respectively.

The seminal *1908 Winters* case ruled that when tribes entered into treaties with the U.S. government and established reservation lands, it was also implied that tribes reserved water rights for those lands at the same time (Brougher, 2011). However, many tribes have not yet gone through the long, expensive process of general stream adjudications, negotiated water rights settlements, or these rights have not yet been fully implemented (Cozzetto et al., 2013). State courts have interpreted water rights for tribes very differently. Yet, in many cases tribes were awarded diminished water rights tied to specific purposes, denied groundwater rights, and provided with limited tribal authority to administer water rights and allocate water on their land (Blumm et al., 2006; MacDonnell, 2015; McNeeley, 2017).

Although there are some commonalities across indigenous communities, the environmental and social factors that affect water availability vary both within and between communities, which creates context-specific vulnerabilities to drought (Hayes et al., 2004; O'Brien et al., 2007; Smit and Wandel, 2006; Wandel et al., 2016). We employ a "determinants" approach to vulnerability assessment. The "determinants" approach does not presume to know which factors drive vulnerability *a priori*, but instead relies on local knowledges and observations of the underlying causes of vulnerability that are unique to local places and contexts (Ford et al., 2010; Füssel and Klein, 2006; Smit and Pilifosova, 2003; Smit and Wandel, 2006). This approach can lead to better understanding of how communities frame drought risk, and the combination of social-ecological factors that contribute to drought vulnerability (McNeeley, 2014; Wandel et al., 2016).

We argue that qualitative social science case studies are needed to document local knowledge and observations of impacts, responses, and the social-ecological "determinants" of vulnerability. Additionally, these methods should be complemented with hydroclimate analyses and drought-specific indices (McNeeley and Shulski, 2011). Integrating these two approaches leads to a nuanced understanding of how drought manifests and is experienced in local contexts.

2.2. Methodological approach

In this section, we lay out the methods employed by both approaches: the social science assessment, and the analysis of the hydroclimate.

2.2.1. Social science

2.2.1.1. Data collection. This case study is part of a regional, comparative study that combines qualitative social science assessment methods with analysis of hydroclimate data and drought indicators to characterize drought risks and responses in high-drought-risk regions on DOI-managed and tribal lands in the north central U.S. (McNeeley et al., 2016). At the WRIR, semi-structured, in-depth interviews (n = 22) were conducted with land and resource managers. Interviewees included water managers from the Office of the Tribal Water Engineer (TWE) and Wyoming State Water Engineer's Office, members of water users' associations on the reservation, agricultural producers, and BIA and U.S. Fish and Wildlife Service staff. Informants were identified purposively, which is a non-random sampling technique that is used to select key informants who have knowledge that aligns with the research objectives (Bernard, 2006). The interviews considered how managers frame and interpret drought and drought risks; the management decisions that are affected by drought; the indicators that are used to determine drought progression and impacts; impacts to key management issues and livelihoods; and the capacities and barriers to responding to drought (Appendix B).

2.2.1.2. Interview data analysis. Interviews were analyzed following a grounded theory method. Grounded theory is a set of prescriptive guidelines for determining meaning, and ultimately building theory, through textual data analysis (Bryant and Charmaz, 2007; Glaser and Strauss, 1967). The approach is intended to be iterative and inductive where codes are applied to segments of text, and are refined, modified, and expanded by constantly comparing across cases (Corbin and Strauss, 2008). Grounded theory helps to identify complex, contextual nuances of local management issues (Beeton and Galvin, 2017; McNeeley et al., 2017; Wilmer and Fernández-Giménez, 2015). This method is a particularly well-suited methodological approach for in-depth, "determinants"-based vulnerability approaches such as this case study, where the goal is to understand the unique and underlying factors that contribute to drought vulnerability in local places. This is not done by presuming the underlying causes of drought vulnerability, nor by relying solely on conventional drought indicators, but by working with local resource managers to document their knowledges, understandings, and observations of drought and climate, and identify how the interplay of social factors combine to increase sensitivity to drought (Smit and Wandel, 2006).

Therefore, in this case study a grounded theory approach was used to document local knowledge and observations of the social processes underway during WY2015, and to frame the types of climate- and drought-related data used, and the timing and scales at which the data were interrogated (See Section 2.2.2 for hydroclimate analyses). This, in turn, also worked to ground truth drought indicators. Our focus on WY2015 was not pre-determined at the start of this assessment. Instead, the focus on WY2015 as an exemplar case was co-determined with researchers and managers at the WRIR following multiple meetings, field-visits, and interviews.

We used qualitative data analysis software to analyze the interviews. We assessed how local land and water resource managers observed climate variability and changes through time (with reference to WY2015 in particular), and the social processes that contributed to the observed water shortage in the Little Wind Basin. We used code co-occurrences and complex query analyses to identify which codes occurred in the same segment of text discussing WY2015, and specifically to highlight the social and hydro-climatic factors that impacted water availability during WY2015. We focus our results on the HUC8 Little Wind Basin where shortages occurred. In the discussion, we provide information from other HUC8 basins to illustrate the spatial variability in drought vulnerability at the WRIR.

2.2.2. Hydroclimate analyses

To assess the hydroclimatic conditions during WY2015, we evaluated the historical climatology and trends in snow water equivalent (SWE), accumulated precipitation, phase of precipitation, streamflow, and through the Evaporative Demand Drought Index (EDDI; detailed below), and the state of these variables during WY2015 relative to the climatology. To provide a longer-term context (i.e. a multi-decadal type drought) in which the WY2015 micro-drought is situated, we also analyzed the dry period at the WRIR and surrounding region since 2000 relative to the prior period of 1981–1999 for which sufficient data is available. Data for these analyses consisted of:

1. Daily SWE and accumulated precipitation from nine Snow Telemetry (SNOTEL) stations (NRCS, 2016) in the Wind River and Owl Creek mountain ranges. Station elevations range from 8350 to 10,100 ft (2600 to 3100 m; Fig. 1). The period of record for most

stations begins in the early 1980s, and we use years through 2015. Station selection was based on proximity to the WRIR and data availability. Overall, there is limited coverage by weather stations at the WRIR and surrounding regions.
2. Homogenized daily maximum and minimum temperature (Oyler et al., 2015) at the nine SNOTEL stations.[1]
3. Gridded daily maximum and minimum temperature from TopoWx (Oyler et al., 2015). Grid resolution is 800 m and period of record is 1948 to 2015, from which we extract data for 1980 to 2015.
4. Daily precipitation from Daymet v.3 (Thornton et al., 2016), originally on a 1-km Lambert Conformal grid, but re-projected to match the TopoWx geographical grid using the Conservative Interpolation Method (Jones, 1999). The period of record is 1980 to 2015.
5. Daily reference evapotranspiration (ET_0) for tall crop (Allen et al., 2005), along with its meteorological drivers (air temperature, humidity, solar radiation, and wind, as described in Hobbins et al., 2016), from NLDAS phase-2 reanalysis output (Xia et al., 2012). These data are on a 0.125° resolution grid covering years 1980–2015. Spatially averaged time series over the WRIR domain are also used.
6. Daily streamflow from five U.S. Geological Survey (USGS) stream gauges within and nearby the WRIR, covering, for the most part, the period 1980–2015. Gauge selection was based on data availability, their proximity to the headwaters, and history of minimal to limited diversions.

2.2.2.1. Partitioning of precipitation by phase. We computed the fraction of precipitation falling as rain or snow, for both the station and the gridded data, using the temperature-based partitioning method recommended by Kienzle (2008) (see Appendix C, Section C1). For the SNOTEL stations only, we computed the daily snowfall and rainfall fractions using accumulated precipitation and the station-based temperature data. Next, we smoothed the annual cycle of rainfall fractions by computing 7-day running averages. To characterize a seasonal transition from snow to rain, we looked for the first date after January 30 on which at least half of the precipitation fell as rain when averaged over the week preceding that date. A climatology of that transition date was established, and WY2015 was compared to the climatology. For the gridded data, we evaluated spatial patterns of annual and seasonal (October-May) totals of snow and rain, and compared the WY2015 to the climatology.

2.2.2.2. Reference ET and the Evaporative Demand Drought Index. We used daily time series of ET_0 to compute the Evaporative Demand Drought Index (EDDI; Hobbins et al., 2016). For a given location and timescale (that can vary from weeks to months), EDDI represents a departure in evaporative demand relative to a historical period (i.e. 1979–2015 in this study). EDDI is computed for various time scales, and is intended to both detect fast-evolving droughts (droughts emerging over weeks to months) and characterize persistent seasonal and long-term droughts (months to years). Here, we computed the EDDI at the 2-week (spatially distributed) and 1-month (spatially averaged for the WRIR) time scales. We also attributed the changes in 2-week ET_0 time series, spatially averaged for the WRIR, into the contributions from its drivers – wind speed (U_2), temperature (T), solar radiation (R_d), and specific humidity (q) – throughout the irrigation season of WY2015 (See Appendix C, Sections C2 and C3).

2.2.2.3. Streamflow analysis. We examined daily stream gauge data to quantify timing shifts in the day of the year when the (a) maximum (MAX) and (b) centroid of water year flow (CTD) occurred. CTD is equivalent to the center of mass day (Clow, 2010; McCabe and Clark, 2005; Stewart et al., 2005) and corresponds to the date on which 50% of the water year flow had passed the stream gauge.

3. Case description: The climate and water management at the WRIR

3.1. The hydroclimatology of the Wind River Basin

The climate of the Wind River Basin is mostly characterized as cold and arid, with some areas of cold desert (Geiger, 1954). The Wind River is a snow-driven watershed, with the bulk of the annual precipitation falling predominantly during the cold season and over the surrounding mountain ranges (Fig. 2). Moisture is brought into the region by mid-latitude transient systems; snowfall dominates at higher elevations, while lower elevations receive mostly rain. Interannual variability of precipitation in the region responds to storm track variability, which ultimately is driven by the state of the climate at the large-scale, such as the sea surface temperatures in the Pacific Ocean and the internal variability of the atmosphere (Cayan et al., 1998). For example, El Niño events (when the eastern tropical Pacific Ocean is warmer than normal) tend to shift the storm tracks northward (Trenberth and Hurrell, 1994), with a potential for drier-than-normal winters over the region.

3.2. Water management in the Little Wind Basin

The Bighorn General Stream Adjudication was initiated in 1977 to determine water rights for all users in the Bighorn River basin. Prior to this, all water on tribal and non-tribal lands at the WRIR was administered according to a 1905 state water right. Following the first ruling of the Bighorn Adjudication (*Bighorn I*), the court afforded the tribes a water right of 500,717 acre-feet per year of tribal reserved water to be used and administered on tribal land. These tribal reserved water rights were considered senior water

[1] Data accessed at ftp://mco.cfc.umt.edu/resources/TopoWx-source/auxiliary_data/station_data/.

