Local understanding of hydro-climatic changes in Mongolia

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Abstract Air temperatures in semi-arid regions have increased more over the past few decades than those in many other parts of the world. Mongolia has an arid/semi-arid climate where large portions of the population are herders whose livelihood depends upon limited water resources. This paper combines local knowledge and understanding of recent changes in water availability in streams, springs and wells, with an analysis of climatic and hydrological change from meteorological station data to illustrate the degree of change among Mongolian water resources. We find that herders' perceptions of hydro-climatic change are very similar to the results of the station-based analysis. Additionally, since station data are spatially limited, local knowledge can emphasize smaller-scale variability in changes to climate and hydrology. For this paper, we focus on a site in the Khangai Mountains and another in the Gobi desert-steppe, both in Central Mongolia.

Key words Mongolia; perceptions of hydro-climatic change; local knowledge; climate change

INTRODUCTION

Due to their intimate relationships with land and water resources, farmers and herders possess local knowledge or memory of changes in climate and hydrology. In semi-arid regions where water resources are limited, herders and farmers rely on their understanding of local water sources for cropping and to water livestock. Local, traditional, and/or indigenous knowledge has proved very useful for identifying the degree and effects of climate change (e.g. the special issue of *Climatic Change* on "Indigenous Peoples' Knowledge of Climate and Weather" edited by Green & Raygorodetsky, 2010), and has been observed and quantified in several studies (e.g. Berkes & Folke, 2002).

With a changing climate, the possibility of reduced water resources (e.g. Milly *et al.*, 2008) has an impact on those reliant on these resources. In Mongolia, ecological changes due to climate variation have been observed (Yu *et al.*, 2003; Angerer *et al.*, 2008), in particular alteration in vegetative patterns related to proximity to water sources (Fernandez-Gimenez & Allen-Diaz, 2001), including the effects of grazing gradients within different climate/ecological zones. However, the linkage between hydrological change and climate change has yet to be illustrated for Mongolia.

Recent work has been successful in using local knowledge to analyse climate change for Mongolia at smaller scales than attainable using downscaled climate models, especially for climate extremes (Marin, 2010). Change in other semi-arid regions, such as drought in Kenya, has been identified using local knowledge (Ifejika Speranza *et al.*, 2010). This paper assesses both climatic and hydrological changes in Central Mongolia and compares them to the observations and perceptions of herders in the region.

MONGOLIAN CLIMATE AND CHANGE

Global air temperatures have increased by 1.34°C per century over the past 50 years, with greater increases in many semi-arid regions (IPCC, 2007). The Mongolian climate is characterized by a long cold winter, dry and hot summer, low precipitation, large temperature fluctuations, and a relatively large number of sunny days (on an average, 260 days per year). Across the country, meteorological records show an extreme minimum temperature of –52.9°C in January and an extreme maximum temperature of 43.1°C in July (Batima & Dagvadorj, 2000). On average, the annual air temperature has increased by approx. 1.6°C in the past 60 years (2.6°C/century) with warming starting in the 1970s and intensifying at the end of the 1980s (Batima & Dagvardorj, 2000). Temperature increases have been more prominent in the winter months with temperature warming of 3.6°C (6°C/century) since the 1940s (Batima & Dagvardorj, 2000). A recent investigation showed that temperatures have seen a significant increase at all locations, with increases in Central Mongolia from 2 to 4°C/century (Jamiyansharav, 2010). These increases have been more noticeable in the mountain areas of western Mongolia, in the Gobi Desert, and the steppe areas, with warming of up to 6°C/century (Jamiyansharav, 2010). Northern areas, such as Lake Hövsgöl, have also warmed more than the average, with maximum and minimum increases of 1.8 (4.5°C/century) and 1.95 (4.9°C/century) degrees in the past 40 years, respectively (Nandintsetseg *et al.*, 2007). These temperature increases have been linked to the accelerated degradation of permafrost in the past 15 years (Sharkhuu *et al.*, 2007).

