Front. Earth Sci. 2020, 14(2): 286–297
https://doi.org/10.1007/s11707-019-0812-6

RESEARCH ARTICLE

Variability and change of climate extremes from indigenous herder knowledge and at meteorological stations across central Mongolia

Sukh TUMENJARGAL[1,2], **Steven R. FASSNACHT** (✉)[1,3,4,5], **Niah B.H. VENABLE**[1,3], **Alison P. KINGSTON**[1,3], **Maria E. FERNÁNDEZ-GIMÉNEZ**[6], **Batjav BATBUYAN**[7], **Melinda J. LAITURI**[1,3], **Martin KAPPAS**[5], **G. ADYABADAM**[8]

1 ESS-Watershed Science, Colorado State University, Fort Collins Colorado, CO 80523-1476, USA
2 Cabinet Secretariat of Government of Mongolia, State House, Ulaanbaatar City 14201, Mongolia
3 Natural Resources Ecology Laboratory, Fort Collins Colorado, CO 80523-1499, USA
4 Cooperative Institute for Research in the Atmosphere, Fort Collins Colorado, CO 80523-1375, USA
5 Cartography, GIS and Remote Sensing Department, Institute of Geography, Georg-August Universität Göttingen, Göttingen 37007, Germany
6 FRS-Rangeland Science, Colorado State University, Fort Collins Colorado, CO 80523-1472, USA
7 Center for Nomadic Pastoralism Studies, Ulaanbaatar 210620, Mongolia
8 Institute of Meteorology, Hydrology and the Environment, Ulaanbaatar 210620, Mongolia

Abstract In semi-arid regions, air temperatures have increased in the last decades more than in many other parts of the world. Mongolia has an arid/semi-arid climate and much of the population are herders whose livelihoods depend upon limited water resources that fluctuate with a variable climate. Herders were surveyed to identify their observations of changes in climate extremes for two *soums* of central Mongolia, Ikh-Tamir in the forest steppe north of the Khangai Mountains and Jinst in the desert steppe south of the mountains. The herders' indigenous knowledge of changes in climate extremes mostly aligned with the station-based analyses of change. Temperatures were warming with more warm days and nights at all stations. There were fewer cool days and nights observed at the mountain stations both in the summer and winter, yet more cool days and nights were observed in the winter at the desert steppe station. The number of summer days is increasing while the number of frost days is decreasing at all stations. The results of this study support further use of local knowledge and meteorological observations to provide more holistic analysis of climate change in different regions of the world.

Keywords climate change, climate extreme indices, indigenous knowledge systems, temperature, precipitation

Received June 25, 2019; accepted December 30, 2019

E-mail: steven.fassnacht@colostate.edu

1 Introduction

Mongolia is a country of extreme and variable climate. General gradients of temperature and precipitation are found from north to south, east to west, and with changes in elevation, which influence the location of different ecozones across the country (Fig. 1). Currently, 120 hydrometeorological stations are operating in Mongolia according to World Meteorological Organization guidelines and procedures (Dagvadorj et al., 2009). Records from these stations and additional information from the Mongolian Institute of Meteorology, Hydrology, and Environment, form the basis of climate information for Mongolia. They supply data used in climate change studies, such as this one, examining changes in climate extremes from station-based analysis and herder observations of change.

Over the period of 1940–2000, the extreme maximum temperature recorded in Mongolia was 43.1°C, with the coldest temperature of -52.9°C occurring in January (Ma et al., 2003; Batima, 2006). Annual mean precipitation is low, ranging between 50 and 100 mm in the southern desert steppe (Gobi/semi desert), 300–400 mm in the northern mountainous regions, and 250–300 mm in the forest steppe regions (Batima and Dagvadorj, 2000; Venable et al., 2015). Rainfall can be intense as noted by herders (e.g., Marin, 2010), with most of the precipitation falling between April to September, of which about 50%–60% falls in July and August. These summer rains are related to atmospheric disturbance from the East Asian

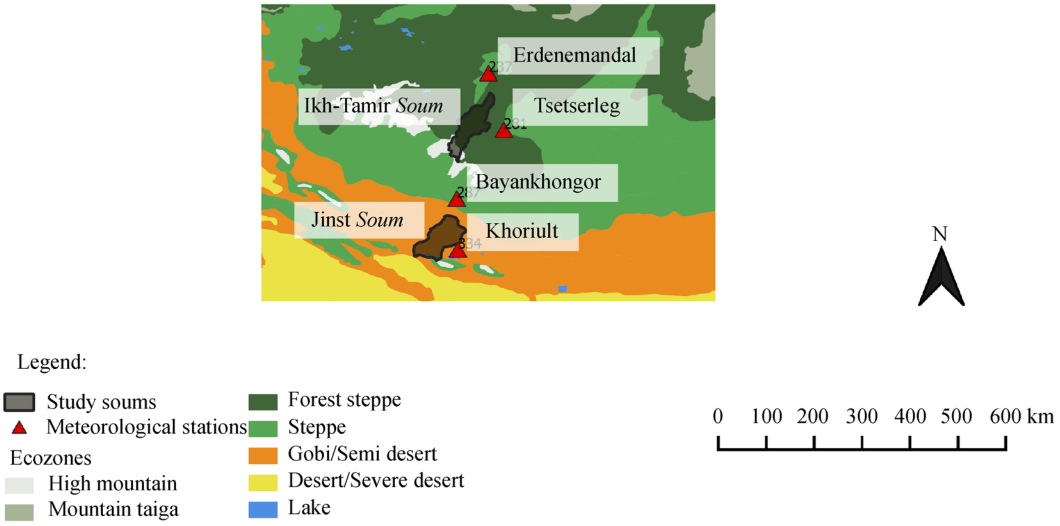


Fig. 1 Location map with associated ecozones for Ikh-Tamir and Jinst *soums*, with the four nearest long-term meteorological stations (Erdenemandal, Tseterleg, Bayankhongor, and Khoriult).

monsoon, though true monsoonal influence does not reach as far north as the Khangai Mountain region in the central part of Mongolia (Dagvadorj et al., 2009; Wen et al., 2010; Nagashima et al., 2013).

According to the National Statistics Office of Mongolia (2019), in 2018 about 73% of the land area was composed of agricultural land, which included pastures and meadows. Earlier estimates of rangeland area were higher, with Angerer et al. (2008) reporting up to 83% of the country dominated by rangelands. Nearly 40% of the population of this arid/semi-arid nation are considered transhumant herders (nomadic pastoralists) (Peart, 1977), who are continuously exposed to the climatic elements as the livestock herds they rely on survive by grazing off natural vegetation (Angerer et al., 2008). Their livelihood also depends upon availability of limited water resources and the effects of a highly variable climate on both forage quantity and accessibility. Harsh weather directly affects animal health and livestock body condition, affecting herder well-being and income.

As a consequence, herders have developed a critical understanding of local climate, i.e., indigenous knowledge (IK) (e.g., Marin, 2010; Fassnacht et al., 2011; Sukh, 2012; Venable et al., 2012; Fernández-Giménez et al., 2015a). Indigenous knowledge (IK) refers to knowledge of a specific place acquired through interaction with the environment over a long period of time (Speranza, et al., 2010). Intimate knowledge of location, place, climate, and other cultural and physical elements needed to sustain a specific way of life (Indigenous Knowledge Systems (IKS)) can prove a valuable source of information different than that obtained through accepted scientific study of the planet (Inglis, 1993; Fernández-Giménez, 2000; Huntington, 2000; Barnhardt and Kawagley, 2005; Bohensky and Maru, 2011; Brooke, 2017). This is particularly true regarding natural resources and their interaction with environmental change (Nakashima and Roué, 2002), changes to climate (Huntington et al., 2004; Gearheard et al., 2010; Speranza et al., 2010; Alexander et al., 2011; Fosu-Mensah et al., 2012; Hou et al., 2012; Simelton et al., 2013; Bruegger et al., 2014; Jiri et al., 2015; Ayanlade et al., 2017) and changes to water resources (Flanagan and Laituri, 2004; Nichols et al., 2004; Fassnacht et al., 2011; Sukh, 2012). There are many IKS studies in Mongolia related to pasture, but fewer are related to regional climate change (Sternberg, 2008; Fernández-Giménez et al., 2015a; Fassnacht et al., 2018a). To understand the climate extremes that herders are exposed to and how those are observed through the lens of indigenous knowledge, we address the following questions for selected areas of the Khangai Mountain region of central Mongolia: a) How have climate extremes changed based on analyses of meteorological station data? and b) What can we learn from IK regarding change of climate extremes in the study area, to provide a more holistic picture of possible impacts of change on herders?

