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Short Communication

Drought dynamics on the Mongolian steppe, 1970–2006

Troy Sternberg,* David Thomas and Nick Middleton
School of Geography, Oxford University, Oxford, UK

ABSTRACT: Drought is an ongoing feature in Mongolia's steppe environment, yet it remains poorly documented. Awareness of drought conditions is important in the countryside because 50% of the rural population derive their livelihood from climate-dependent pastoralism. In this study, precipitation records, 1970–2006, from five meteorological stations in three steppe provinces were analysed using the Standard Precipitation Index to identify drought events at 1-, 3-, 5- and 17-month timescales. Results found that the probability of drought occurrence in the steppe was slightly less than expected and that the occurrence, intensity and duration were site-specific characteristics. Additionally, its distribution was neither spatially consistent nor uniform over time at different sites. The most serious drought, in terms of severity and duration, was in progress in 2006 at the end of the study. Copyright © 2010 Royal Meteorological Society

KEY WORDS drought; Mongolia; Standard Precipitation Index; steppe

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1. Introduction

Droughts, regarded as a significant negative variation from mean precipitation, are a recurrent feature in the Mongolian steppe; their severity is affected by climate variability in a region where precipitation volatility, rising temperatures and extreme events impact natural hazards and influence pasture conditions (Intergovernmental Panel on Climate Change, 2007; Nandintsetseg *et al*., 2007; Davi *et al*., 2009). These factors contribute to more frequent and persistent droughts in the region, reflected in increased dry periods in China since the 1970s and widespread droughts in recent decades in Mongolia (Bordi *et al*., 2004; Li *et al*., 2007; Shinoda *et al*., 2007). Although drought events are increasing in the Mongolian steppe (Sasaki *et al*., 2009), they remain poorly described despite the assertion put forward by Bohannan (2008, p. 567) that the grasslands are on the verge of 'ecological collapse' due to climate change. As precipitation variability and drought frequencies are the key factors driving livestock dynamics and human subsistence in this dryland region, understanding of drought patterns is of particular concern for Mongolia (Barfield, 1993; Li *et al*., 2007).

Awareness of drought patterns is of particular concern in Mongolia, where it may accelerate pasture desertification and threaten nomadic pastoralism – the dominant rural livelihood (Bayarjargal *et al*., 2006; Johnson *et al*., 2006). Livestock are raised outdoors in severe weather conditions and are exposed to hazards including extreme winter conditions, drought, sand storms, high winds and land cover change. Nandintsetseg *et al*. (2007) identified marked warming in the country over the last 40 years with a 1.8 °C temperature increase. Rising temperatures and variable precipitation patterns and intensity are projected to increase climate unpredictability and extremes (Davi *et al*., 2009). Such uncertainties make drought an integral, though little understood or documented, natural hazard in the steppe (FAO, 2006; Sasaki *et al*., 2009).

A consistent framework is essential for the study of drought in Mongolia, with the main factors requiring investigation being effective moisture levels because these are impacted by precipitation and potential evapotranspiration (PET). However, in drylands, especially in the developing world, data on PET are sparse. Investigating drought through precipitation data is therefore justified, both by practical considerations and because it is the primary factor influencing meteorological drought in such regions (Sonmez *et al*., 2005). For Inner Asia, drought classification using available precipitation data is practical as well as robust, with such indices often outperforming more complex hydrological indices (Guttman, 1999; Keyantash and Dracup, 2002; Lloyd-Hughes and Saunders, 2002). Of these, the Standard Precipitation Index (SPI) has received much attention since its introduction by McKee *et al*. (1993). Recommended as a simple and objective measurement of meteorological drought, it has been applied effectively to dryland settings in countries on six continents, including Argentina, Australia, China, India, Iran, Kenya, Mexico, South Africa, Spain, Turkey and the United States (Hayes *et al*., 1999; Wu *et al*., 2001; Seiler *et al*., 2002; Ntale and Gan, 2003; Rouault

* Correspondence to: Troy Sternberg, School of Geography, South Parks Road, Oxford, OX1 3LZ, UK.
E-mail: troy.sternberg@geog.ox.ac.uk

and Richard, 2003; Sonmez *et al.*, 2005; Bhuiyan *et al.*, 2006; Vicente-Serrano and Cuadrat-Prats, 2006; Hallack-Alegria and Watkins, 2007; Morid *et al.*, 2007; Mpelasoka *et al.*, 2007).