The average annual precipitation in Mongolia is highest in the northern regions and decreases southward; it ranges from 50 mm in the Gobi Desert to 400 mm in the northern parts, with more than 60% occurring during the summer months. Batima & Dagvardorj (2000) saw no changes in total annual recorded precipitation when combining stations across Mongolia, while Jamiyansharav (2010) reported increased precipitation across central Mongolia and decreased precipitation in drier areas such as the Gobi Desert. Changes in precipitation were less statistically significant than temperature increases. Changes in indices of precipitation extremes (taken from Nicholls & Murray, 1999) have been observed (e.g. Nandintsetseg *et al.*, 2007). However, these changes in precipitation extremes are less distinctive than changes in temperature.

Previous studies on climate change in Mongolia have used one station per aimag (province). For example, Jamiyansharav (2010) used 17 stations to investigate national trends. Over the area of Mongolia (1.6×10^6 km^2), this yields about one station per 100 000 km^2. Other areas of the world with extreme climates, such as the Arctic region, had almost an order of magnitude more hydrological monitoring sites (Shiklomanov *et al.*, 2002). Therefore, the use of local knowledge can provide an expanded spatial coverage, or as suggested by Marin (2010), address changes at the regional or local scale.

To date, Mongolian hydrological data have not been analysed for changing trends. In other parts of the world, these have been defined by changes in annual runoff volume, annual peak flow, the timing of peak flow, and the timing or centroid of the runoff volume (Fassnacht, 2006). For example, Stewart *et al.* (2005) observed an earlier peak flow in most of the US Pacific Northwest, associated with a change in the timing of peak snow accumulation.

STUDY SITES

This work examines potential climate change, in terms of the variability of precipitation, temperature, and hydrology for Jinst soum (county) of Bayankhongor aimag and Ikhtamir soum of Arkhangai aimag (Fig. 1). For the meteorological analysis, the Horiult and Bayankhongor stations were used to represent Jinst, and the Erdenemandal and Tsetserleg stations were used to represent Ikhtamir. The Horiult station had 25 complete years of record for daily maximum, minimum and average temperature and precipitation data, while the other three stations had at least 45 complete years of record (Table 1).

Daily streamflow was recorded at the following four stations in the area that had at least 25 complete years of record: Tuin River at Bayankhongor and Bogd (Jinst), Khoit Tamir River at Ikhtamir and Hanui River at Erdenemandal (Ikhtamir) (Table 2). The Tuin River originates from the south slope of the Khangai Mountains and flows to Orog Lake, and is part of the internal drainage basin of Central Asia. Orog Lake has dried up in recent years, but filled again in 2010 due to late season snows. The river runs for 243 km and has a basin area of 9410 km^2. Summer floods dominate, with 60% of the Tuin River's annual runoff coming from summer rainfall. The summer floods usually begin in early July, reaching their peaks in late July through early August.