2 Study area

The areas under study here comprise the Ikh-Tamir and Jinst *soums* (smaller administrative units of Government in Mongolia) selected to examine the variability of precipitation and temperature extremes in two different ecological zones (Fig. 1). Ikh-Tamir covers 4877 km^2 and is located in the forest steppe ecological zone, with some of the high mountain zone found in the southern part of the *soum.* It is within Arkhangai *aimag* (administrative province of Government in Mongolia), a region encompassing high mountain, forest steppe, and steppe ecozones covering

55313 km^2 (Dorligsuren et al., 2011, National Statistics Office of Mongolia, 2019). About 70% of the *aimag* area is considered agricultural, including pasture and meadow lands (from 2010 data to correspond to the end of the meteorological record used in these analyses, National Statistics Office of Mongolia, 2019). Ikh-Tamir has mean maximum and minimum temperatures of about +7°C and −7°C (Table 1) at the Erdenemandal and Tsetserleg meteorological stations (Fig. 1) and average annual precipitation between 284 and 338 mm (Table 1). Jinst is 5158 km^2 in size and is primarily in the desert steppe (Gobi/semi desert) ecological zone, with a very small portion of the mountainous south-eastern area considered part of the steppe zone (Fig. 1). Jinst is within Bayankhongor *aimag*, with a size of 45705 km^2. Some sources suggest that 95% of it is rangeland (e.g Baival et al., 2011), but the National Statistics Office of Mongolia (2019) considers 79% of the *aimag* area to be agricultural land, including pasture and meadow lands (2010 data). Average annual precipitation ranges from 196 mm at the Bayankhongor station to 75 mm at the Khoriult meteorological station to the south (Fig. 1), with more variation in temperature in this *soum* than that of Ikh-Tamir (Table 1).

Data from the Bayankhongor meteorological station is used to illustrate variability in the climate record of the region (Figs. 2 and 3). From the early 1960s until 2010, January minimum temperatures averaged −25°C and July maximum temperatures averaged + 25°C (Fig. 2(a)), with a consistent average of 15°C between the daily maximum and minimum temperature (Fig. 2(a)). In the winter (October through March), the coolest maximum and minimum temperatures are as low as −28°C and −40°C, respectively, and the warmest summer (April through September) maximum and minimum temperatures are as high as +35°C and +20°C, respectively (Fig. 2(b)). Annual precipitation can vary by half an order of magnitude with totals ranging from 107 mm in 2001 to 340 mm in 1976. Large inter-annual variability is common in the record (e.g., 314 mm in 1999 and 114 mm in the following year) (Fig. 3(c)). Summer rains can start as early as April (e.g., 1965) and as late as August (e.g., 1974) (Fig. 3(b)).

3 Methods

Extreme indices were calculated using maximum (TX) and minimum (TN) temperature and precipitation data obtained from the Mongolian Institute of Meteorology, Hydrology, and Environment. Ten indices of temperature and precipitation extremes (Table 2) were selected from the list of indices for surface data recommended by the Expert Team for Climate change Monitoring and Detection Indices (Karl et al., 1996; Nicholls et al., 1996; Folland et al., 1999; Groisman et al., 1999; Nicholls and Murray, 1999; Peterson et al., 2001). These indices were used to characterize the region's warm season from April through September and the cool season from October through March. They are named: summer days (SU25), frost days (FD-5), warm days for the two seasons (TX90p), warm nights for the two seasons (TN90p), cool days for the two seasons (TX10p), cool nights for the two seasons (TN10p), indicator of hot days (IHD), indicator of cold days (ICD), the simple daily intensity index (SDII) for precipitation and number of heavy precipitation days (R05mm) (Table 2).

The indices were computed from daily data when fewer than 15 days of record were deemed missing or of poor quality. No further discrimination was needed since periods of missing data were continuous and a month or more in length. The statistical significance of the annual or seasonal trend for each extreme index, given in days per decade except in the case of SDII where it is in mm/day/decade, was computed using the Mann-Kendall test (Mann, 1945; Kendall and Gibbons, 1990) with the rate of change was determined from the Theil (1950) Sen (1968) slope (Gilbert, 1987) method (Table 3).

A questionnaire was administered to Mongolia herders to record their observations of climate change (Fassnacht et al., 2011; Sukh, 2012; Fassnacht et al., 2018a). Herder households were randomly selected in each study location. Each herder had at least 15 years of herding experience, and the discussion focused on comparing when the herders were in their 20s to their current age. The average age of the 20 Ikh-Tamir herders was 53 years while the average age of the 17 Jinst herders was 48. Unlike the point data obtained from meteorological stations, information from

Table 1 Meteorological stations used in this study. The Ikh-Tamir *soum* is represented by the Erdenemandal and Tseterleg meteorological stations. Jinst *soum* is represented by the Bayankhongor and Khoriult meteorological stations. All station records started in the early 1960s and have between 46 and 50 years of complete record (< 5% of the days missing), except the Khoriult station that started in 1971 which had 26–33 years of complete record (differing for each of the three meteorological variables)

Station name	Station number	Latitude °N	Longitude °E	Elevation /m	Average maximum temperature /°C	Average minimum temperature /°C	Average annual precipitation /mm	Coefficient of Variation /%
Erdenemandal (Эрдэнэманда)	48501400	48.32	101.23	1510	+ 7.1	−7.2	284	19
Tsetserleg (Цэцэрлэг)	47401500	47.27	101.28	1693	+ 7.6	−5.3	338	17
Bayankhongor (Баянхонгор)	46100700	46.08	100.41	1859	+ 7.5	−6.1	196	32
Khoriult (Хориулт)	46100700	45.17	100.73	1280	+ 11.9	−2.3	75	32

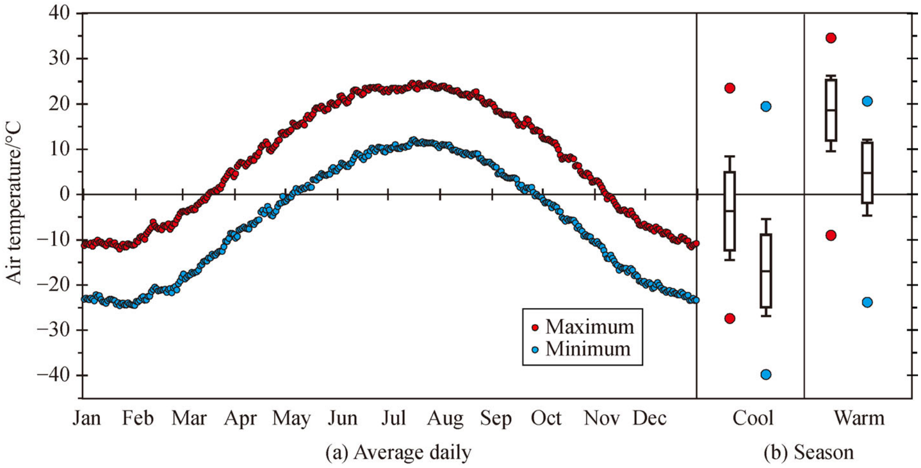


Fig. 2 Temperature summary for the period from 1964 to 2010 at the Bayankhongor meteorological station illustrating (a) the average daily maximum and minimum air temperature, and (b) the winter (October through March) and summer (April through September) seasonal maximum (red) and minimum (blue) temperature summaries. The box and whisker plots illustrate the warmest and coldest observed temperatures (circles), 90th and 10th percentiles (whiskers), one standard deviation (box), and the mean (center).

herders is a composite of experience and association with a particular part of the landscape. The spatial extent of these observations varies depending on length of herder experience, seasonality of observations, and interactions with other herders under customary and formal institutions defining and allocating pasture use (e.g., Fernández-Giménez, 2000).