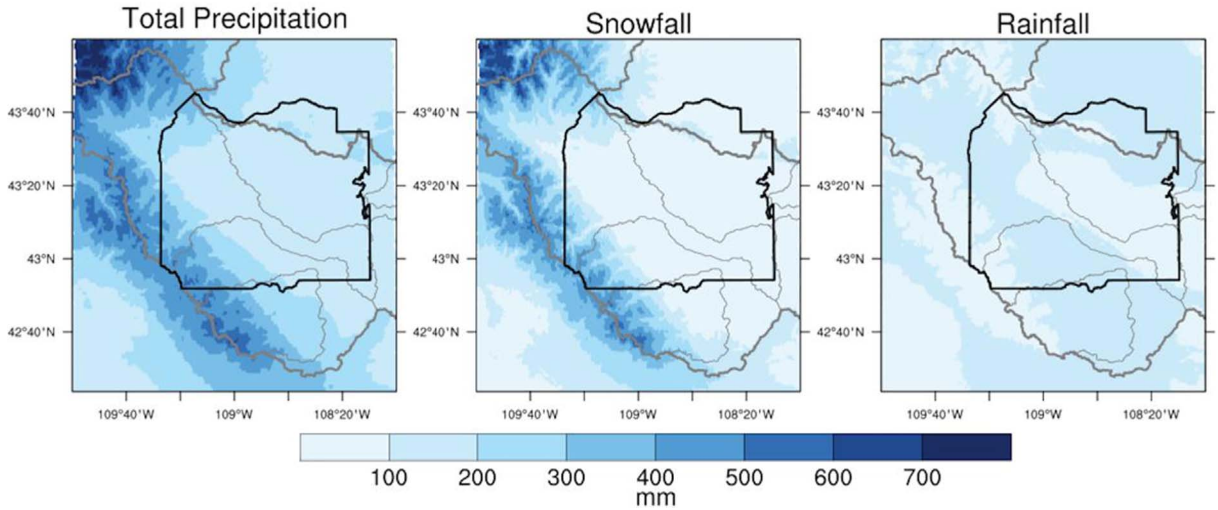

Fig. 2. Historical (1981–2015) means of cold season (October-May) precipitation, snowfall, and rainfall at the Wind River Indian Reservation. Dark gray line that encompasses all but the northeast corner of the reservation is the Wind River Basin, and lighter grays represent the HUC8 basins therein. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

rights with a priority date of 1868 (Hannum, 1992; Robison, 2015). In subsequent decisions, the Supreme Court of Wyoming ruled that the primary purpose of the reservation was for agricultural production, and narrowly tied water rights to agriculture. The rulings did not extend rights to groundwater, and gave the Wyoming State Engineer's Office legal responsibility for administering all water rights (tribal and non-tribal) at the WRIR (Kinney, 1993; McNeeley, 2017; Robison, 2015).

In the Little Wind Basin, the BIA Wind River Federal Irrigation project supplies water for approximately 30,000 acres of land from the Little Wind River and tributaries, Washakie Reservoir, and Ray Lake (Fig. 3). The Ray Canal Water Users Association, a group of tribal and non-tribal producers above Ray Lake and west of Fort Washakie rely on Washakie Reservoir and direct flows from the South Fork of the Little Wind River. Washakie Reservoir also provides water for users further downstream (e.g., Coolidge, Sub-Agency, and Left Hand Irrigation districts) who receive water from a number of sources, including Washakie Reservoir, Ray Lake, and the North Fork and South Fork of the Little Wind River. Both Washakie Reservoir and Ray Lake are small reservoir facilities, holding 7940 and 8100 acre-feet, respectively (BIA Rocky Mountain Regional Office, personal communication). Typically, Washakie Reservoir is filled from early snowmelt in April and May, which is eventually released into the Little Wind River where it feeds users in the Ray Canal, on to the Wind River, and then into Boysen Reservoir. Ray Lake is filled from the Little Wind River during irrigation off-season, and during periods of high water early in the spring. The irrigation season officially starts on May 1 and last until October 11.

The Wyoming State Engineer's Office generally allows the Office of the Tribal Water Engineer (TWE) to administer water in the Little Wind Basin, which is where the majority of the tribal communities and ranches are located. The TWE monitors snowpack and reservoir levels each irrigation season, and makes determinations on the current year's hydrological conditions (e.g., surplus, normal, or drought). If a drought is declared, then the TWE allocates water according to prior appropriation. In this case, the TWE could restrict junior water rights (State right of 1905 or later) in order to ensure that water is available for senior water (1868 tribal reserved water right), and the 1868 rights holders each get an equal allocation of available water.

However, the TWE's ability to administer water is limited. For example, the BIA ultimately has authority over reservoir releases, and therefore determines when to release water from Washakie Reservoir. Further, deferred maintenance costs for the Wind River Irrigation Project are estimated at $32 million (U.S. Government Accountability Office, 2015), resulting in leaky and poorly maintained irrigation canals that cause significant transit losses and reduce water availability during normal and dry years (McNeeley, 2017).

4. Results

4.1. Comparing WY2015 to other drought episodes

Drought events are not unusual at the WRIR and surrounding area. However, several drought episodes in the past two decades have caused devastating impacts around the reservation, particularly during the early-mid 2000s and 2012–2013. During 2015, there was ample precipitation to keep the WRIR and surrounding area out of a meteorological drought (defined as precipitation deficit), but water shortages during the late summer were reported locally. In this section, we examine the climate conditions during previous drought episodes in comparison to WY2015.

According to local observations, drought impacts were particularly devastating during 2002 and 2006. In WY2002, precipitation at the reservation was approximately 70% of normal following two years of even higher precipitation deficit (Fig. 4a), with SWE

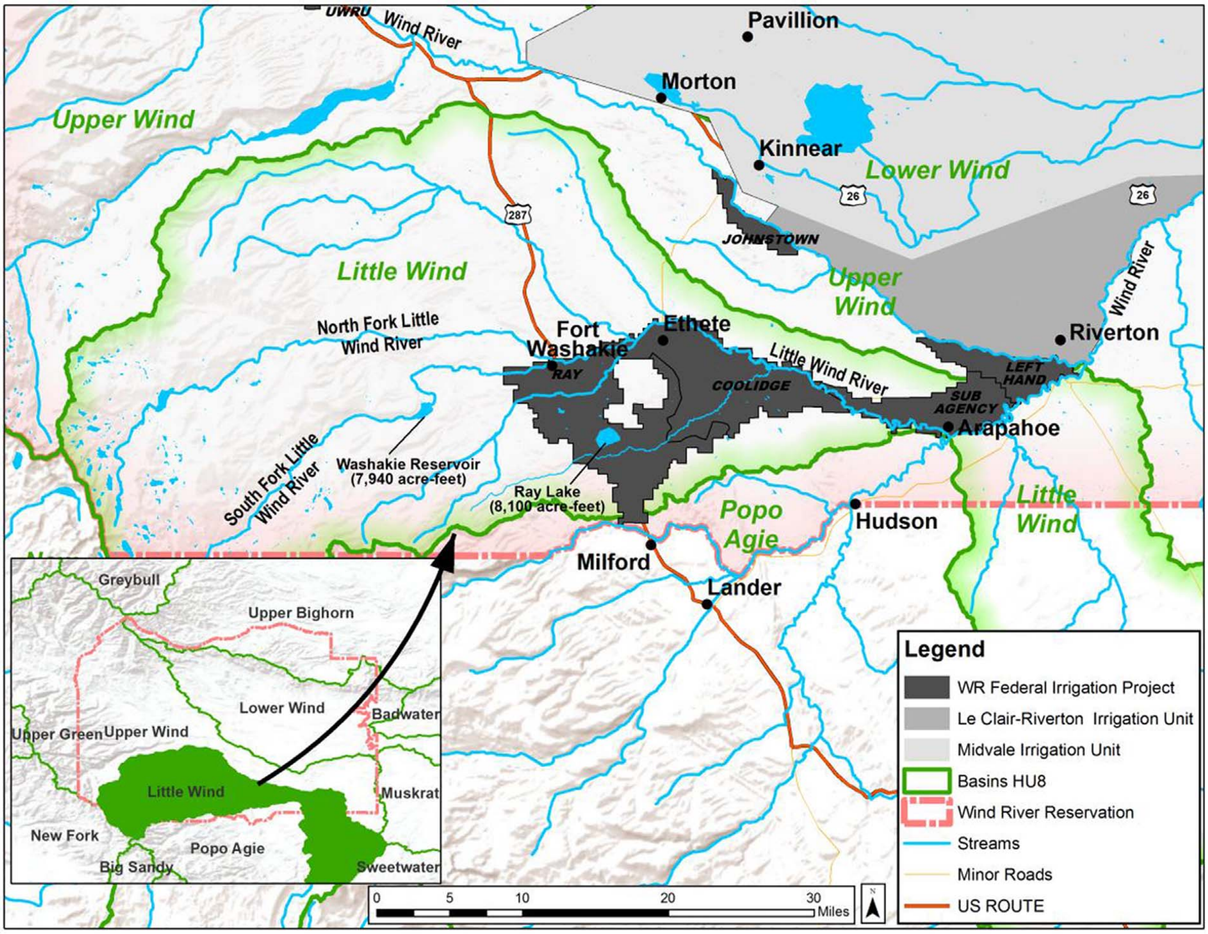

Fig. 3. Little Wind Basin and surrounding area. Washakie Reservoir and Ray Lake storage capacities verified by BIA Rocky Mountain Regional Office.

remaining below normal during the entire water year at most SNOTEL sites around the region (Fig. 5, red lines). The U.S. Drought Monitor (USDM) showed that the majority of the Wind River Basin, which includes the WRIR, was in extreme drought (D3 designation) during WY2002 (NDMC, 2016). Similarly, in WY2006 precipitation was 60% of normal at the WRIR (Fig. 4a), temperatures were above normal (Fig. 4b), and SWE again remained below normal during the entire snowpack season at most SNOTEL sites in the region (Fig. 5, purple lines). According to the USDM, the Wind River Basin began WY2006 in moderate drought (D1 designation), with conditions improving during the winter and spring. However, warm and dry conditions during the late spring and early summer caused drought to intensify, resulting in most of the basin being placed in the extreme drought category (D3) in July, where it remained throughout the rest of the water year.