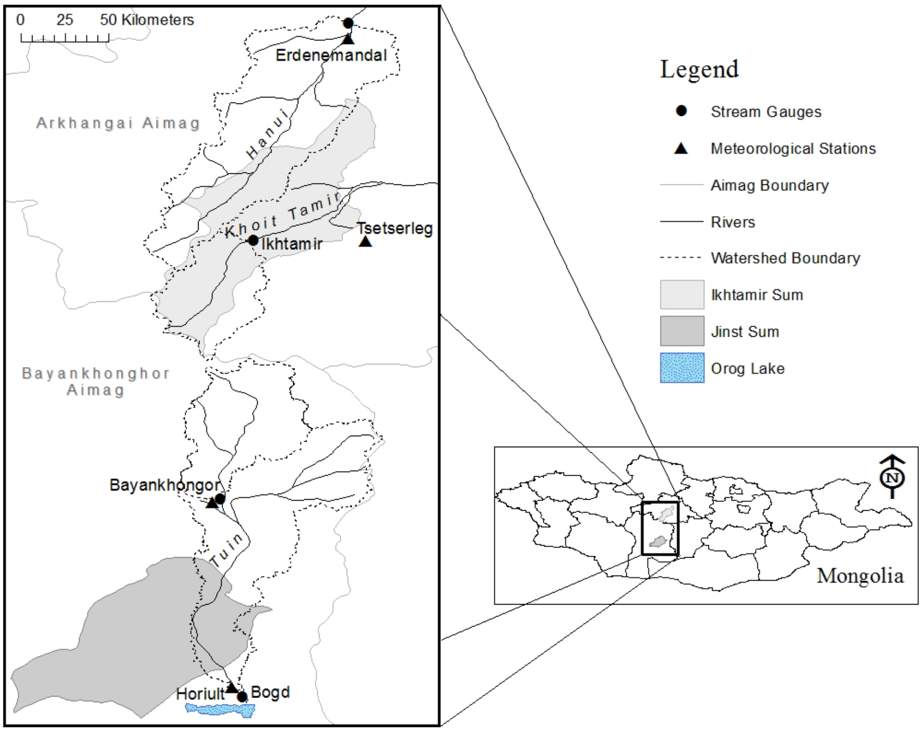

Fig. 1 Location of the Jinst and Ikhtamir soum study sites within Mongolia.

Table 1 Annual trend summary for Mongolian case study meteorological stations from daily data. Statistical significance is given as + for >90%, * for >95%, ** for >99%, and *** for >99.9% significant.

	Temperature (°C):			Precipitation:	
	Average	Maximum	Minimum	Annual (mm)	Days
	Horiult (25 years: 1971–2008)				
Mann-Kendall Z-score	2.6	1.2	3.0	0.44	3.1
Statistical significance	**		**		**
Sen's slope (per century)	4.3	1.9	4.7	23	50
	Bayankhongor (46 years: 1963–2008)				
Mann-Kendall Z-score	4.7	2.8	5.2	–1.3	–0.18
Statistical significance	***	**	***		
Sen's slope (per century)	5.0	3.5	5.3	–94	0
	Erdenemandal (45 years: 1964–2008)				
Mann-Kendall Z-score	4.9	3.4	5.9	–2.2	–1.9
Statistical significance	***	***	***	*	+
Sen's slope (per century)	5.4	4.1	7.3	–190	–25
	Tsetserleg (48 years: 1961–2008)				
Mann-Kendall Z-score	4.8	3.9	5.0	–1.8	–0.66
Statistical significance	***	***	***	+	
Sen's slope (per century)	4.4	4.4	4.2	–120	–6.0

The Hanui and Khoit Tamir rivers originate from the north slope of the Khangai Range and flow mostly through high mountainous areas. These rivers belong to the Arctic Ocean drainage basin. The Khoit Tamir River is a tributary of the Orkhon River and the Hanui River is a tributary of the Selenge River. Streamflow, temperature, and precipitation data were obtained from the Mongolian Institute of Meteorology and Hydrology (http://www.icc.mn/Meteoins/index.html). All data underwent a series of quality control evaluations implemented by the Institute.

Table 2 Trend summary for Mongolian case study hydrometric stations from daily data. Statistical significance is given as + for >90%, * for >95%, ** for >99%, and *** for >99.9% significant.

	Annual average discharge	Annual maximum daily discharge	Date of peak flow
	Tuin River at Bayankhongor (28 years: 1976–2008)		
Mann-Kendall Z-score	–2.0	–0.85	–0.73
statistical significance	*		
Sen's slope (per century)	–7.4	–30	–36
	Tuin River at Bogd (32 years: 1971–2008)		
Mann-Kendall Z-score	–0.86	0.61	–1.1
statistical significance			
Sen's slope (per century)	–2.4	18	–64
	Khoit Tamir River at Ikhtamir (26 years: 1976–2005)		
Mann-Kendall Z-score	–4.4	–3.6	0.93
statistical significance	***	***	
Sen's slope (per century)	–41	–310	63
	Hanui River at Erdenemandal (25 years: 1976–2005)		
Mann-Kendall Z-score	–4.3	–4.4	–0.72
statistical significance	***	***	
Sen's slope (per century)	–25	–170	–48

METHODS

The climate change analysis was performed using the annual average daily maximum, average, and minimum temperatures, as well as the annual total amount of precipitation and the number of precipitation days per year. Since most of the precipitation occurred seasonally as rainfall, there was less analytical emphasis on precipitation as snow. Zhang *et al.* (2004) corrected the daily precipitation due to biases, with the largest being undercatch of solid precipitation due to wind effect on gauge catch. However, wind speed data were not available for the entire period of record. A standard undercatch ratio, such as the gauge efficiency for solid and liquid precipitation of 50% and 90% used by Knowles *et al.* (2006), could not be applied since the phase of precipitation was not recorded. Therefore the precipitation data used in this study were gauge measurements without bias corrections.