In the quantitative portions of the climate change questionnaires closed-ended questions (Likert, 1932) to determine herder observations of changes in climate extremes were not specifically asked. However, the questionnaires were followed by an open-ended discussion to document qualitative narratives of observations of change. The narratives of the surveys were analyzed using a technique similar to that of Auerbach and Silverstein (2003). The qualitative responses were analyzed by thematic coding and then sorted. When initial coding was completed, quotations related to each theme were reviewed. The frequency of specific themes across the interviews was calculated by recording the number of passages coded for each theme.

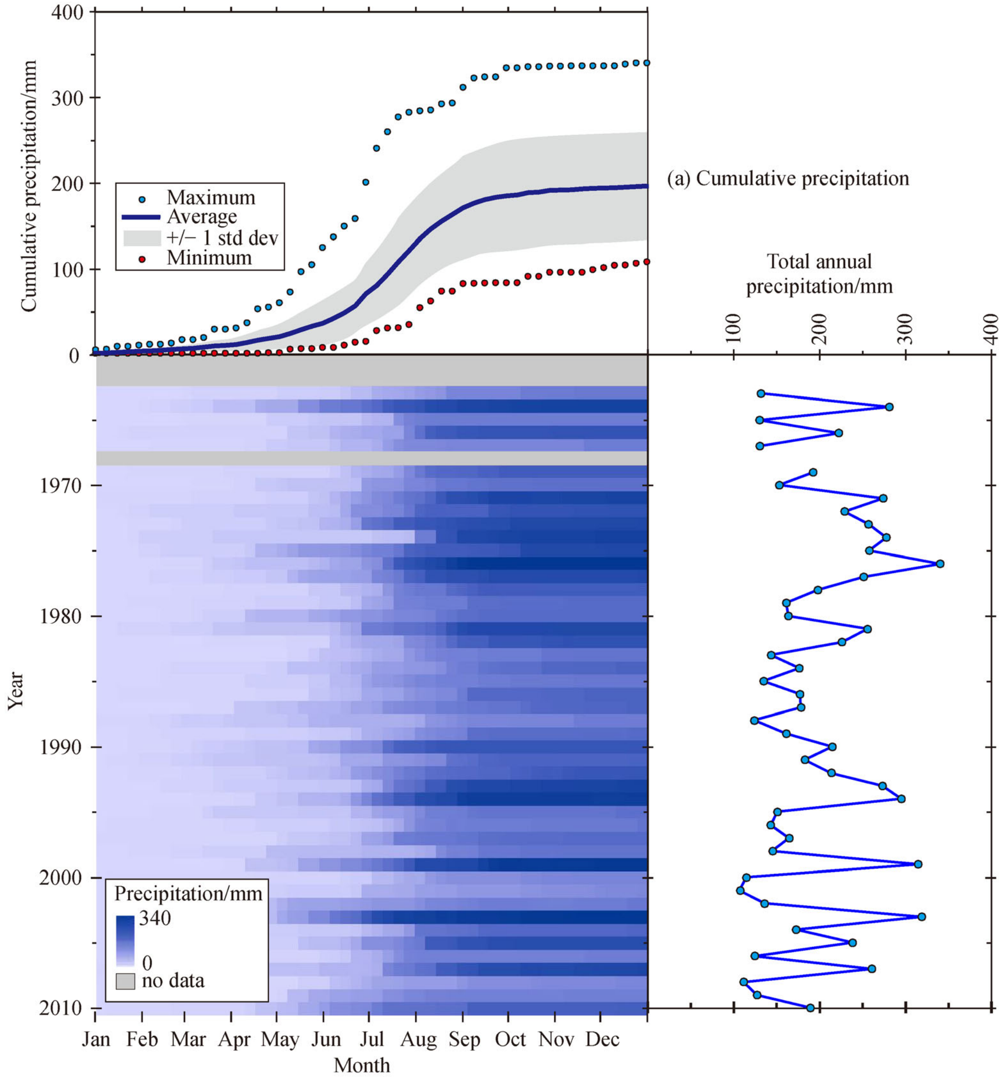
4 Results

4.1 Station-based changes in extreme climate

The time series trends for the four meteorological stations show significant annual and monthly warming over the period of analysis from 1961 to 2010, with the greatest warming occurring at all stations in February (0.8 to 1.1°C/decade), April (0.7 to 1.0°C/decade), July (0.5 to 1.0°C/decade) and August (0.4 to 0.5°C/decade) (Fig. 4). Warming was not significant at any station in January and November and was only significant at Erdenemandal in March and December with this station illustrating the greatest annual warming (0.39 and 0.64°C/decade for maximum and minimum temperatures, respectively). Statistically significant warming of annual maximum temperatures was not observed at Khoriult (Fig. 4), possibly due to the shorter period of record starting in 1971 (Venable et al., 2012).

A decrease in precipitation was observed from July through September, yet it was only significant for the annual totals at Erdenemandal and in August at Tsetserleg (Fig. 4(b)). Year to year variability in precipitation is quite high (e.g., Fig. 3(c)). Autocorrelation of the annual precipitation amounts was low overall; it was 0.21 at Erdenemandal, 0.19 at Tsetserleg, 0.10 at Bayankhongor, and 0.03 at Khoriult. Autocorrelation refers to relation between one data point and the next, meaning that when autocorrelation is high the data are correlated, which reduces the effective size of the data set biasing trend analysis results toward statistical significance. In this case, the result of low autocorrelation in the annual values strengthens confidence in the trend results at that timestep. The precipitation time series was detrended with the Sen's slope to compute the coefficient of variation. It was higher in Bayankhongor *aimag* (32% at both stations) than Arkhangai *aimag* (19% at Erdenemandal and 17% at Tsetserleg) since precipitation was much less in the south (Table 1). The standard deviation was between 60 and 70 mm for all stations except Khoriult where it was 33 mm.

Many of the various extreme indices selected to match the herder observations illustrated that significant change has occurred (Table 3). The number of summer days has increased by 4.8 to 5.8 days per decade for the three northerly stations (Erdenemandal, Tsetserleg, Bayankhongor) and at a lesser rate of 2.9 days per decade at Khoriult (Table 3). Conversely, the number of frost days decreased



(a) Cumulative precipitation

(b) Year-by-year cumulative precipitation

(c) Total annual precipitation

Fig. 3 Precipitation summary for the period from 1964 to 2010 at the Bayankhongor meteorological station illustrating (a) cumulative precipitation showing the maximum (blue circles), minimum (red circles), one standard deviation (gray shading), and the mean (blue line), (b) year-by-year cumulative precipitation for each year (in 7-day periods), and (c) total annual precipitation for each year.

Table 2 The name, abbreviation (ID) and definition for temperature and precipitation indices

Indicator Name	ID	Definitions
summer days	SU25	frequency of days when TX (daily maximum) > + 25°C
frost days	FD-5	frequency of days when TN (daily minimum) < −5°C
warm days for the two seasons	TX90p	percentage of days when TX > 90th percentile
warm nights for the two seasons	TN90p	percentage of days when TN > 90th percentile
cool days for the two seasons	TX10p	percentage of days when TX < 10th percentile
cool nights for the two seasons	TN10p	percentage of days when TN < 10th percentile
indicator of hot days	IHD	days with at least 6 consecutive days when TX > 90 percentile
indicator of cold days	ICD	days with at least 6 consecutive days when TN < 10 percentile
simple daily intensity index*	SDII	annual total precipitation divided by the number of wet days (defined as precipitation ≥ 1.0mm in the year)
number of heavy precipitation days**	R05mm	annual count of days when precipitation ≥ 5mm

Note: The units are days, except the (*) simple daily intensity index which has units of mm/day. The warm season is April through September and the cool season is October through March. The daily minimum temperature is denoted as TN and the daily maximum temperature is denoted as TX. Often a threshold of 10 mm is used to define heavy precipitation, but due to the arid nature of Mongolia, a threshold of 5 mm per day was used by about 4.0 days per decade at all stations, except Erdenemandal that saw 5.0 fewer frost days per decade (Table 3). This station also saw the greatest warming (Fig. 4(a)).