A much shorter-lived but very intense drought developed across the reservation in 2012 and continued into 2013. While winter-snow accumulation was near normal at most stations in the region (Fig. 5; yellow lines), higher winter and spring temperatures caused the mountain snowpack to melt early, which was followed by low spring and summer precipitation. The drought rapidly developed during summer 2012. Precipitation at the WRIR closed the water year at just 60% of normal and temperature hit a near record-high anomaly (Fig. 4). A large part of the Wind River Basin was in extreme drought (D3) or worse from September 2012 – April 2013. Conditions improved a little during the late spring, but snowpack was again below normal during this time. While conditions had slightly improved by late spring 2013, another warm and dry summer caused stress on the reservation's water supplies.

WY2015 yielded both similarities and differences to the water years examined above. Temperatures for the water year were nearly 2 °F (~1 °C) above normal; however, precipitation at the WRIR was more than 120% of normal (Fig. 4). According to the USDM, wet conditions kept the reservation out of drought for the entire water year (NDMC, 2016). With this scenario, it would seem that water shortages should not have occurred across the reservation in 2015 but they did. Below, we further examine the hydro-climatic context of WY2015 in conjunction with social factors in order to understand how drought manifested in the Little Wind Basin during this year.

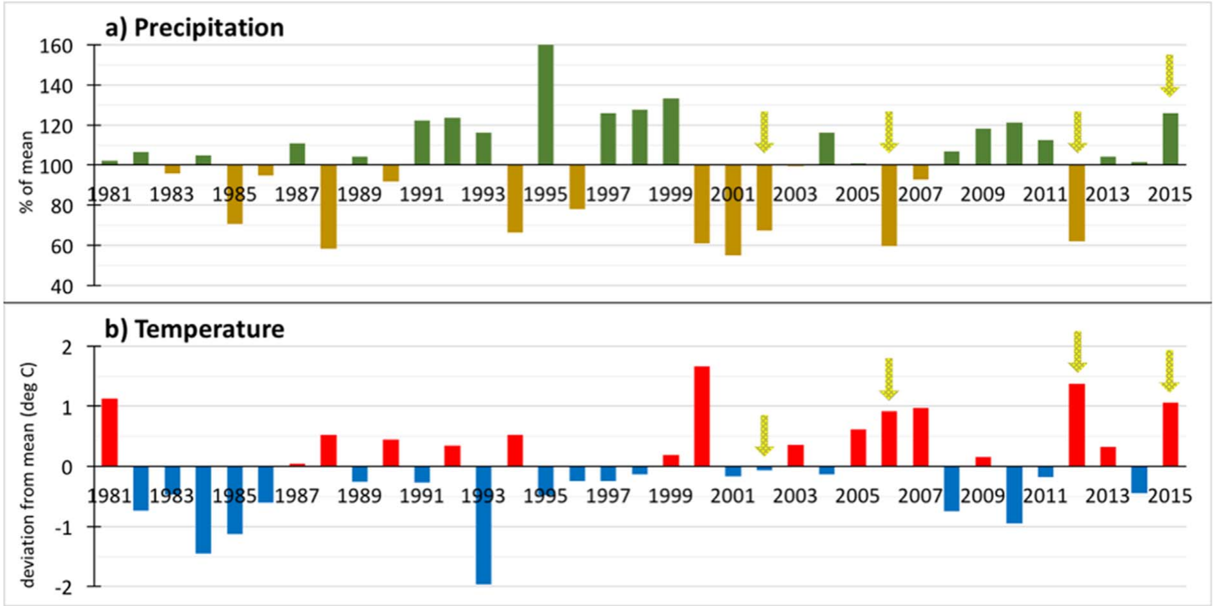

Fig. 4. Departures in annual (a) precipitation (%) and (b) temperature (°C) [for anomalies in °F, multiply by 1.8] relative to the 1981–2015 average at the WRIR. The time series were obtained by spatially averaging the gridded data from Daymet and TopoWx, respectively, over the Wind River Indian Reservation domain. Arrows highlight the drought years 2002, 2006, 2012, and 2015.

4.2. Environmental and social factors impacting water availability during WY 2015: Integrating local observations and hydroclimate analysis

Informants reported that snowpack in December was about average, followed by a sharp decline through the winter and into March and April, which were described as uncharacteristically warm and dry. One informant who conducted a snow survey in March said that the snowpack had a "wet texture" that never compacted, and suggested that it would melt rapidly.

According to data from SNOTEL stations in the region, the accumulated precipitation in WY2015 was close to average up until May, then jumped above average in early summer. After August, there was little accumulation at most stations. SWE, however, was generally below average throughout the season, with the annual peak occurring earlier and the melt-out occurring faster than average (Fig. 6).

For a regional perspective, we examine cold season (October-May) anomalies in total precipitation, snowfall, and rainfall (Fig. 7). A deficit in total precipitation was observed over the Wind River Range, while lower elevations saw a surplus. The temperature-based partitioning of precipitation shows that while the mountains received 20–40% below average snowfall, they received much higher (80–160%) than normal rainfall. Lower elevations (central areas of the Wind River Basin) received above normal snowfall and rainfall. As expected, temperature anomalies during November-April (Fig. 8, left plot) were positive overall and even larger at higher elevations, where anomalies approached 7 °F (4 °C).

In May, hydroclimatic conditions changed abruptly as record-setting precipitation fell throughout the central Rockies. Informants at the WRIR described that precipitation fell primarily in the form of rain with little snow until the later part of the month. Indeed, the cold season wet anomaly shown in Fig. 7 appears to be largely driven by May precipitation, which fell mostly as rain (in some areas more than 400% of normal; Fig. 9). The extremely anomalous wet conditions observed in May 2015 were also depicted by the 1-month EDDI (Fig. 10a), which showed an unprecedented negative EDDI value (i.e., low evaporative stress) in the record going back to 1980. This excessive wetness brought May average temperatures down over the region. However, anomalies were negative mostly in lower-elevation areas, while temperature remained near normal or slightly above normal over the Wind River mountain range (Fig. 8, center plot).

Fig. 11 shows a summary of metrics evaluated at the regional SNOTEL stations and stream gauges. When ranking the years in the 1986–2015 period (period in which all SNOTEL stations in the region have data) for annual precipitation and SWE, we found that most stations show that SWE for WY2015 was one of the lowest in the southern Wind River range, particularly in the Little Wind and Popo Agie basins (which are most relevant for tribal water resource managers), despite the fact that WY2015 precipitation was closer to the median for most stations. This is consistent with the snowfall/rainfall maps shown above suggesting that, at these locations, a larger proportion of the precipitation fell as rain rather than snow. Furthermore, all stations had rainfall earlier in the spring of 2015, with shifts ranging from 15–58 days (~2 to ~8 weeks). The timing of the snow-to-rain transition and temperature anomalies (especially at higher elevations) during the cold season adds evidence to support the low SWE reports, and is consistent with the lower snowpack, "wet texture", and warmer conditions observed by local managers.

Although the Little Wind Basin received ample precipitation throughout May, informants reported that there was very little water (12–25 cubic feet/s) coming into Washakie Reservoir until the latter part of the month as the majority of snowpack was still up in the

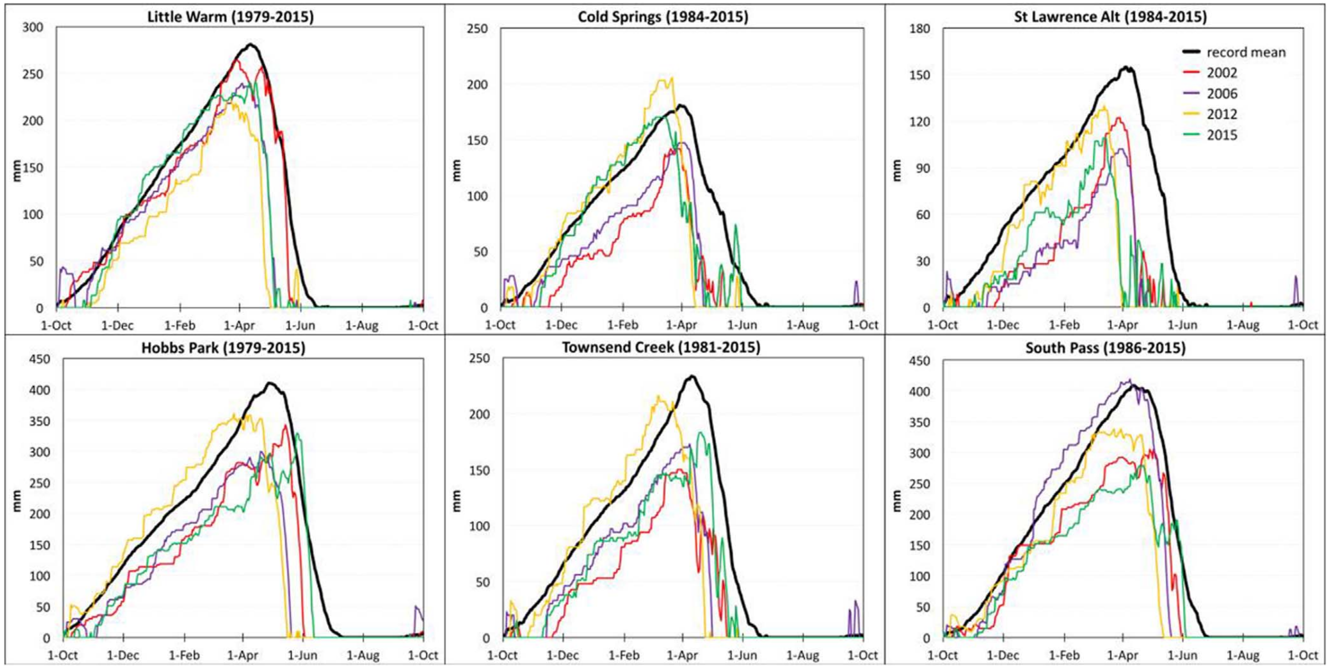

Fig. 5. Evolution of snow water equivalent (SWE) during the water year at 6 SNOTEL stations in the Wind River mountain range. Thin lines depict drought years: 2002 (red), 2006 (purple), 2012 (yellow), and 2015 (green), while thicker black line depicts the mean annual cycle over the station's record. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