Annual averages were computed from daily data when less 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. Missing data were more common for the streamflow records than the meteorological records.

The statistical significance of the annual trend was computed using the Mann-Kendall test and the rate of change was determined from the Sen's slope (Gilbert, 1987). For the Mann-Kendall test, the data are ordered into sequential time series, with missing years of data allowed. For each time series record starting at the first year, all subsequent years are computed to determine whether an increase or decrease is observed. The total number of increases between pairs are subtracted from the total number of decreases and converted into a probability using the number of points in the time series (Gilbert, 1987). This probability is equivalent to the z-score. This non-parametric test is not biased by outliers or missing data, i.e. years with no average value. The Sen's slope is subsequently computed as the median slope (50th percentile) computed from the slopes between all data pairs. These methods are routinely used for climatic change analysis (e.g. IPCC, 2007) and hydrological change analysis (e.g. Burn *et al.*, 2010).

To determine local perceptions of climate and hydrological changes, in the summer of 2010 we conducted a short closed-end survey of 17 herders in Jinst and 20 herders in Ikhtamir, followed by a more open-ended discussion. Herder households were randomly selected in each area. Herder's ages ranged from 30 to 78 and each had at least 14 years of experience in the field of livestock husbandry. Survey questions focused on herders' perception of climatic change, including precipitation, questions related to temperature, and hydrological changes related to streamflow and river characteristics, and the state of springs and wells. It was deemed that questions very specific to temperature change were difficult to assess, thus questions were asked about changes to seasonal conditions, including their length and timing. The survey period of focus compared the current status of hydro-meteorological conditions with that which the herders perceived to exist when they were in their 20s. Responses to the closed-end survey questions were summarized and the frequencies of responses were computed. Qualitative discussion results were recorded and summarized. The narratives of the survey were analysed using a technique similar to that of Auerbach & Silverston (2003).

RESULTS

Temperature trends

Increasing trends in the annual mean average, maximum and minimum temperatures (Fig. 2) are statistically significant at all stations, except for the maximum temperature at Horiult (Table 1). The average temperatures are increasing by 4.3 to 5.4 °C per century, while the maxima are increasing by 3.5 to 4.4 °C per century when significant, i.e. not Horiult. As observed in many semi-arid regions, average minima are increasing the most at Horiult (4.7°C/century), Bayankhongor (5.3°C/century), and Erdenmandal (7.3°C/century). At Tsetserleg, the annual averages and maximums are increasing by 4.4°C per century, and 4.2°C for the annual minimum.

Precipitation trends

There has been a decrease in the annual precipitation from 1961 to 2008 at the Erdenemandal station (Fig. 3) computed to be 186 mm per century, and a less significant decrease in the

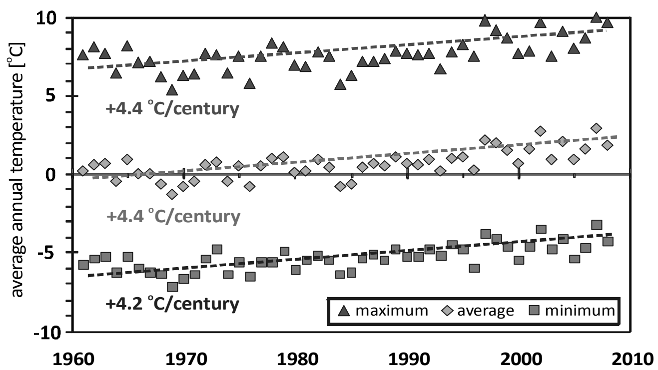

Fig. 2 Annual time series of average daily minimum, daily average and daily maximum air temperature at Tsetserleg.