Warm season warm days increased significantly by 4.3 to 5.6 days per decade (Table 3) primarily since the mid-1990s (Fig. 5(a)), warm season cool nights decreased significantly from 1.9 to 3.7 days per decade (Table 3, Fig. 5(b)), cool season warm days only increased significantly by 1.4 days per decade at Bayankhongor (Table 3, Fig. 5(c)), and cool season cool nights decreased significantly by 2.5 days at Erdenemandal and 2.1 days at Bayankhongor, respectively (Table 3, Fig. 5(d)). Conversely to the latter trend, the number of cool days and nights increased during the cool season at Khoriult, though this result was not significant.

During the 2010 cool season, there were many more cool nights than all previous years, with the exception of 1969 (Fig. 5(d)). This is due to the extreme cold in the winter of 2009–2010. An extreme winter weather disaster, called *dzud*, occurred that winter in Arkhangai and Bayankhongor (Fernández-Giménez et al., 2012; Venable et al., 2012; Fernández-Giménez et al., 2015b). The annual timestep indicator of hot days at all stations showed the same significant trends as warm days over the warm season with 1.4 to 2.5 more days per decade (Table 3). The indicator of cold days only showed Bayankhongor to be significantly decreasing at a rate of 1.5 days per decade (Table 3).

Of the two extreme indices used for assessing rain intensity (simple daily intensity index-SDII and number of heavy precipitation days-R05mm), there were significant decreases in the number of heavy precipitation days at Tsetserleg and Bayankhongor of 1.1 and 0.9 to days per decade, respectively (Table 3). A decrease in the simple daily intensity index (SDII) of 0.38 mm per day per decade was seen at the Bayankhongor station (Table 3). The three northern stations saw a decrease (Bayankhongor's increase was significant) in the simple daily intensity index, while Khoriult saw a non-significant increase in SDII (Table 3).

4.2 Herder observations of changes in extreme climate

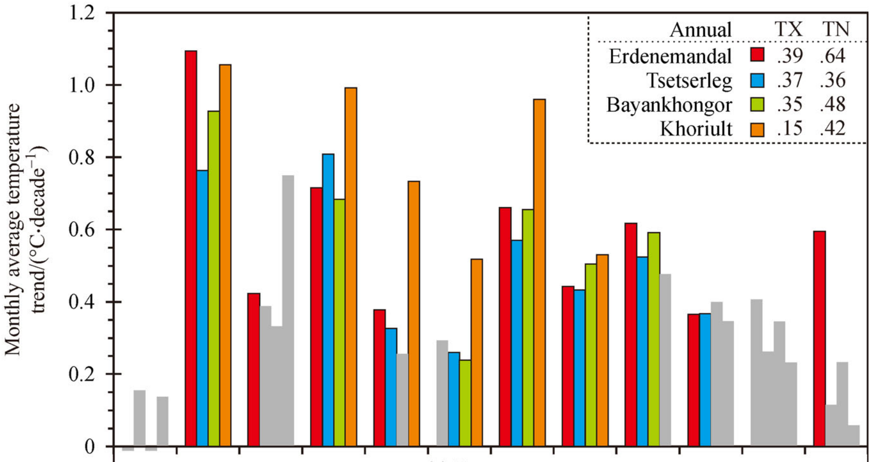
Local herders in both Ikh-Tamir and Jinst *soums* described the basic processes of climate changes based on their experiences and observations with nomadic herding practices. The herders stated that their environment has become more challenging due to frequent extreme or harsh weather events. All herders in both *soums* stated that drought and windstorms were occurring more often with droughts lasting longer. Almost all (80% to 95%) herders also stated that extreme winter storms (*dzud*) and sandstorms were occurring more often, with *dzud* lasting longer. In conversation, herders commented that extreme hot and cold days were occurring more often, with the narratives suggesting an increase in the number of hot summer days, cold summer nights, and warm winter days and nights.

Many herders reported that the average temperature had increased in recent years. This warming temperature was observed to be greater in the cool season with February and April warming the most, followed by July (Similar results to Fig. 4(a)). Herders have been adapting to this warmer weather during the last 10 to 20 years. One herder in Jinst said that "in the 1970s, I never observed snowmelt in winter. But in the past few decades, I have observed

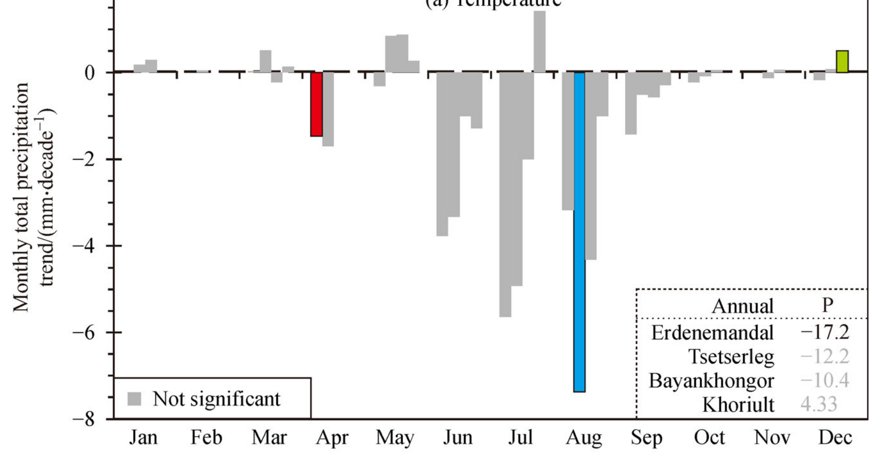
Table 3 Annual or seasonal trends for indices of temperature and precipitation extremes, as defined in Table 2

Index	Figure	Season	Erdenemandal	Tsetserleg	Bayankhongor	Khoriult
SU25	-	annual	+ 5.8 ^{a}	+ 4.8 ^{a}	+ 5.5 ^{a}	+ 2.9 ^{a}
FD-5	-	annual	−5.0 ^{a}	−4.0 ^{a}	−3.8 ^{a}	−3.8 ^{a}
warm days	4a	warm	+ 5.6 ^{a}	+ 5.0 ^{a}	+ 4.3 ^{a}	+ 5.0 ^{a}
TX90p	4c	cool	+ 0.87	+ 0.79	+ 1.4 ^{a}	+ 1.0
warm nights	-	warm	+ 5.0 ^{a}	+ 4.1 ^{a}	+ 4.7 ^{a}	+ 6.7 ^{a}
TN90p	-	cool	+ 2.3 ^{a}	+ 1.9 ^{a}	+ 1.8 ^{a}	+ 2.9 ^{a}
cool days	-	warm	−2.0 ^{a}	−2.1 ^{a}	−1.0	−1.0
TX10p	-	cool	−0.67	−1.1	−1.1	+ 2.9
cool nights	4b	warm	−2.9 ^{a}	−1.9 ^{a}	−2.4 ^{a}	−3.7 ^{a}
TN10p	4d	cool	−2.5 ^{a}	−1.6	−2.1 ^{a}	+ 0.92
IHD-TX90p	-	annual	+ 1.8 ^{a}	+ 1.7 ^{a}	+ 1.4 ^{a}	+ 2.5 ^{a}
ICD-TN10p	-	annual	−1.6	0	−1.5 ^{a}	−1.5
SDII	-	annual	−0.15	−0.059	−0.38 ^{a}	+ 0.074
R05mm**	-	warm	−0.59	−1.1 ^{a}	−0.91 ^{a}	0

Note: All trends are in days per decade, except SDII which is in mm/day/decade. Statistical significance is given as ^{a} for $p < 0.05$. The plus (+) sign has been added into increasing trends to differentiate from decreasing (-) trends. i) the trends in consecutive dry days (CDD) were not significant (negative for all stations except Erdenemandal) and the trends in consecutive wet days (CWD) were zero for all stations, ii) ** the trends were not significant using a threshold of 10mm to define heavy precipitation, but were significant using a threshold of 5 mm per day.