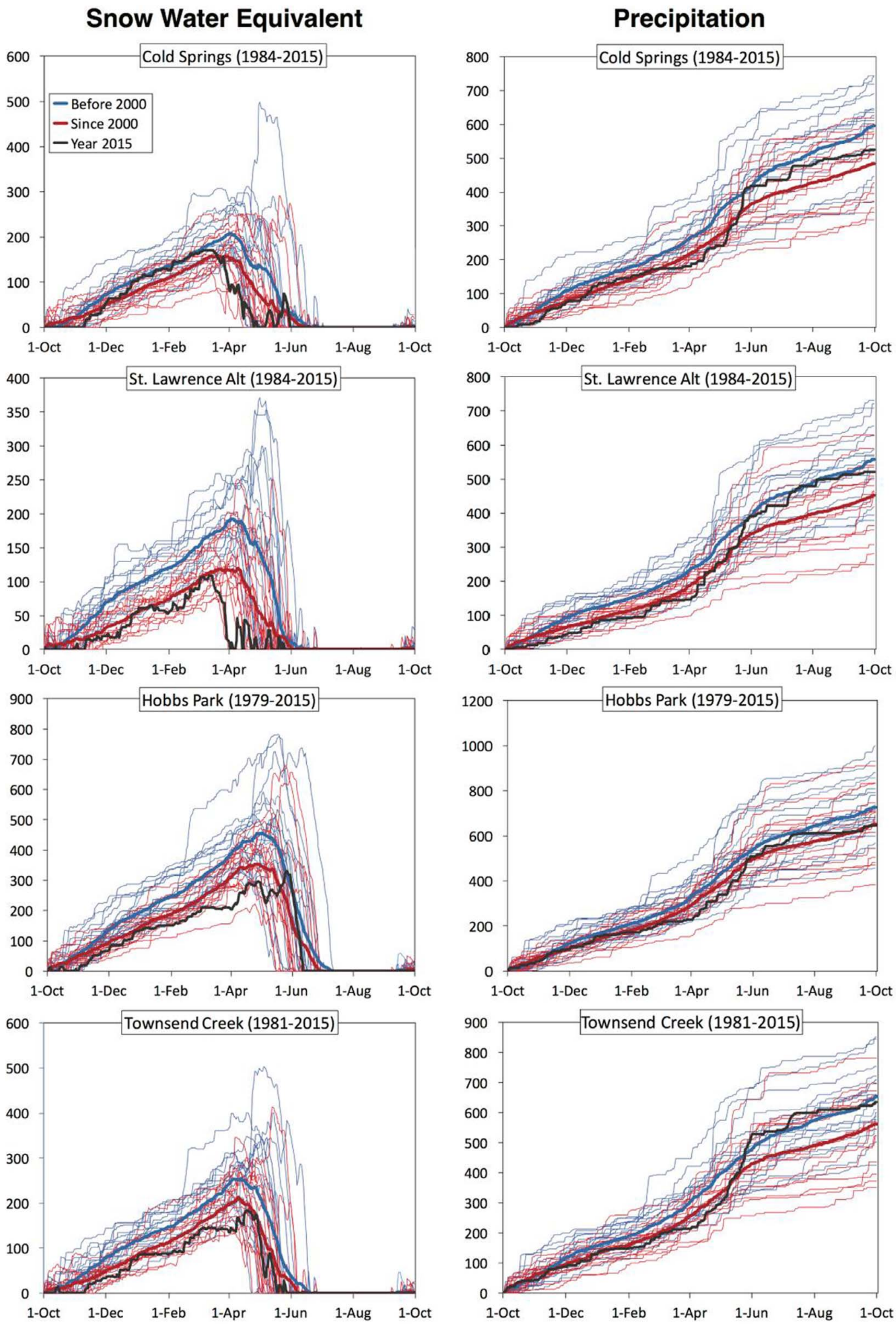

Fig. 6. Water year SWE (left) and accumulated precipitation (right) at four SNOTEL stations between WY1981-WY2015 in the Wind River Basin relevant to water supply in the southern section of the Wind River Indian Reservation. Daily values are plotted for all the years in the station record before (blue) and since (red) 2000; thicker blue and red curves depict the means for those two periods respectively. WY2015 is separately highlighted in black. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

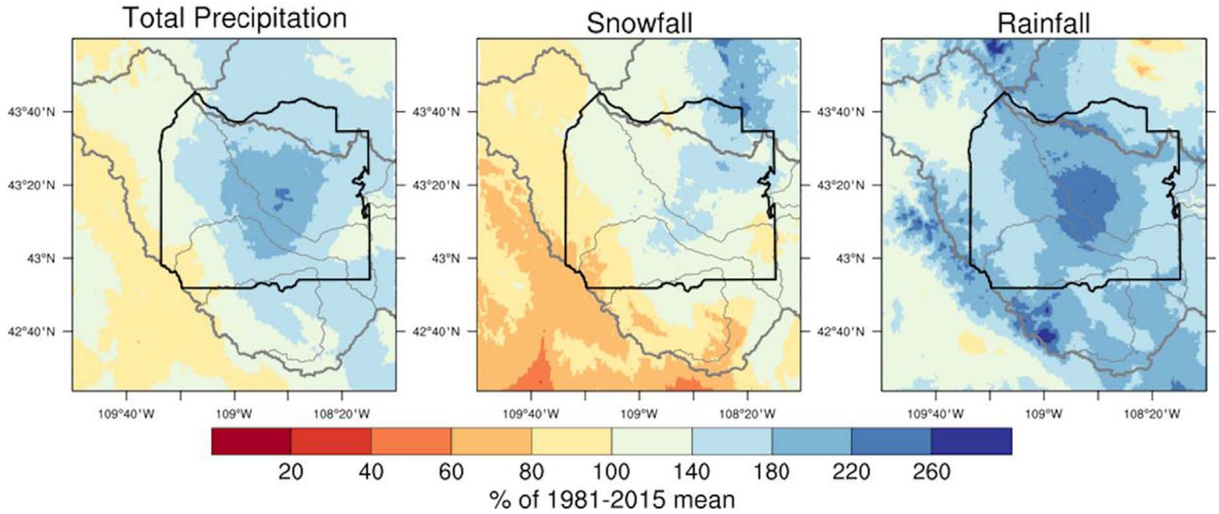

Fig. 7. Percent anomalies in cold season (October-May) precipitation, snowfall, and rainfall for the year 2015 relative to 1981–2015.

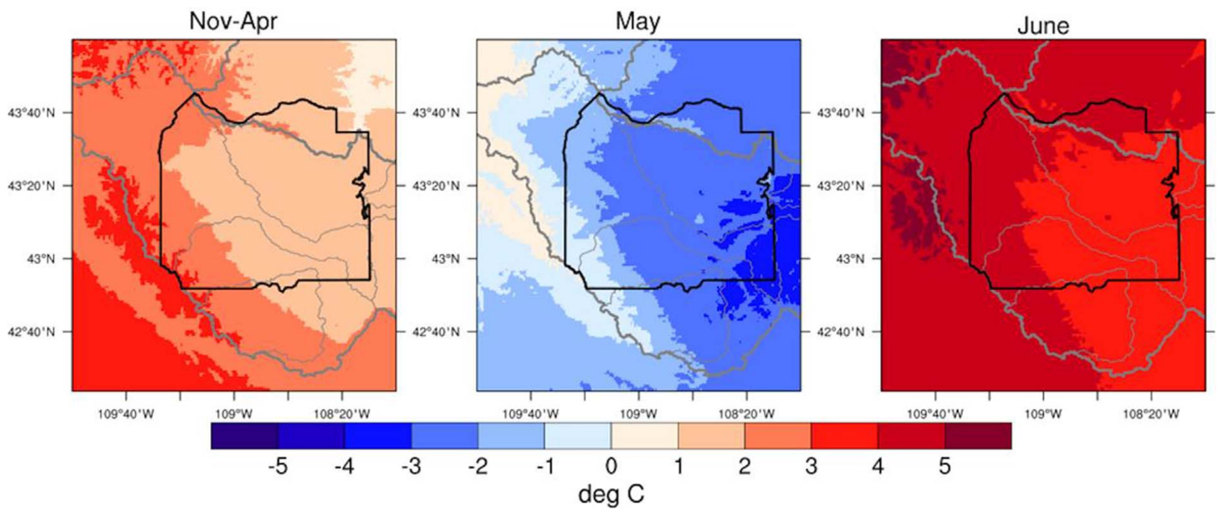

Fig. 8. Temperature anomalies (˚C) during November-April, May, and June of 2015 relative to 1981–2015 [for anomalies in ˚F, multiply by 1.8].

mountains. Local managers reported that the lack of snow during the winter and increased temperature in late May to early June together contributed to a rapid decline in snowpack and earlier runoff, which has historically occurred in the second or third week of June. For instance, water managers started increasing water storage in Washakie Reservoir on May 12; by Memorial Day, temperatures increased and snowmelt accelerated which caused the reservoir to fill and marked the start of the irrigation season in the Little Wind Basin. These reports from local managers are consistent with the climate analysis which shows near normal May temperatures at higher elevations (Fig. 8, center plot) in contrast with June, when more extreme warm conditions returned with anomalies spiking up higher than 9 ˚F (5 ˚C) over the mountains (Fig. 8, right plot). An earlier melt-out of the snow was also observed as indicated by the CTD. Across five gauges, the CTD in WY2015 occurred anywhere from 4 to 13 days earlier than the long-term mean with the earliest CTD date observed at the Dinwoody Creek Above Lakes station (Fig. 11).

The heavy, record-setting precipitation in May led to an optimistic expectation among local water users that the upcoming summer would be void of drought. However, because the reservoir was full, early season flows could not be held in Washakie Reservoir and since users were not yet calling for the water, much of the water was let downstream before it could be put to use. Local managers observed that on August 1st the water level was below the spillway, which is when the TWE estimates having about 2 weeks left of water usage. Subsequently, on August 21, water managers reported that the reservoir was down to stock water (i.e., just for animals to drink). It was at this point that the irrigation season, which can last until October 11 during normal climate conditions, had to be closed for the Ray Canal Water Users Association irrigators.