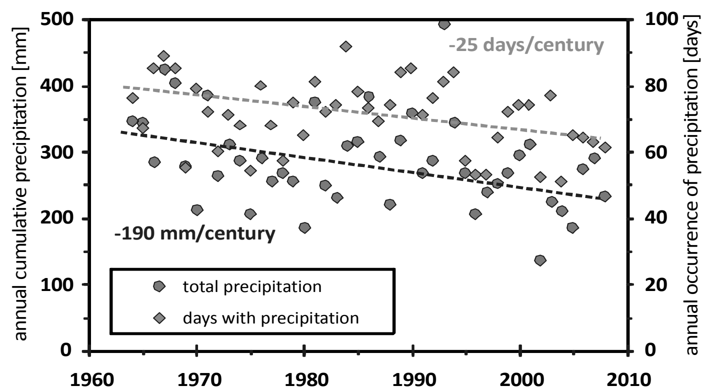

Fig. 3 Time series of annual cumulative precipitation and occurrence of precipitation at Erdenemandal.

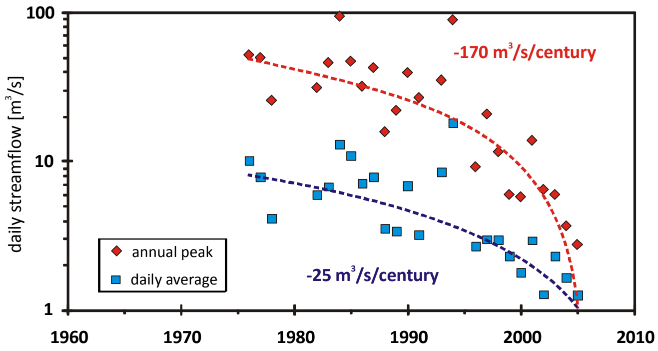

Fig. 4 Time series of annual daily maximum and average daily streamflow on the Hanui River at Erdenemandal.

occurrence of precipitation by almost 25 days per year per century (Table 1). The decrease in annual precipitation at Tsetserleg of 122 mm per century is less statistically significant. The increase in the number of days with precipitation of 50 days per year per century at Horiult was more statistically significant than other changes in precipitation.

Streamflow trends

The Hanui River at Erdenemandal (Fig. 4) and the Khoit Tamir River at Ikhtamir have seen a highly statistically significant decrease in the average annual streamflow of 24.7 and 40.7 m^3/s per century, respectively, and in the annual maximum daily discharge of 166 and 314 m^3/s per century, respectively ($p < 0.001$ for both quantities and locations, as seen in Table 2). The Tuin River at Bayankhongor saw a less significant ($p < 0.05$) decrease in annual streamflow of 7.44 m^3/s per century.

Herder observations

The survey questions were quantitative and addressed changes in precipitation and changes related to temperature, i.e. snowmelt (Table 3), as well as changes in streamflow and spring characteristics (Table 4). The supplemental notes provided a qualitative assessment of all these aspects (Table 5).

Table 3 Percentage change in the amount of precipitation observed by local pastoral herders. Questions were asked on changes in the amount rainfall and snowfall, rainfall intensity and the timing of snowmelt.

Location	Large decrease / much less intense / much earlier	Small decrease/ less intense / earlier	No change	Small increase/ more intense / later	Large increase / much more intense / much later
	The amount of rainfall has …?				
Jinst	71	29	0	0	0
Ikhtamir	100	0	0	0	0
	The amount of snow has ...?				
Jinst	24	29	35	6	6
Ikhtamir	55	15	25	5	0
	The rains have become ...?				
Jinst	0	6	29	65	0
Ikhtamir	0	15	5	80	0
	The timing of is snowmelt is ... ?				
Jinst	0	18	41	29	12
Ikhtamir	0	30	25	40	0

Table 4 Percentage changes in hydrological variability observed by local pastoral herders.

Location	Have you observed any changes in amount of water magnitude and flow in river basin?			YES	NO
Jinst				100	0
Ikhtamir				100	0
	Large decrease / much earlier	Small decrease /earlier	No change	Small increase /later	Large increase / much later
	Has the volume of water in the river …?				
Jinst	73	27	0	0	0
Ikhtamir	100	0	0	0	0
	Has the timing of peak flow become …?				
Jinst	0	0	40	53	7
Ikhtamir	5	35	35	20	5
	Have you observed any river / spring dry up over time?				
	Slight	Moderate		Severe	Complete
Jinst	14 / 0	43 / 11		29 / 11	14 / 78
Ikhtamir	0 / 10	20 / 5		50 / 15	30 / 80

While there were no direct questions related to changes in temperature, herders mentioned specific changes in seasonal extremes, such as hotter summer days and cooler summer nights, and that winters were warming (Table 5). From the seasonal change questions, there was more consistency at Ikhtamir than at Jinst, but some general trends were observed. All herders perceived that summer started later and all but 12% at Jinst thought that summer was shorter. The start of winter was different for the two sites, with 47% perceiving a later start at Jinst (35% earlier and 18% no change) while 75% at Ikhtamir perceived an earlier start to winter. A majority thought that spring started earlier (59% Jinst and 75% Ikhtamir). However, while most thought that autumn started earlier in Ikhtamir (90%), all in Jinst thought there was no change (59%) or it started later (41%).