(a) Temperature



(b) Precipitation

Fig. 4 Monthly and annual (a) temperature trends (°C/decade), and (b) precipitation trends (mm/decade) at the four meteorological stations. Significant trends at $p < 0.05$ are shown in black and/or are outlined.

snowmelt earlier in winter occasionally due to higher temperatures; this is an unusual and unseasonal phenomenon." An Ikh-Tamir respondent also reported that "in the 1970s, the winters were very cold with lower temperatures reached minus 40 degree Celsius and we used fur coats, felt boots and sheep skin hat at that time. Due to rising temperature we had not used any of these warm clothes since the 1990s." One female elder added that they kept their warm clothes in small house at the *soum* center or in winter shelters and did not need to use them. However, herders in the Ikh-Tamir *soum* and to a lesser extent in Jinst experienced an extremely cold winter in 2009-2010 with lower temperatures, resulting in needing warm clothes again (Sukh, 2012). The lower temperatures started in December with both animals and herders getting frostbite on their noses and ears.

Variable precipitation patterns, changing rainfall intensities, and rising temperatures are key factors of increasing climate unpredictability, with extreme events identified as affecting herders (Davi et al., 2009). Herders in the forest steppe, steppe, and desert steppe (Gobi/semi desert) ecological zones commented on their concerns about changes in the amount of precipitation, patterns, timing, and magnitude over the past decade. Seventy-one percent of herders surveyed in Jinst and one hundred percent of those in Ikh-Tamir noted that there has been a large decrease in rainfall, with the remaining Jinst herders perceiving a small decrease in rainfall (Sukh, 2012).

In recent years, observations suggest that the duration of rainfall has become shorter and has been seen to last only a few hours with high intensity and low infiltration into the soil which adversely affects the recharge and availability of water sources such as shallow wells and springs. From the quantitative survey, 80% of Ikh-Tamir herders and 65% of Jinst herders observed more intense rain, which was observed with low infiltration. For example, Ikh-Tamir herders stated that, "In the past few years, short and intense rainfall has occurred which produced high runoff and did not saturate the soil moisture. Previously, rainfall duration was longer with soft rain and it's enough to saturate soil moisture and affect good quality grass growing." Herders in Ikh-Tamir also reported that "20 years ago, we had a long duration of rain which lasted 3 or 4 days and we did not have any dry clothes (deel traditional clothing) to wear

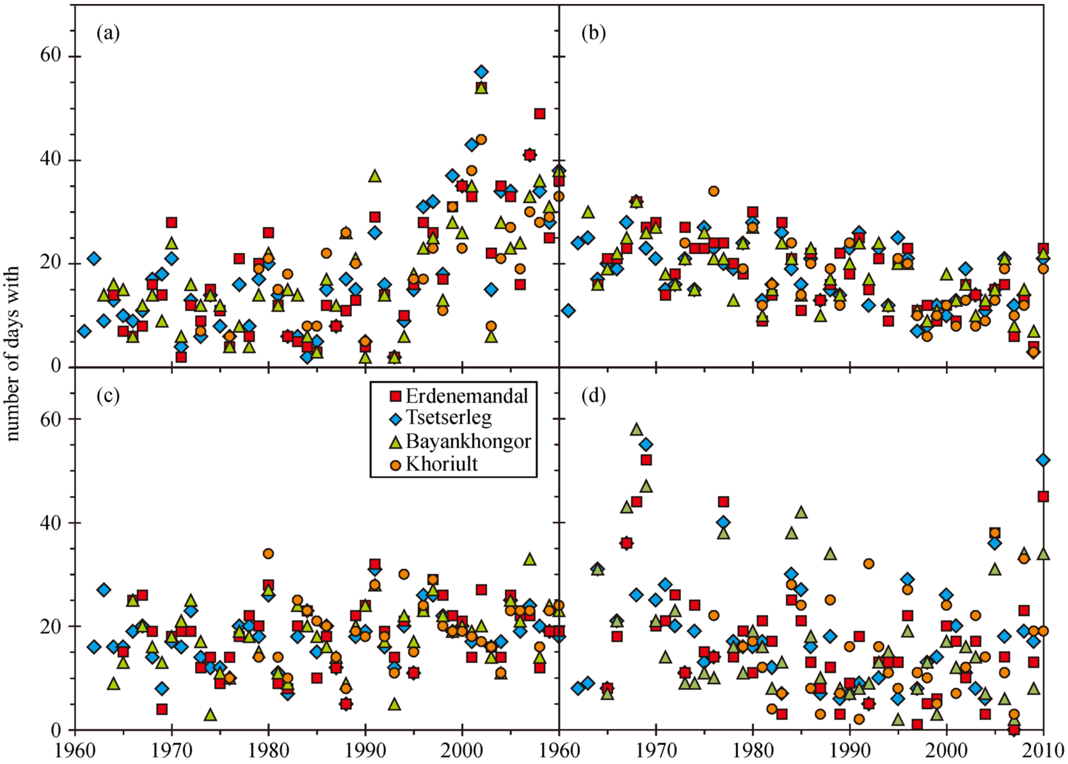


Fig. 5 Time series for the indices of (a) warm season (April through September) warm days (TX90), (b) warm season cool nights (TN10), (c) cool season (October through March) warm days (TX90), and (d) cool season cool nights (TN10).

and hardly found dry trees to make fire for cooking at that time." One herder in Jinst said that "in the summer of 2009, rainfall occurred only in May and less rain than previous which caused prolonged drought during the summer and animal did not gain enough weight." Many of herders said that "generally, summers were very dry here (with) hardly any rain in recent years."

5 Discussion

Due to its location, fragile natural ecosystems, lifestyle of the people, and the economic situation, Mongolia is extremely sensitive to climate changes (Sternberg, 2008). Over 66 million head of livestock are herded across Mongolia, supporting one third of the country's population and about 14% of the national economy (National Statistical Office of Mongolia, 2019). As such, the livelihood of Mongolian pastoralists depends to a great extent on the effects of extreme weather elements and forces them to observe and record quantitative and qualitative characteristics of a large number of climate variables (Marin, 2010). The most significant impacts of climate change to herders are likely to arise from shifts in the intensity, frequency, and duration of extreme weather events (Beniston and Stephenson, 2004, Goulden et al., 2016). As an example, due to the warm winters, herders and many in Ikh-Tamir felt extremely cold in the winter of 2009–2010 when temperatures were among the lowest on record (Venable et al., 2012). Indeed, herders affected by climate extremes state that the changes have influenced pasture quality, livestock production and thus their livelihoods (Fernández-Giménez et al., 2015a and 2017). Though it has also been shown that pastoralist knowledge of climate variables and extremes can influence their strategies to reduce vulnerability to weather events and, in a broader sense, to adverse climate change (Speranza et al., 2010).

5.1 Temperature

Understanding the complex and dynamic nature of the climate system is a serious challenge (Nichols et al., 2004), especially in Mongolia, a country that has seen some of the strongest warming trends in the world, with the greatest warming occurring during the past 60 years (Batima, 2006). Nandintsetseg et al. (2007) further illustrated that warming is most pronounced in the cool season (February and April in Fig. 4(a)), which corresponds to herders' observations in this work (Sukh, 2012; Fernández-Giménez et al., 2015a). Batima (2006), concluded that air temperature increases were much higher in mountainous regions than in the Gobi Desert (Batima, 2006), but in the study areas here, these differences were limited (Venable et al., 2015; Fig. 4).