Many users delayed fulfilling their irrigation needs due to expectations of higher water availability. This is reflected by a statement from a water manager at the WRIR,

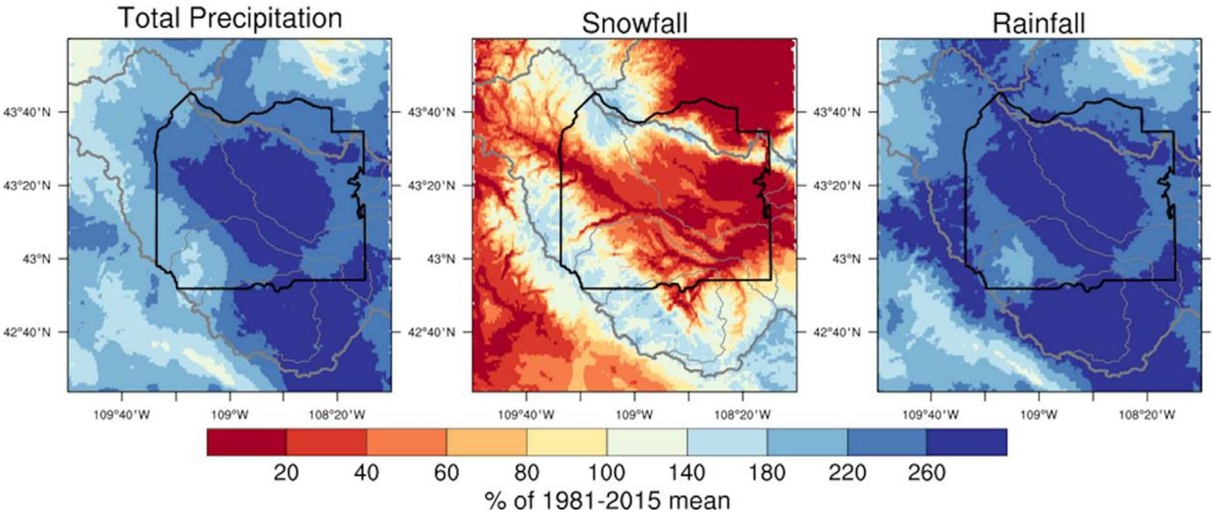

Fig. 9. Percent anomalies in precipitation, snowfall, and rainfall in May of 2015 relative to 1981–2015.

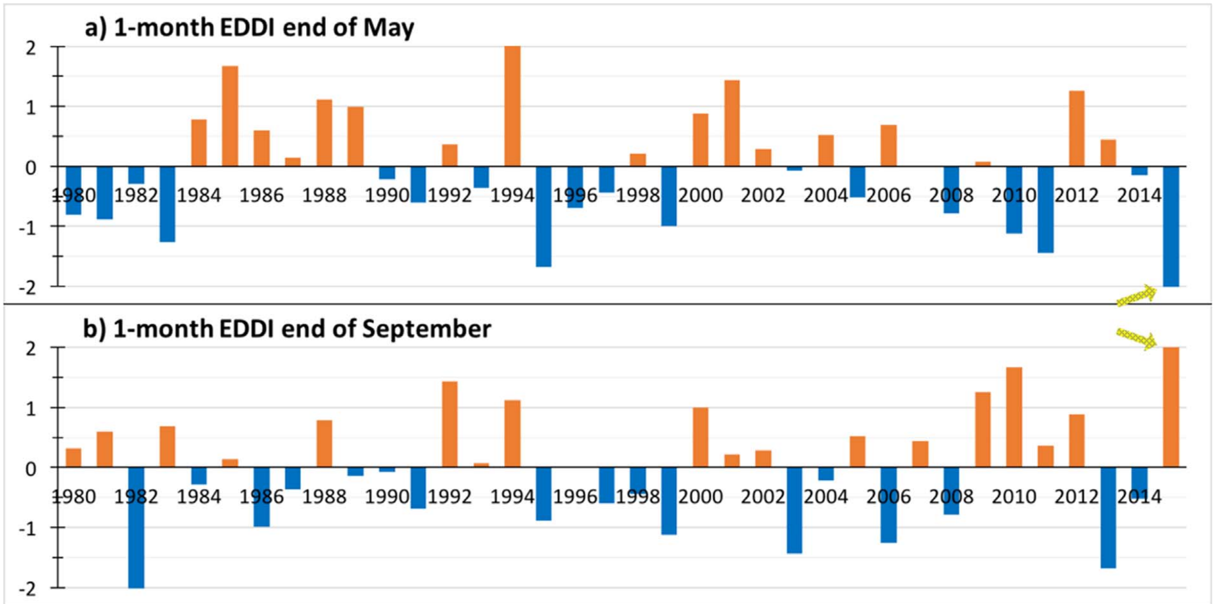

Fig. 10. Time series of 1-month EDDI at the end of May (top) and September (bottom).

"I think what people thought was because we had such a wet spring that there was [sic] all kinds of water up there. But, they just don't seem to understand that Washakie only holds about 8000 acre feet."

Tribal water managers and producers reported devastating impacts in the upper part of the Little Wind Basin. For instance, low reservoir levels caused adverse impacts on local ranching and farming, especially impacts to hay production and concerns about stock water availability through the winter, instream flows for fisheries and riparian ecosystem health, and increased fire hazards (WRIR Climate Summary, 2015).

The 2-week and 1-month EDDI provide a more detailed depiction of the "rapid" drought development from May-September, and places the timing of the water management events mentioned above in a physical climate context. EDDI concentrates on the demand for evaporation of available water rather than its supply through precipitation. The season started with an abnormally wet May (with the lowest 1-month EDDI at the end of May in a record going back to 1980; Fig. 10a), and was followed by a drier and warmer June (Fig. 12). Although July brought more wet conditions, by early August the EDDI detected a rapid drying. In September, the dryness intensified, and peaked halfway through the month. In fact, the 1-month EDDI for September is the maximum value (i.e. high evaporative stress) in the record (Fig. 10b). It is important to note that a drying trend did not appear in the US Drought Monitor during the growing season until September 29 (Fig. 12).

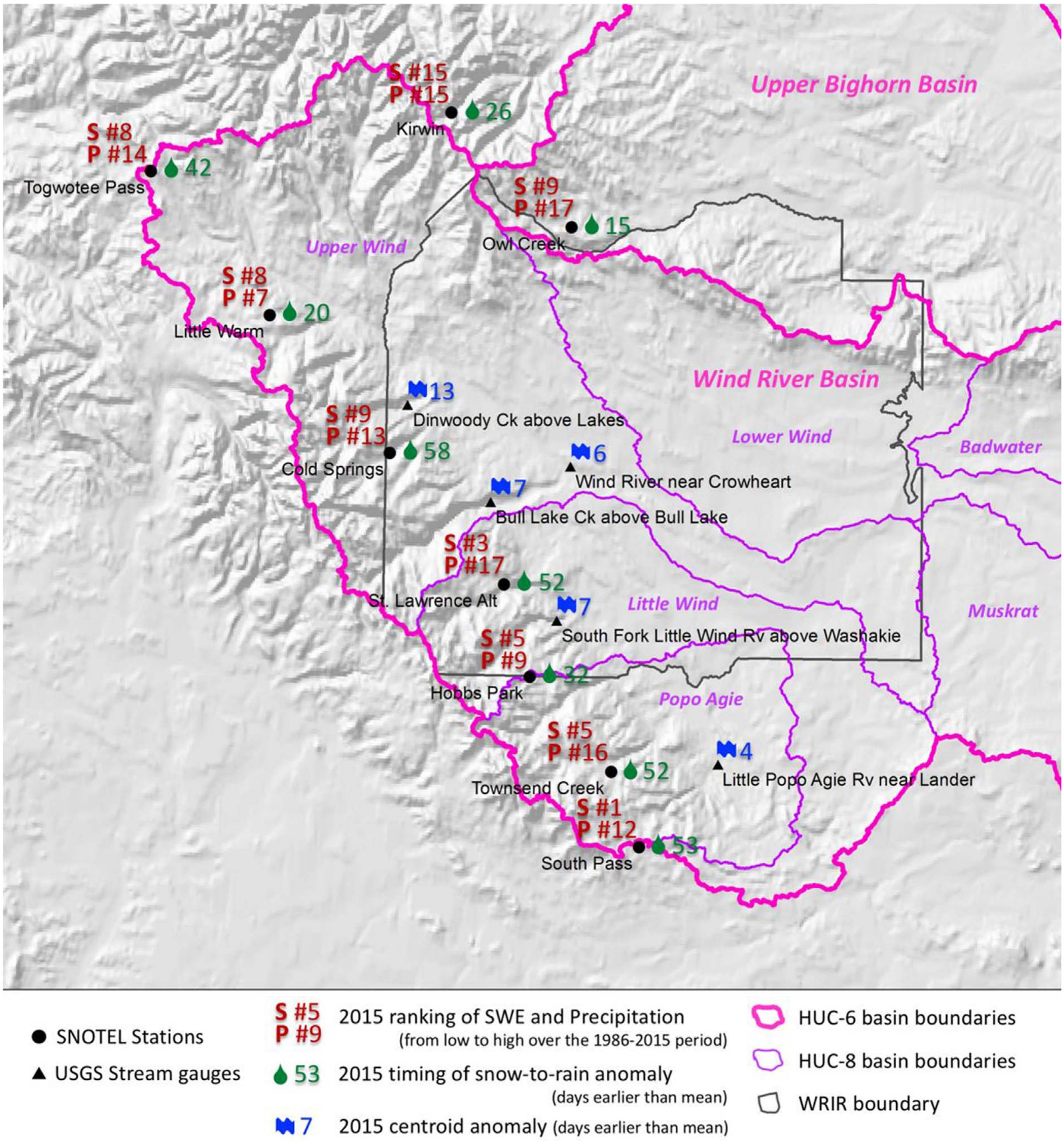

Fig. 11. Summary of hydroclimatic metrics for the region's stations: (i) WY2015's rank for maximum SWE (S) and total annual precipitation (P) (ranking from low to high value within the 1986–2015 period; e.g., the lowest SWE recorded at South Park in 2015 gets ranked #1 out of 30); (ii) shift in timing of the snow-to-rain transition during the spring of 2015, indicated by days earlier than the record mean; (iii) shift in timing of the centroid of the water year flow at the stream gauges for 2015, indicated by days earlier than the record mean.

Managers described these changes to the water cycle and timing of water availability as a recent trend very different to conditions during the 80s and 90s, when water was typically available from mid-April to October. These observations are consistent with the observed climate for the period 1980–2000 relative to the period 2000–2015. For instance, SNOTEL stations along the Wind River Mountains show lower mean total precipitation and SWE for the period 2000–2015 than for 1980–2000 (Fig. 6).