Most herders perceived that the amount of rainfall has decreased greatly (71% in Jinst and 100% in Ikhtamir) or decreased somewhat (29% in Jinst). While a majority saw a large or small decrease (Table 3), 35% in Jinst and 25% in Ikhtamir saw no change and several herders perceived increases. The rainfall was seen to be more intense (65% at Jinst and 80% in Ikhtamir).

Snowmelt was perceived to start earlier now by some, and later by others. Changes were due in part to these warmer temperatures. Herders commented that the warmer winters have made it more difficult to distinguish between the winter and spring seasons. In Mongolia, much more precipitation occurs in the summer related to the Indian Monsoon. Precipitation has been observed to decrease, including shorter rainfall events, less infiltration, and less snowfall. Despite more intense rainfall events, discharge in the rivers has decreased with less depth and decreased velocity. Springs have been seen to dry up and the water level in wells has gone down.

DISCUSSION

Climate conditions of the mountain regions of Mongolia are changing, as indicated by a long-term warming trend during the last 45 years (Batima & Dagvadorj, 2000; Jamiyansharav, 2010; Tables 1 and 5). Change in climate variability and extremes of weather events have received increased attention in the last few years. Understanding changes in climate variability and extremes is made difficult by interactions between the changes in the mean and variability (Meehl *et al.*, 2000).

Mongolia's livestock are raised in open pastures that directly depend on favourable climate conditions year round. Extreme natural events such as drought and severe winter weather are serious events in Mongolia that cause great damage, not only to the livestock sector, but also to the national economy (Batima *et al.*, 2005).

Table 5 Summary of herder observations and perceptions of climate and hydrology at Jinst and Ikhtamir.

Variable	Jinst	Ikhtamir
Change in climate		
Temperature	Herders in this region have the same perceptions as those in Ikhtamir soum. They have observed climate and weather changes over the years, with winters warming since the 1980s.	Climate and weather have changed over the last 20 years. The number of extremely hot days in summer has increased, while the nights and mornings are getting colder. Herders have stated that it is more difficult to distinguish spring from winter, implying that winters are getting warmer and springs are getting colder. Since the 1980s winters have got warmer, and have been similar to spring, while in the 1970s herders had never observed snowmelt in the winter. In the past few decades, they have observed snowmelt earlier in the winter due to warmer winter temperatures.
Precipitation	Herders identified that from the 1970s through the 1980s, the occurrence of rainfall with low intensity increased and lasted for 1 to 3 days with high infilt-ration. Recently, precipitation comes about a month later at a higher intensity lasting much less time, 3 to 4 hours, with less infiltration. Precipitation has become more patchy. The amount of snowfall has decreased in the past few years, except in 2000 and 2002 which had much more snowfall and resulted in the death of a number of livestock.	Summer precipitation amounts have decreased considerably in recent years. Some herders mentioned that when they were children, the rainfall duration was longer, lasting 3 or 4 days. All of their clothes would get wet and they did not have any dry clothes to wear. Rainfall is now considered rare, with the duration of rainfall becoming shorter with high intensity, low infiltration, and high runoff. The amount of snowfall has decreased in the past few years, with 20 to 30 cm falling 20 years ago.
Change in hydrology		
Streamflow	The water level in the Tuin River has severely decreased and been cut off in some places, especially near Jinst soum. In the 1970s and 1980s the water level was much deeper with more rainfall.	The water level in the Ikhtamir River has decreased every year. Herders mentioned that 20 years ago water in the Ikhtamir River was deeper with stronger stream velocities, and horses and cars could not cross through the river. Currently, the river flows have decreased and rivers are much narrower. However, water levels have been higher this year due to more snowfall and rainfall occurring earlier. The Hanui River has dried up and been cut off in some places. This year, the river has started to flow again.
Springs and well	Most of the springs and lakes used by herders have dried up in the last few years. Water levels in wells have decreased since 2008. Some of the herders have been using wells due to water shortages.	Herders state that most springs have dried up in the last few years. They used to access springs at their winter and spring sites, some of which were very large and flowed year round. Most of these have dried up completely. Due to these water shortages, herders have started using wells in the last few years, and the well water levels are decreasing every year, which is attributed to drought and reduced rainfall.