The Khangai Mountain region spans several ecological zones (forest steppe to steppe and desert steppe (Gobi/semi desert)), and herders in all of these ecozones have observed changes to local and regional hydrometerology and climate which relate to those changes observed in the meterological record analyzed here (Table 3, Figs. 4 and 5) (Fassnacht et al., 2011 and 2018a; Sukh, 2012). Herders have reported experiencing and adapting to warmer weather during the last decade, and in recent years have not used any of their traditional warm clothes made of felt and fur (Sukh, 2012). This finding is reflected in the long term station time series for extreme temperature indices which show that in the two study areas there have been significant decreases in the frequency of extreme cold days at some stations and decreases in cool nights in both the warm and cool seasons at most stations. This change is accompanied by increases in the frequency of extreme hot days, with significant increases in warm season warm days (Table 3, Fig. 5). However, some herders have also reported more cold nights during the last decade. A reduction of cold extremes during warming periods for the winter indicates the opposite (Yan et al., 2002). Given the spatially indistinct nature of herder's observations as compared to point-based meteorological records, it is possible that the herder observations reflect localized conditions.

These localized conditions may be reflected in the finding that the station-based temperature trends for cool days in the cool season, and cool nights in the cool season at Khoriult were opposite of those at the other three stations, though annual frost days were decreasing significantly, as with the other stations (Figs. 4(a) and 5; and Table 3). These results may also be due to the trends being not significant and/or to the station having a length of record that is shorter than the other stations (Fig. 5) (Venable et al., 2012). They could also be related to the fact that Khoriult is located is in a different ecozone than the other stations (Venable et al., 2012; Fassnacht et al., 2018a). It is is in the desert steppe ecozone and located in a topographic basin in proximity to complex terrain, which could affect local temperatures. Other research has shown that trends in cooling and warming between stations, even without complex terrain, can differ significantly (e.g. Pielke et al., 2002; Fassnacht et al., 2016).

In some regions of the world, increasing temperatures have been driven not by a changing climate but rather by changes at or near the recording stations. Large increases in some locations have been due to instrumentation changes (e.g., a 2°C warming over 20 years observed in Northern Colorado by Fassnacht et al., 2017; Ma et al., 2019; Fassnacht et al., 2018b). This may not be a problem in Mongolia, however as the same monitoring equipment has been used since the 1960s. At other locations, populations have increased dramatically in urban centers and the associated infrastructure change has created an urban heat island effect that produces an apparent warming trend at the recording stations. In Mongolia, population increases have been dramatic only in the capital of Ulaanbaatar (National Statistical Office of Mongolia, 2019). There have been some increases in population at *aimag* centers (Tsetserleg and Bayankhongor) but less so at the *soum* centers (Erdenemandal and Khoriult). Three of these stations were visited (all except Erdenemandal); all stations were located away from the urban center (Bayankhongor and Khoriult) or had a large buffer zone without infrastructure around the station (Tsetserleg). Therefore, infrastructure or urbanization induced warming has likely been minimal for the stations under study.

5.2 Precipitation

Fluctuations in precipitation, such as the amount, timing and magnitude, coupled with increasing temperature trends create an environment where variability and extreme events affect drought occurrence in Mongolia (Gong and Wang, 2000). Herders have observed changes in time scale, spatial distribution, and magnitude of precipitation. All surveyed herders in Jinst and Ikh-Tamir observed a general decrease in precipitation (Fassnacht et al., 2018a). Their statements regarding decreased amounts of rainfall were quite consistent. They stated that "rainfall has decreased a lot." The herder observations match the overall decrease in summer precipitation observed at the stations (Venable et al., 2015; Fig. 4(b)). Annual precipitation decreases were only significant in Ikh-Tamir (Erdenemandal and Tsetserleg stations, Fig. 4(b)) with precipitation decreasing for most months (Venable et al., 2015; Fassnacht et al., 2018a). However, these decreases were significant for only two months. Conversely, Khoriult saw increases in annual precipitation, though only December had a significant increase (Fig. 4(b)). Considerations for changes in the phase of the precipitation, i.e., rain versus snow (Fassnacht et al., 2013), are also relevant but not investigated here.

This general decrease is also seen in the negative trends in the simple daily intensity index (SDII) and number of heavy precipitation days (R05mm), but is only significant at the Tsetserleg (R05mm only) and Bayankhongor stations (Table 3). Variation in the summer rains in Mongolia and monsoonal rains further south are common (Wen et al., 2010; Nagashima et al., 2013) and may be reducing summer precipitation overall (Venable et al., 2015; Fig. 4(b)). Iwasaki and Nii (2006) have explained the break in mid-July rains as a result of the development of a barotropic ridge (where upper atmospheric conditions are fairly uniform over a large area, leading to a degree of stability in that area) in Central Mongolia, effectively suppressing all rains except local, heavy rains due to thermally induced local circulation around mountains.

North-west of the study area at Lake Khövsgöl, an increase in the frequency of short heavy rains has been observed by both herders and at meteorological stations. Here, herders referred to what they perceived was "more intense and shorter rain" relating to its impact on soil moisture, vegetation and runoff. In other studies, herders note different intensities of rain, such as hard and soft (Marin, 2010) and *namira boroo* (very light rain), *shivree boroo* (small drops lasting several hours), *zuser boroo* (low to medium intensity lasting several days), and *aadar boroo* (intense rain) (NAMHEM, 2008). Subsequent herder questionnaires should incorporate such terminology to understand rain intensity (Goulden et al., 2016).

Herders provided IKS of climatic conditions functions as an assessment of climate change over the landscape (Sternberg, 2008; Fernández-Giménez et al., 2015a; Fassnacht et al., 2018a). Results from point-based station analysis can be used to design questions for herder surveys to better merge IKS and station data (Fassnacht et al., 2018a). Further, analysis combining data types could use the concept of boundary objects, as has been applied to this study area (Venable, 2017). Examining indigenous knowledge is crucial for understanding why certain actions among pastoralists create different exposures to extremes and increased or reduced sensitivity to harm, something that is difficult to determine using meteorological data analysis results alone. Future investigations of changes in climate and water resources, especially in regions with limited station data (Venable, 2016) should use IKS to supplement the station data.

6 Conclusions

This study compares indigenous knowledge from nomadic pastoral herders with statistical analysis from meteorological station records to examine indicators of extreme climate variability and change in the Khangai Mountain region of central Mongolia. The herders surveyed provided a detailed quantitative and qualitative description of weather and climate elements they have experienced. While observations by herders do not cover the same spatial scale as point-based meteorological observations, they provide important supportive information on changing climate extremes using multiple indicators.

The three northerly stations (Tsetserleg, Erdenemandel, Bayankhongor) showed the same trends in climate extremes, while the southern-most station (Khoriult) had similar trends for some variables and opposite trends for others, mostly like due to the effects of record length or localized conditions. Warm days and nights were occurring more often at all stations, while cool days and nights were becoming fewer at the three northerly stations. Summer days were increasing and frost days were decreasing at all stations. Almost all of these trends were significant, and many were reflected in the observations of change made by herders. They observed a general increase in frequency of extreme precipitation, but this increase was not captured by station record trend analysis. Station records showed that rainfall intensity and days with heavy rain were decreasing at the three northerly sites, while intensity was increasing at Khoriult.

Indigenous knowledge about climate extremes and climate change comes from herders' interactions with their natural environment that forces them to gather, interpret and transmit weather and climate observations. This process strengthens the credence of their observations of change, generally complementing the findings of meteorological station data analysis for stations in the study area. It is recommended that indigenous knowledge from herders be combined with station record analysis to provide more holistic information about climate extremes and changes using different approaches, covering different spatial scales, and to increase the relevance of future assessments for herder adaptations to climate change.