Because the 2-week EDDI is based on anomalies of 2-week ET_0, we next discuss the attribution of these short-term changes in evaporative demand (ET_0). Fig. 13 demonstrates, for the period May 12 through September 29, 2015, the evolution of the WRIR-mean 2-week ET_0 and decomposes (attributes) the changes in ET_0 into the contributions from its drivers: wind speed (U_2), temperature (T), solar radiation (R_d), and specific humidity (q). It is instructive to examine these spatial mean time series in conjunction

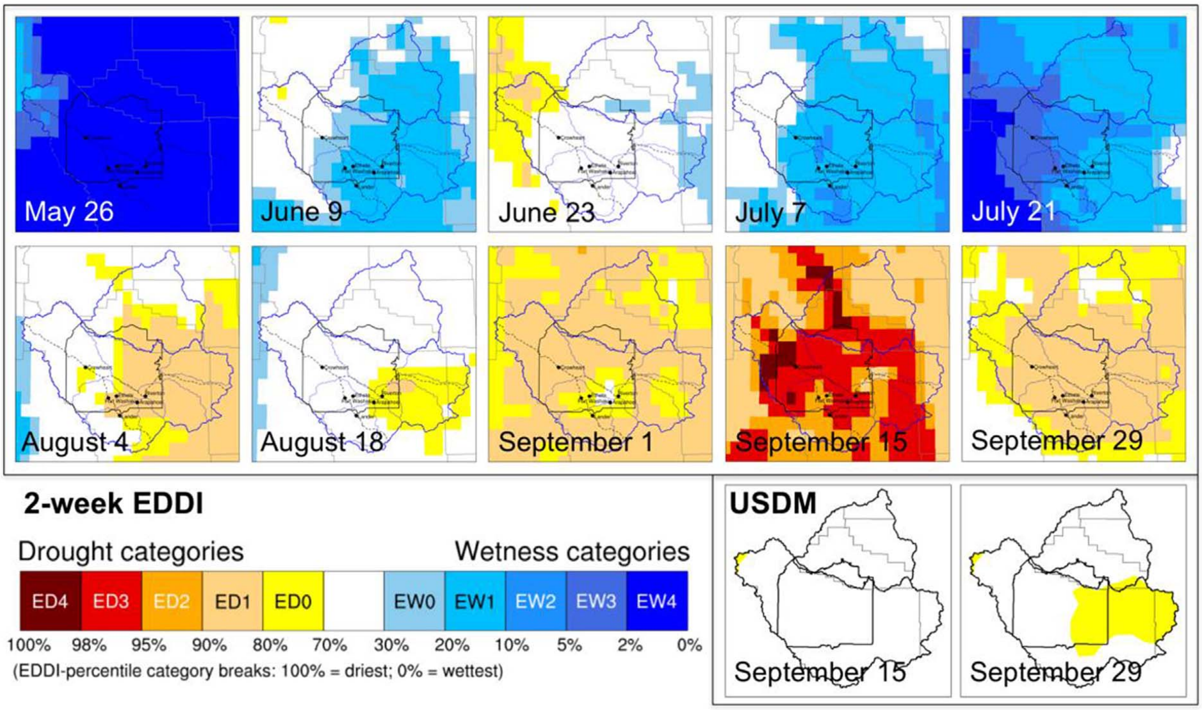

Fig. 12. Drought development in the Wind River Indian Reservation across the irrigation season as measured by the 2-week EDDI at 2-week intervals. USDM diagnostics for September are depicted in the bottom right maps.

with the evolution of drought at the WRIR as estimated by the 2-week EDDI (Fig. 12).

ET_0 remained, almost entirely, below normal from the start of the period until around July 24 (Fig. 13a, black line), corresponding to the period of negative (wet) 2-week EDDI (Fig. 12) up to and including July 21. Until this point, low wind speed (Fig. 13c) and high humidity (Fig. 13f) were contributing to below normal ET_0 anomalies. Counteracting these effects, both temperature and solar radiation were above normal for a time during this early period (Fig. 13d and e) contributing to a brief return of ET_0 to near normal conditions around June 23 (Fig. 12). During early August, positive ET_0 anomalies resulted from above normal wind speed and solar radiation, and below normal humidity (Fig. 13a). From the last week of August and through the end of September, all drivers were making positive contributions to the ET_0 anomaly, with above normal wind speed being the largest and sustained contributing driver. The positive contribution of temperature trailed that of the other drivers, indicating that the land surface drying had led to an increase in near-surface warming (and not vice versa). The rapid increase in ET_0 during the first half of September, following the evaporative stress that had occurred in the previous month, lead to a rapid onset and intensification of drought during the period, as shown in the EDDI maps for September 1 through 29 (Fig. 12).

5. Discussion

5.1. The Little Wind Basin micro-drought in 2015

Across the Little Wind Basin, WY2015 can be characterized as starting slow, arriving abruptly, and ending earlier than normal. Above average temperatures during the winter snowpack season and late spring especially at higher elevation, below normal SWE, and an earlier seasonal transition of precipitation falling as rain versus snow, all contributed to an accelerated snowmelt and early runoff. Water availability was very low in the system until the record-setting precipitation in May, which provided an optimistic outlook for the summer irrigation season. Yet, the size of Washakie Reservoir was insufficient to hold these early season flows, and while irrigators were not calling for water, the majority of the available water had to be released downstream before it could be put to use. Later, when drought intensified, all the snowpack had melted and there was no water left in the reservoir. This caused the irrigation season to close over a month earlier than normal and resulted in significant impacts to local producers in the upper part of the Little Wind Basin.

These recent changes to the water cycle and water availability were described as a trend that is different from the 1980–1990s. As we have shown, these local observations are consistent with the observed climate; total precipitation and SWE were lower for the period 2000–2015 when compared to 1980–2000. While decadal-scale climate variability is likely to be driving these changes (Gray et al., 2003; Hunter et al., 2006; Nowak et al., 2012; Rangwala et al., 2015), which implies that above average moisture supply can occur again in subsequent decades, the background of overall increasing temperature is a threat to future snowpack (Walsh et al., 2014). This raises the need for better understanding and preparedness for unfamiliar and emerging drought conditions within the

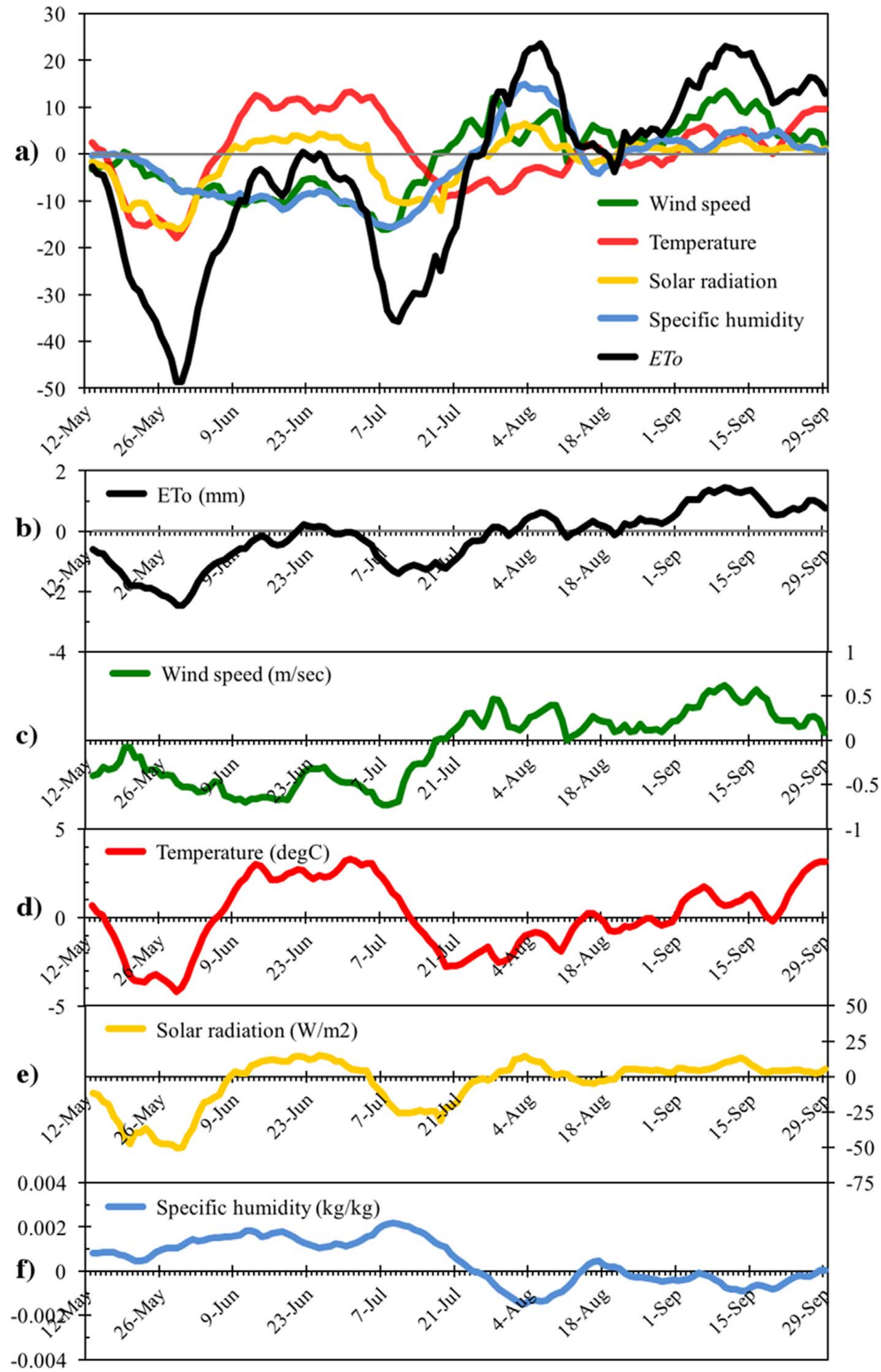

Fig. 13. Attribution of changing ET_0 spatially averaged across the WRIR during the period May 12 through September 29, 2015. Panel (a) shows depth changes (mm) in ET_0 aggregated over a 14-day window moving daily and ending on the day plotted, and the contributions to ET_0 changes due to anomalies in each of its four drivers. Panels (b)–(f) show the anomalies in ET_0 (b) and each of the four drivers (c–f) relative to their means for the relevant 14-day period in the climatology period of 1981–2010.

social-ecological context of the region.