Any analysis of climate change needs to examine the detailed characteristics of the changes. Specifically, since humans and the environment often respond to extremes, it is important to determine the variability or trends in a range of extreme values, rather than just mean conditions. The herder observations correspond well with the computed trends in climate and hydrology. As temperatures have increased significantly (more so in Ikhtamir than Jinst), precipitation amounts have decreased, which corresponds to a decrease in streamflow, in particular the average annual streamflow and the annual peak discharge. At Erdenemandal, the number of days with precipitation has decreased, while at Horiult is has increased significantly.

Beyond the decreases in precipitation, the decline in streamflow has likely been influenced by hydrological processes, such as increased evaporation, due to increased temperatures. There could also be a change in the phase of precipitation, with more rainfall occurring than snowfall, resulting in less snowpack or earlier onset of melting. These changes could have significant impacts (in terms of flooding, drought, water availability, etc.) on the local and regional environment.

The long-term average streamflow of the Tuin River has not changed significantly, while the herders have observed a depletion of water resources in the area. This is interesting because the drainage point of the Tuin River, Orog Lake, has been completely dry for a number of years. This may be due to a seasonal depletion of water resources from a change of river water regime. The infiltration of water into soil has been seen to decrease and has been attributed by some locals to pasture overgrazing, soil compaction, forest logging activity impacts, fires and insect outbreaks. Consequently, direct surface runoff may have increased, contributing to river flow while precipitation has decreased, resulting in lowered water tables.

The livelihood of Mongolian pastoral herders is directly associated to a large extent with weather extremes, forcing them to observe and record both quantitative and qualitative characteristics of a large number of climatic variables (Marin, 2010). The amount of snowfall has varied in the Jinst area over the past 11 years, resulting in several dzud events, the last of which occurred in 2010, killing a large number of livestock in the area.

When herders were asked about observed changes in precipitation, they all responded that changes had occurred in the past few decades. They stated that the duration of rainfall has become shorter, and that it lasted only a few hours, with a high intensity and high amount of runoff (Table 4). As a result of shortened precipitation durations and reduced rainfall amounts, most of the young herders had no experience with raincoats, while Russian military rain gear was regularly used by herders 20 years ago.

All the temperatures in the study areas were noted as increasing at a rate greater than the global average. Assuming precipitation in later years was less likely to fall as snow, and since gauge efficiency for rain is higher than for snow, it follows that actual precipitation amounts, (with wind bias held constant) would increase due to less undercatch (e.g. Knowles *et al.*, 2006). However, at Erdemendal and Tsetserleg, where a significant change in precipitation occurred (5% and 10%, respectively), the annual amounts decreased by 186 and 122 mm per century, respectively. At Horiult, the number of days with precipitation increased (50 days per century at a 1% significance level), but this should not be influenced by gauge undercatch or related biases.

CONCLUSIONS

This study examined meteorological trends in environmentally sensitive areas in the western mountain and steppe regions of Mongolia. The climate of the western region of Mongolia is warming. Warming is most pronounced in the high mountainous areas and their valleys. The average, maximum and minimum temperatures have significantly increased by at least 2°C between 1961 and 2008. These temperature changes corresponded to warming conditions observed by the herders.

In Ikhtamir, annual precipitation amounts and to a lesser extent the number of days with precipitation have decreased, corresponding with a decrease in the average and peak streamflow. These trends have been observed by herders, as well as the drying up of springs and decreased water levels in wells. In Jinst, the only observed precipitation change is an increase in the number of days at Horiult, but there are no measured overall streamflow changes. Despite the instrument measured results, the herders have seen less water in the rivers and springs (and wells) of the area.

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