Acknowledgements This research was supported by the National Science Foundation Dynamics of Coupled Natural and Human Systems (CNH) Program (award BCS-1011801 entitled Does Community-Based Rangeland Ecosystem Management Increase Coupled Systems' Resilience to Climate Change in Mongolia?). The herder data were collected through contributions from the Center for Collaborative Conservation at Colorado State University, and the World Bank (award 7155627 entitled Understanding Resilience in Mongolian Pastoral Social-Ecological Systems: Adapting to Disaster Before, During and After the 2010 *Dzud*).

References

Alexander C, Bynum N, Johnson E, King U, Mustonen T, Neofotis P, Oettlé N, Rosenzweig C, Sakakibara C, Shadrin V, Vicarelli M, Waterhouse J, Weeks B (2011). Linking indigenous and scientific knowledge of climate change. Bioscience, 61(6): 477–484

Angerer J, Han G, Fujisaki I, Havstad K (2008). Rangelands, 30(3): 46–51

Auerbach C F, Silverstein L B (2003). Qualitative Data: an Introduction to Coding and Analysis. New York: New York University Press

Ayanlade A, Radeny M, Morton J F (2017). Comparing smallholder farmers' perception of climate change with meteorological data: a case study from southwestern Nigeria. Weather Clim Extrem, 15: 24–33

Baival B, Oyuntulkhuur B, Altanzul T, Fernández-Giménez M E (2011). A case study of community-based rangeland management in Jinst Soum, Mongolia. In: Fernández-Giménez M E, Wang X, Baival B, Klein J, Reid R, eds. Restoring Community Connections to the Land: Building Resilience through Community-based Rangeland Management in China and Mongolia. Wallingford: CABI Press

Barnhardt R, Oscar Kawagley A (2005). Indigenous knowledge systems and Alaska Native ways of knowing. Anthropol Educ Q, 36(1): 8–23

Batima P (2006). Climate Change Vulnerability and Adaptation in the Livestock Sector of Mongolia: A Final Report Submitted to Assessments of Impacts and Adaptations to Climate Change (AIACC), International START Secretariat: Project No. AS 06

Batima P, Dagvadorj D (2000). Climate Change and Its Impacts in

Mongolia. Mongolia: JEMR Publishing

Beniston M, Stephenson D B (2004). Extreme climate events and their evolution under changing climatic conditions. Global Planet Change, 44(1-4): 1–9

Bohensky E L, Maru Y (2011). Indigenous knowledge, science, and resilience: what have we learned from a decade of international literature on integration? Ecol Soc, 16(4): 6

Brooke L F (2017). The participation of indigenous peoples and the application of their environmental and ecological knowledge in the Arctic Environmental Protection Strategy. In: Proceedings of the Inuit Circumpolar Conference. Ottawa, 28–30

Bruegger R A, Jigjsuren O, Fernández-Giménez M E (2014). Herder observations of rangeland change in Mongolia: indicators, causes, and application to community-based management. Rangeland Ecol Manag, 67(2): 119–131

Dagvadorj D, Natsagdorj L, Dorjpurev J, Namkhainyam B (2009). Mongolia: Assessment Report on Climate Change. Ministry of Nature, Environment and Tourism, Mongolia

Davi N K, Jacoby G C, D'Arrigo R D, Baatarbileg N, Jinbao L, Curtis A E (2009). A tree-ring based drought index reconstruction for far-western Mongolia. Int J Climatol, 29(10): 1508–1514

Dorligsuren D, Batbuyan B, Bulgamaa D, Fassnacht S R (2011). Lessons from a territory-based community development approach in Mongolia: Ikh-tamir Pasture user groups. In: Fernández-Giménez M E, Wang X, Baival B, Klein J, Reid R, eds. Restoring Community Connections to the Land: Building Resilience through Community-based Rangeland Management in China and Mongolia. Oxfordshire: CABI Press

Fassnacht S R, Sukh T, Fernández-Giménez M E, Batbuyan B, Venable N B H, Laituri M, Adyabadam G (2011). Local understanding of hydro-climatic changes in Mongolia. In: IAHS Proceedings of symposium Cold Region Hydrology in a Changing Climate held during IUGG2011. Melbourne: 120–129

Fassnacht S R, Venable N B H, Khishigbayar J, Cherry M L (2013). The probability of precipitation as snow derived from daily air temperature for high elevation areas of Colorado, United States. In: IAHS-IAPSO-IASPEI Proceedings of symposium Assembly Cold and Mountain Region Hydrological Systems Under Climate Change: Towards Improved Projections, Gothenburg: 65–70

Fassnacht S R, Cherry M L, Venable N B H, Saavedra F (2016). Snow and albedo climate change impacts across the United States Northern Great Plains. Cryosphere, 10(1): 329–339

Fassnacht S R, López-Moreno J I, Ma C, Weber A N, Pfohl A K D, Kampf S K, Kappas M (2017). Spatio-temporal snowmelt variability across the headwaters of the southern Rocky Mountains. Front Earth Sci, 11(3): 505–514

Fassnacht S R, Allegretti A M, Venable N B H, Fernández-Giménez M E, Tumenjargal S, Kappas M, Laituri M J, Batbuyan B, Pfohl A K D (2018a). Merging indigenous knowledge systems and station observations to estimate uncertainty of precipitation change in central mongolia. Hydrology, 5(3): 46

Fassnacht S R, Venable N B H, McGrath D, Patterson G G (2018b). Sub-seasonal snowpack trends in the Rocky Mountain National Park area, Colorado USA. Water, 10(5): 562

Fernandez-Gimenez M E (2000). The role of Mongolian nomadic pastoralists' ecological knowledge in rangeland management. Ecol Appl, 10: 1318–1326

Fernández-Giménez M E, Batkhishig B, Batbuyan B (2012). Cross-boundary and cross-level dynamics increase vulnerability to severe winter disasters (*dzud*) in Mongolia. Glob Environ Change, 22(4): 836–851

Fernández-Giménez M E, Angerer J P, Allegretti A, Fassnacht S R, Byamba A, Chantsallkham J, Reid R, Venable N B H (2015a). Integrating herder observations, meteorological data and remote sensing to understand climate change patterns and impacts across an eco-climatic gradient in Mongolia. In: Fernández-Giménez M E, Batkhishig B, Fassnacht S R, Wilson D, eds. Proceedings of Building Resilience of Mongolian Rangelands: A Trans-disciplinary Research Conference, Ulaanbaatar, 228–234

Fernández-Giménez M E, Batkhishig B, Batbuyan B, Ulambayar T (2015b). Lessons from the *dzud*: community-based rangeland management increases adaptive capacity of Mongolian herders to winter disasters. World Dev, 68: 48–65

Fernández-Giménez M E, Venable N H, Angerer J, Fassnacht S R, Reid R S, Khishigbayar J (2017). Exploring linked ecological and cultural tipping points in Mongolia. Anthropocene, 17: 46–69

Flanagan C, Laituri M (2004). Local cultural knowledge and water resource management: the Wind River Indian Reservation. Environ Manage, 33(2): 262–270

Folland C K, Miller C, Bader D, Crowe M, Jones P, Plummer N, Richman M, Parker D E, Rogers J, Scholefield P (1999). Workshop on indices and indicators for climate extremes, Asheville, NC, USA, 3–6 June 1997 Breakout Group C: Temperature Indices for Climate Extremes. Clim Change, 42(1): 31–43

Fosu-Mensah B Y, Vlek P L, MacCarthy D (2012). Farmers' perception and adaptation to climate change: a case study of Sekyedumase district in Ghana. Environ Dev Sustain, 14(4): 495–505

Gearheard S, Pocernich M, Stewart R, Sanguya J, Huntington H (2010). Linking Inuit knowledge and meteorological station observations to understand changing wind patterns at Clyde River, Nunavut. Clim Change, 100(2): 267–294