Although water shortages and impacts to irrigation were experienced by upstream users in the Little Wind Basin, other areas of the reservation did not report shortages during WY2015 despite exposure to similar climate conditions. For instance, informants reported that the lower portion of the Little Wind Basin, where producers receive water from Ray Lake, Washakie Reservoir, and the North and South Fork of the Little Wind, had plenty of stored water (Fig. 14). Additionally, in Crowheart (Upper Wind Basin), water

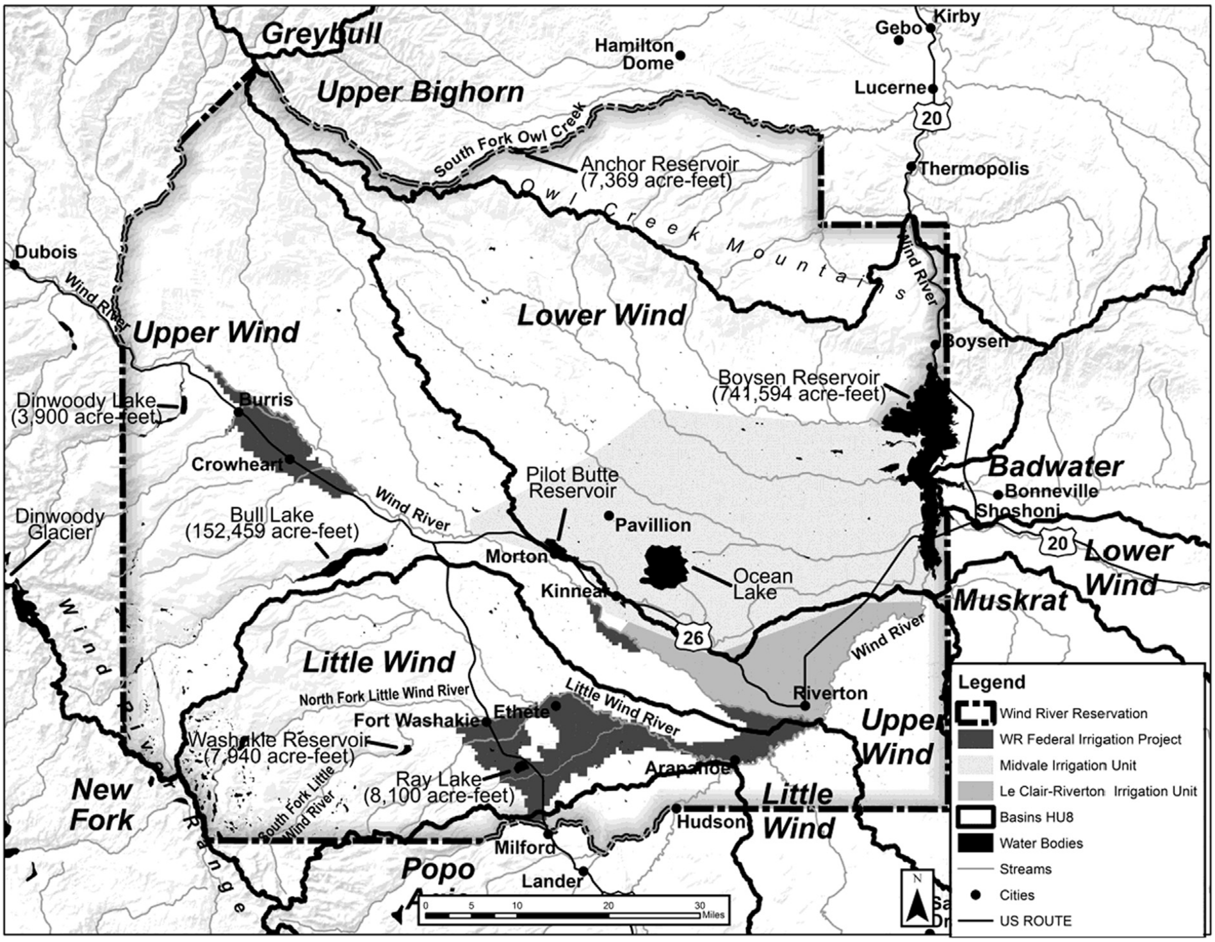

Fig. 14. Map of Wind River Indian Reservation, including reservoir location and capacity, and irrigation districts within HUC8 basins. Reservoir capacities for Boysen Reservoir, Bull Lake, and Anchor Dam were verified by the Bureau of Reclamation Wyoming Area Office. Reservoir capacities for Washakie Reservoir and Ray Lake were verified by the Bureau of Indian Affairs Rocky Mountain Regional Office. Reservoir capacities for Dinwoody Lake based on MWH Americas et al. (2010).

users rely on water stored in Dinwoody Lake, and runoff from Dinwoody Glacier for late-season streamflow (Fig. 14). Although there was very little streamflow during the month of May, informants reported that the rain in May was sufficient to satisfy water users in the early part of the irrigation season and carry the system through until Dinwoody Glacier began to shed water. In fact, as of August 27, 2015, Crowheart had "bank-to-bank water in the canal."

Further, Anchor Dam is a small reservoir located on the South Fork Owl Creek of the Upper Bighorn Basin (Fig. 14). Informants described the WY2015 as a phenomenal year in the Upper Bighorn Basin partly due to the rains in May, which carried the system through the early part of the year. The later part of the irrigation season was supplemented by releases from Anchor Dam. Although Anchor Dam was described by informants as leaky and insufficient in size for the number of its dependent users, one informant reported that Anchor Dam held more water in WY2015 than any other year since he started monitoring the dam in 2003.

Finally, the Bureau of Reclamation operates two large reservoirs at the WRIR: Bull Lake in the Upper Wind Basin and Boysen Reservoir in the Lower Wind Basin (Fig. 14). Bull Lake provides water to Midvale, LeClair, and Riverton Valley Irrigation Districts. One informant reported that Midvale Irrigation District started withdrawing storage from Bull Lake around mid- to late-July which is expected, and although natural flows were lower than what was typically expected for late August, the system was in good shape for the remainder of the irrigation season. This is because Bull Lake holds 152,459 acre-feet, and was described as well-maintained with modern infrastructure when compared to the BIA-managed reservoirs and Anchor Dam. Therefore, while each of these basins experienced similar climate conditions to the upper part of the Little Wind Basin during the 2015 irrigation season, none of them experienced water shortages as they had sufficient water storage to capture early season flows and provide water for irrigators later in the season.

5.2. Drought preparedness at the WRIR

This research is part of an ongoing project with foundational partnerships with the Eastern Shoshone and Northern Arapaho at the WRIR, and over 15 government agencies and university partners. The science was driven by information needs and drought priorities identified by the tribes, and the ultimate goal was to co-produce actionable science that supports drought preparedness. This entails the development of an early warning/monitoring system; vulnerability and impact assessment; and identification of the barriers, but also feasible and desirable drought adaptation strategies (Hayes et al., 2004; Wilhite, 2009; Wilhite et al., 2005). Below, we first describe our efforts underway to develop an early warning/monitoring system at the WRIR. We specifically highlight how the joint hydroclimatic and social analysis has helped add to and refine monitoring efforts, which highlights the iterative nature of this project. Second, we describe major barriers to drought management, and provide a snapshot of several drought preparedness options that are available to, or are being considered by, local managers. In doing so, we specifically describe how access to the climate and drought information presented here can assist local managers in drought preparedness and management, among other current options.

Prior to this work, the TWE lacked a systematic monitoring and early warning system to assess climate conditions and declare drought during the irrigation season. In 2014, water managers from the TWE, and scientists from the North Central Climate Science Center (NCCSC), High Plains Regional Climate Center (HPRCC), and National Drought Mitigation Center (NDMC) co-produced quarterly climate and drought summaries (hereafter referred to as “Summaries”), which is led by the HPRCC. The Summaries convey the following information to stakeholders at scales relevant to local land and water managers: climate conditions for the previous season; an update on drought conditions; water-related information such as snow-water equivalent (SWE), streamflow, and reservoir levels, and local observations when provided; and outlooks for the upcoming season for temperature, precipitation, flooding, drought, wildfire potential, and the El Niño-Southern Oscillation (ENSO) cycle (http://tribalwaterengineers.org/). The TWE contributes impact information which has helped validate data and add context to the Summaries. The Summaries are comprised of a mix of maps, data tables, and text descriptions written in a non-technical format intended for a public audience. They are produced to coincide with climatological seasons.

Production of the Summaries began in March 2015, and four were released during WY2015 (March, May, June, and September 2015). Although informants at TWE reported that the Summaries have been useful and were consulted during the 2015 and 2016 irrigation seasons, it is important to note that the Climate Prediction Center U.S. Seasonal Drought Outlook in the May 2015 Summary indicated that the removal of drought in southern Wyoming and south of the Wind River region during May-July was likely, and that drought was not likely to develop. As such, the TWE did not issue a drought declaration, and subsequent summaries did not capture emerging micro-drought conditions during the WY2015. This time lag that occurred with the release of the quarterly summary that primarily used more conventional drought indicators at the time is testament to the need for a monitoring system that includes multiple lines of evidence and ways of knowing that we describe herein. This is especially true in this type of rapid-onset, micro-drought situation that is so localized.

The joint social and hydroclimatic analyses have helped inform future development of information products for the early warning system in a number of ways. First, as we illustrated the EDDI did capture the fast-evolving nature of the micro-drought during the summer of WY2015 more quickly than the U.S. Drought Monitor (USDM). The fine scale nature of the EDDI output (compared to the broader scale USDM that includes many inputs) allowed for the early identification of the drought conditions in this situation. The EDDI was tested and ground-truthed with managers retrospectively, as were other innovative drought tools such as the Drought Risk Atlas (http://droughtatlas.unl.edu/) and the Drought Impact Reporter (http://drought.unl.edu/MonitoringTools/DroughtImpactReporter.aspx). It is through this iterative co-development and ground-truthing of innovative tools that we hope to provide usable information to support preparedness planning. Efforts are ongoing to incorporate the EDDI into future Summaries to complement existing products and better capture the full spectrum of drought onset.

Second, the joint hydroclimatic and social analysis helps to inform additional types of climate and drought-related information that will be useful to consider in future Summaries and other monitoring-related products. For instance, metrics that capture the timing of runoff, and phase of precipitation would be useful data to consider moving forward. Also, snow water equivalent, as measured at SNOTEL sites, is one tool that local managers relied on to forecast drought conditions and the amount/timing of runoff. However, the changes to the timing and phase of precipitation, coupled with warmer temperatures identified here can make SNOTEL less accurate in determining the amount of water stored in snow, and in turn for forecasting runoff characteristics. One future objective should be looking into useful indicators, supported by remote sensing to supplement that kind of information. This could include using observed precipitation data with modeling approaches to get a better sense of the snowpack.

This collaborative study also helps to identify important temporal scales for analysis during the water year, in particular, and for placing individual water years in its climatological context. For instance, observations of past drought enable the comparison across drought periods to identify differences in onset, intensity, and persistence, and the specific climatic drivers that contribute to drought conditions on the ground. Drought events are not uniform and therefore different indicators, data, and responses are required depending on the way in which drought presents on the landscape.