Gilbert R O (1987). Statistical Methods for Environmental Pollution Monitoring. New York: John Wiley & Sons

Gong D, Wang S (2000). Severe summer rainfall in China associated with enhanced global warming. Clim Res, 16: 51–59

Goulden C E, Mead J, Horwitz R, Goulden M, Nandintsetseg B, McCormick S, Boldgiv B, Petraitis P S (2016). Interviews of Mongolian herders and high resolution precipitation data reveal an increase in short heavy rains and thunderstorm activity in semi-arid Mongolia. Clim Change, 136(2): 281–295

Groisman P, Karl T, Easterling D, Knight R, Jamason P, Hennessy K, Suppiah R, Page C, Wibig J, Fortuniak K, Razuvaev V, Douglas A, Forland E, Zhai P (1999). Changes in the probability of extreme precipitation: important indicators of climate change. Clim Change, 42(1): 243–283

Hou X Y, Han Y, Li F Y (2012). The perception and adaptation of herdsmen to climate change and climate variability in the desert steppe region of northern China. Rangeland J, 34(4): 349–357

Huntington H (2000). Using traditional ecological knowledge in science methods and applications. Ecol Appl, 10(5): 1270–1274

Huntington H, Callaghan T, Fox S, Krupnik I (2004). Matching traditional and scientific observations to detect environmental change: a discussion on Arctic terrestrial ecosystems. Ambio, 13 (Spec No): 18–23

Inglis J T (1993). Traditional Ecological Knowledge: Concepts and Cases. Ottawa: Canadian Museum of Nature

Iwasaki H, Nii T (2006). The break in the mongolian rainy season and its relation to the stationary rossby wave along the Asian Jet. J Clim, 19 (14): 3394–3405

Jiri O, Mafongoya P L, Chivenge P (2015). Indigenous knowledge systems, seasonal 'quality' and climate change adaptation in Zimbabwe. Clim Res, 66(2): 103–111

Karl T R, Knight R W, Easterling D R, Quayle R G (1996). Indices of climate change for the United States. Bull Am Meteorol Soc, 77(2): 279–292

Kendall M G, Gibbons J D (1990). Rank Correlation Methods. 5th ed. London: Edward Arnold, a Division of Hodder and Stoughton

Likert R A (1932). Technique for the measurement of attitudes. Arch Psychol, 140: 1–55

Ma C, Fassnacht S R, Kampf S K (2019). How temperature sensor change affects warming trends and modeling—an evaluation across the State of Colorado. Water Resour Res, 55(11): 9748–9764

Ma X, Yasunari T, Ohata T, Natsagdorj L, Davaa G, Oyunbaatar D (2003). Hydrological regime analysis of the Selenge River Basin in Mongolia. Hydrol Processes, 17(14): 2929–2945

Mann H B (1945). Nonparametric tests against trend. Econometrica, 13 (3): 245–259

Marin A (2010). Rider under storms: contributions of nomadic herders observations to analyzing climate change in Mongolia. Glob Environ Change, 20(1): 162–176

Nagashima K, Tada R, Toyoda S (2013). Westerly jet-east Asian summer monsoon connection during the Holocene. Geochem Geophys Geosyst, 14(12): 5041–5053

Nakashima D, Roué M (2002). Indigenous knowledge, peoples and sustainable practice. In: Timmerman P, ed. Encyclopedia of Global Environmental Change: Social and economic dimensions of global environmental change, 5: 314–324

NAMHEM (2008). Manual for issuing hazardous weather, hydrologic, and natural phenomena (in Mongolian). 4th ed, National Agency of Meteorology, Hydrology, and Environment Monitoring, Ulaanbaatar

Nandintsetseg B, Greene J S, Goulden C E (2007). Trends in extreme daily precipitation and temperature near Lake Hovsgol, Mongolia. Int J Climatol, 27(3): 341–347

National Statistics Office of Mongolia (2019). Data from the Mongolian Statistical Information Service Tables

Nicholls N, Gruza G V, Jouzel J, Karl T R, Ogallo L A, Parker D E (1996). Observed climate variability and change. In: Houghton J T, Meira Filho L G, Callander B A, Harris N, Kattenberg A, Maskell K eds. Climate Change 1995. The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 133–192

Nicholls N, Murray B (1999). Workshop on indices and indicators for climate extremes: Asheville, NC, USA, 3–6 June 1997. Breakout Group B: Precipitation. Clim Change, 42(1): 23–29

Nichols T, Berkes F, Jolly D, Snow N B, Sachs Harbour (N.W.T.) T C (2004). Climate change and sea ice: local observations from the Canadian Western Arctic. Arctic, 57(1): 68–79

Peart N (1977). Xanadu. Track 2 on A Farewell to Kings, Anthem, Toronto Ontario Canada

Peterson T C, Folland C, Gruza G, Hogg W, Mokssit A, Plummer N (2001). Report on the Activities of the Working Group on Climate Change Detection and Related Rapporteurs 1998–2001. Southampton: ICPO Publication

Pielke R A Sr, Stohlgren T, Schell L, Parton W, Doesken N, Redmond K, Moeny J, McKee T, Kittel T G F (2002). Problems in evaluating regional and local trends in temperature: an example from eastern Colorado, USA. Int J Climatol, 22(4): 421–434

Sen P K (1968). Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc, 63(324): 1379–1389

Simelton E, Quinn C H, Batisani N, Dougill A J, Dyer J C, Fraser E D G, Mkwambisi D, Sallu S, Stringer L C (2013). Is rainfall really changing? Farmers' perceptions, meteorological data, and policy implications. Clim Dev, 5(2): 123–138

Speranza Ch, Kiteme B, Ambenje P, Wiesmann U, Makali S (2010). Indigenous knowledge related to climate variability and change: insights from droughts in semi-arid areas of former Makueni District, Kenya. Clim Change, 100(2): 295–315

Sternberg T (2008). Environmental challenges in Mongolia's dryland pastoral landscape. J Arid Environ, 72(7): 1294–1304

Sukh T (2012). Local understanding of hydro-climate changes in Mongolia. Dissertation for Master's Degree, Fort Collins: Colorado State University

Theil H (1950). A rank-invariant method of linear and polynomial regression analysis, I, II, III. Proc R Neth Acad Sci, 53: 386–392, 521–525, 1397–1412

Venable N B H, Fassnacht S R, Adyabadam G, Tumenjargal S, Fernández-Giménez M E, Batbuyan B (2012). Does the length of station record influence the warming trend that is perceived by Mongolian herders near the Khangai Mountains? Pirineos, 167(0): 69–88

Venable N B H, Fassnacht S R, Hendricks A D (2015). Spatial changes in climate across Mongolia. In: Fernández-Giménez M E, Batkhishig B, Fassnacht S R, Wilson D, eds. Proceedings of Building Resilience of Mongolian Rangelands: A Trans-disciplinary Research Conference. Ulaanbaatar: 2015, 73–79

Venable N B H (2016). Trends and tree-rings: an investigation of the historical and paleo proxy hydroclimate record of the Khangai Mountain region of Mongolia. Dissertation for the Doctoral Degree. Fort Collins: Colorado State University

Venable N B H (2017). Hydroclimatological data and analyses from a headwaters region of Mongolia as boundary objects in interdisciplinary climate change research. Frontiers of Earth Science, 11: 457–468

Wen R L, Xiao J L, Chang Z G, Zhai D Y, Xu Q H, Li Y C, Itoh S (2010). Holocene precipitation and temperature variations in the East Asian monsoonal margin from pollen data from Hulun Lake in northeastern Inner Mongolia, China. Boreas, 39(2): 262–272

Yan Z, Jones P D, Davies T D, Moberg A, Bergström H, Camuffo D, Cocheo C, Maugeri M, Demarée G R, Verhoeve T, Thoen E, Barriendos M, Rodríguez R, Martín-Vide J, Yang C (2002). Trends of extreme temperatures in Europe and China based on daily observation. Clim Change, 53(1/3): 355–392