Local observations and understandings of past drought provide rich descriptions of the multiple and interacting drivers (climatic and non-climatic) and consequences of drought events. Local observations of drought also help contextualize how changes in climate trends through time relate to the effectiveness of current water management practices. Relatedly, and with respect to the scale of individual water years, the results of this analysis emphasize the importance of not decontextualizing hydroclimate analyses from water management decision timelines. In other words, there is a need to analyze hydroclimate at scales relevant to critical decision-points, which for WRIR means analysis at the scale of months, temperature during the cold season, and the specific time at which snow transitions to rain or when water flow thresholds are reached, for example. All of these factors can help make the science that is produced more usable for managers on the ground. The tools tested and technical assistance provided contribute to the development of an early warning system and builds capacity for accessing climate- and drought-related information. Further, training and educational opportunities have encouraged tribal resource managers to contribute to, and conduct their own, research, monitoring, and planning. For instance, the NDMC and HPRCC provided training for tribal water technicians, the goal of which is to build tribal capacity to enable these managers to develop and refine future Summaries internally.

The project partners also carried out an assessment of key climatological and social-ecological drought vulnerabilities, barriers, and response options at the WRIR. The assessment, upon which this paper is based, helped to identify the "determinants" of drought and climate change vulnerability, and those factors that enable or constrain adaptive capacity (Hayes et al., 2004; Hill and Engle, 2013; Smit and Wandel, 2006; Wandel et al., 2016). As the results indicate, the water cycle at the WRIR is changing, and climate change projections of reduced snowpack, earlier runoff, and changes in the amount, timing, and phase of precipitation, all combine to impact future water availability. Therefore, it is important for managers to develop feasible strategies that address these changes.

In the context of the WRIR, this includes additional reservoir infrastructure, greater access to climate information, and control of the water resources they manage, among others. As we illustrated, a major barrier to drought adaptation in the upper part of the Little Wind Basin is the insufficient storage capacity to capture enhanced early season flows. In 2014, the tribes initiated a storage feasibility study with funds from the Wyoming State Legislature and Wyoming Water Development Commission (WWDC) to assess feasibility of developing new and/or increasing existing storage facilities in the Upper Wind and Little Wind Basins. While the project is moving forward, the WWDC suggested that a reasonable timeline for completion of the study and building new infrastructure is 15–20 years, whereas the tribes are experiencing water shortages now.

This necessitates identification of response options currently available to tribes that increase water availability and enhance drought response. In the Little Wind basin, the state generally allows the TWE to administer water during the irrigation season and declare drought conditions. The integration of EDDI and other climate and drought-related tools that can better capture emerging drought conditions can help the TWE to more rapidly identify drought and therefore declare drought conditions. This formal process then allows the TWE to administer water in the Little Wind River according to prior appropriation and ration water users when necessary.

The tribes are also working to take more control of water resources. For instance, producers at the WRIR recently established the Crowheart and Ray Canal Water Users Association through cooperative agreements with the BIA to gain more control over water allocation and infrastructure maintenance. Similarly, the tribes have secured funding for upgrades to the irrigation canal in the dilapidated BIA-managed system, including the construction of fish ladders and fish screens at diversion points to help maintain the fishery without diminishing water for irrigation. These efforts by the tribes and Water Users Associations enhance efficiency, reduce leakage, and increase water availability in the system. The Water Users Associations have also developed a formal process for rationing/allocating water during water short years, to which the BIA, TWE, and water users have all agreed. This helps ensure that senior, tribal producers receive their water first in the event of drought. Water users and the TWE are also working towards the development of a formal enactment of the Public Law 638 (which stemmed from the *1975 Indian Self-Determination Act 638 contracts and compacts*) to give the TWE and Water Users Associations even more authority over water allocation and delivery across the reservation (McNeeley, 2017).

Many of the stream gauges on the reservation were previously de-commissioned by the BIA and USGS due to federal budget cuts. Yet, the tribes are working with the USGS and BIA to re-commission many of the stream gauges so that water can be more accurately measured and allocated during times of drought. The tribes have also worked with the US Fish and Wildlife Service, TWE, and individual water users in the Little Wind Basin to implement a minimum instream flow requirement to maintain water in the system for fisheries and other uses throughout the year. Producers are considering options on an individual allotment level to increase water availability and efficiency through investment in more water-smart irrigation technologies and practices. However, barriers do exist as more seasoned producers may be reluctant to change practices while others simply cannot afford to make these changes. Producers could also consider crop varieties that are drought resistant and/or require water at earlier periods in the growing season to maximize changes in runoff.

In sum, although inadequate storage is a major barrier to drought management at WRIR, and additional water storage seems unlikely for several years, the tribes are taking matters into their own hands by increasing access to climate and drought-related information that will help managers more quickly and accurately assess and respond to drought conditions, and taking more control of water resources on the reservation, which will ultimately help increase water availability during drought. The TWE are using these insights and tools to initiate a planning process to prioritize future drought mitigation and response measures to be implemented, further refine the selection of indicators to trigger drought conditions, and formalize the roles and responsibilities of relevant tribal agencies during drought events.

6. Conclusions

Drought results from complex interactions between biophysical and social factors. Although drought is part of the natural variability in climate at the WRIR, water shortages have become more common since the turn of the 21st century. Therefore, understanding the nexus of physical and social factors is critical for drought risk assessment and water management. This paper provided an assessment of the 2015 water year at the WRIR. We combined a social science assessment with analysis of the hydroclimate to deconstruct how shortages manifest at the WRIR. Specifically, we (1) described the hydroclimatic and social processes under way that contributed to the 2015 water year micro-drought in the Little Wind Basin; (2) compared water availability conditions in other basins at the WRIR to illustrate how micro-droughts are due to the social and environmental features specific to local systems; and (3) described how this project is supporting drought preparedness at the WRIR. The tribes are working to gain access and control of water resources at the WRIR and enhance efficiency. Yet, there are a number of barriers that limit drought preparedness and response, most notably the combination of hydroclimatic changes combined with a lack of storage to capture early season flows. Due to this, in WY2015 producers in the Little Wind Basin were forced to close the irrigation season more than a month prior to the official closure date, while producers in other basins, who were exposed to similar climatic conditions, had ample water throughout the irrigation season.

This partnership is supporting drought preparedness through the co-production of an early warning system and monitoring infrastructure, capacity building, and conducting a community-driven social-ecological system vulnerability assessment. These insights will be used to directly inform drought planning and help identify short- and long-term adaptation strategies that are actionable at the WRIR. While this assessment is particular to the WRIR case, the insights gleaned from this research and co-production process can serve as a model which can be transferred to other tribal contexts and communities in the north central region and beyond.

Acknowledgments

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Conflicts of Interest

None.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.crm.2017.09.004.

B Interview questions

(1) How do you define or think about drought in the context of your landscape?
(2) Do you view drought as a significant risk to your management activities?
(3) [if yes to #2] At what time of year is drought most problematic (how/why) [this is getting at seasonality/timing issues)?
(4) What year (or years) was the worst drought in this area? What happened?
(5) What management decisions do you have to make that are affected by drought?
(6) a. What, if any, indicators do you use to know if/when/how drought is going to cause negative impacts on your landscape?
 b. What do you consider to be the best source or sources of information on drought?
(7) Are there fish, wildlife, and/or plant species you haven't mentioned impacted by drought in your landscape?
(8) a. Are there human livelihoods or other activities impacted by drought in your landscape?
 b. Does this cause any conflicts?
 c. Do you collaborate with other stakeholders or jurisdictions on drought-related issues? If so, with whom and how?
(9) Do you have the capacity to either respond to or prepare for drought?
(10) Are there barriers that inhibit your ability to respond to or prepare for drought?
(11) Anything else we haven't discussed?

Appendix C

C1. Partitioning of precipitation by phase

The Kienzle method (Kienzle, 2008) considers two empirical parameters: a threshold temperature (T_T), where 50% of precipitation falls as rain, and a range of temperatures where both rain and snow can occur (T_R). While these values can be calibrated to optimally represent the locations of interest, independent measurements of rain and snow fractions are needed to do so. In the absence of these, Kienzle recommends adopting the values of 2 °C for T_T and 13 °C for T_R, which they found to be representative of mid-latitude northern hemisphere mountainous regions. The rainfall proportion (P_{rain}) of daily precipitation, ranging between 0 and 1, is computed as follows:

for $T \leqslant T_T$ and $P_{rain} \geqslant 0$, where T is the mean daily air temperature in °C,

$$P_{rain} = 5*\left(\frac{T-T_R}{1.4*T_R}\right)^3 + 6.76*\left(\frac{T-T_R}{1.4*T_R}\right)^2 + 3.19*\left(\frac{T-T_R}{1.4*T_R}\right) + 0.5 \tag{1}$$

and for $T \geqslant T_T$ and $P_{rain} \leqslant 1$,

$$P_{rain} = 5*\left(\frac{T-T_R}{1.4*T_R}\right)^3 - 6.76*\left(\frac{T-T_R}{1.4*T_R}\right)^2 + 3.19*\left(\frac{T-T_R}{1.4*T_R}\right) + 0.5. \tag{2}$$

Snowfall proportion is obtained as the complement fraction to P_{rain}.

C2. The Evaporative Demand Drought Index

We computed the Evaporative Demand Drought Index (EDDI; Hobbins et al., 2016) at the 2-week (spatially distributed) and 1-month (spatially averaged for the WRIR) time scales. For each aggregation period (i.e., time scale), reference evapotranspiration (ET_0) is accumulated and ranked against the same period in previous years (which form the historical baseline; we used 1981–2015). Empirical rank probabilities are computed and then mapped to an inverse normal approximation to obtain standardized EDDI values. A zero EDDI value indicates that ET_0 accumulated over the aggregation period in a given year is equal to the median value from the reference period; negative values (lower ET_0) indicate wet anomalies and positive values (higher ET_0) indicate dry anomalies.

C3. Decomposition of reference ET

We decomposed (attributed) the changes in 2-week ET_0 time series, spatially averaged for the WRIR, into the contributions from its drivers – wind speed (U_2), temperature (T), solar radiation (R_d), and specific humidity (q) – throughout the irrigation season of WY2015, following the approach presented in Hobbins et al. (2016). Changes in ET_0 are estimated as anomalies observed in the 2-week period of interest relative to its 2-week mean across 1981–2010, and are decomposed as follows:

$$\Delta ET_0 = \frac{\partial ET_0}{\partial U_2}\Delta U_2 + \frac{\partial ET_0}{\partial T}\Delta T + \frac{\partial ET_0}{\partial R_d}\Delta R_d + \frac{\partial ET_0}{\partial q}\Delta q \tag{3}$$

where ΔX represents the anomaly in quantity X {either ET_0, U_2, T, R_d, or q} across the 2-week period and $\partial ET_0/\partial Y$ represents the sensitivity of ET_0 to its driver Y {either U_2, T, R_d, or q} for the 2-week period.

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