Determining regional and local processes is key to understanding the factors that make drought a major natural hazard in Mongolia. Event identification and awareness of nature–human interactions can increase drought knowledge and inform decision making at both the household and government level. Although indices based on precipitation are available, drought assessment is lacking in Mongolia. The goal of this study is to analyse meteorological drought in Mongolia, identifying drought onset, frequency, intensity, duration and dynamics at different timescales in a representative region of the steppe grasslands.

2. Methods

2.1. Study area

Five meteorological stations reflecting the steppe to the desert-steppe zone encompassing >50% of the country were selected in south-central Mongolia. This region, situated between the Hangai Mountains to the north and the Gobi Desert to the south, consists of Dundgovi, Ovorhangai and Omnogovi Provinces, covering 300 000 km^2 (Figure 1, Table I). The terrain is comprised of rolling gravel plains at an elevation of 1000–2000 m a.s.l. (Hilbig, 1995). The area has a harsh continental climate with distinct seasons and large daily and annual temperature fluctuation. In Omnogovi, Ovorhangai and Dundgovi, 49, 57 and 63% of the population, respectively, are engaged in weather-dependent pastoral livelihoods (Mongolian Statistical Yearbook, 2006).

Figure 1. Mongolia with meteorological station locations and surveyed provinces.

Table I. Site characteristics.

	Elevation	Latitude	Longitude	Zone
Arvaheer	1813	46.25	102.76	Steppe
Bulgan	1400	44.11	103.55	Desert steppe
Dalanzadgad	1465	43.58	104.44	Desert steppe
Mandalgovi	1396	45.75	106.26	Desert steppe
Saixan Ovoo	1317	45.45	103.90	Steppe–Desert steppe

2.2. Standard Precipitation Index

The SPI was developed to identify and monitor droughts at multiple timescales with minimum data requirements – long-term ($\geq$30 years) monthly precipitation records (McKee *et al.*, 1993). It assesses anomalous and extreme precipitation by giving a numeric value to the precipitation, enabling tracking and comparison of meteorological drought across areas with different climates. The SPI is based on the probability of precipitation distribution at a given meteorological station for a selected time period, and reflects the number of standard deviations that an observed value deviates from the long-term mean. To calculate the index, precipitation values are transformed to follow a normal distribution. Calculation involves fitting a gamma probability distribution to monthly time periods of interest. The resulting function provides the cumulative probability for precipitation at a specific station for a given month and period of interest. In this way, drought initiation, intensity, frequency and duration can be computed (Ntale and Gan, 2003; Rouault and Richard, 2003; Mihajlovic, 2006).

The SPI's direct approach has proved robust in comparison with other drought indices including the Palmer Drought Severity Index, the Bhalme–Mooley and the Rainfall Anomaly Index (Guttman, 1999; Keyantash and Dracup, 2002). Cancelliere *et al.* (2007) identified the advantages of SPI over other indices; these include statistical consistency, capacity to describe short- and long-term drought and the ability to carry out drought risk analysis. Further benefits of the SPI are ease of computation, requiring only precipitation data and index calculation at different scales for the same time period (Bordi *et al.*, 2004). Being normally distributed, the index reflects local aberrations rather than distinguishing drought-prone regions. The straightforward requirements of the SPI make it well suited to rural Mongolia where a lack of long-term data availability (soil moisture, evapotranspiration and recharge rates) inhibits drought quantification (Klein Tank *et al.*, 2006). However, the limited length of available precipitation records in Mongolia restricts this study to monitoring recent conditions; a longer record would improve the reliability of SPI values (Wu *et al.*, 2005). A further problem in arid zones and in dry seasons with marked seasonal precipitation distribution is that relatively small rainfall anomalies may skew SPI values; consequently in drylands duration of drought is a more critical factor than its severity (Wu *et al.*, 2007).

Currently used in 60 countries (Wu *et al*., 2005), the SPI has been applied to East Asia in China (Wu *et al*., 2001; Bordi *et al*., 2004) and Korea (Mi *et al*., 2003), but is new to Mongolia (Sternberg *et al*., 2009).

SPI values vary between 3 and −3 with the magnitude of divergence from zero representing the probability of drought occurrence (McKee *et al*., 1993). Positive values indicate wet conditions and negative values signify dry periods (Hayes *et al*., 1999). The SPI has been calibrated in previous studies to map onto the beginning and duration of a drought event. In this survey's dryland setting, we use SPI crossing the −1.0 level for drought initiation and cessation: thus only months where SPI is ≤ -1 are considered to be in drought (Wu *et al*., 2007).

The probability that an SPI value ≤ -2.0 (extreme drought) will occur over a 100-year time period is 2.3, severe drought 4.3, mild drought 9.2, with a cumulative drought probability of 15.9%. Droughts per 100 years for different timescales at each location and drought intensity class (Labedzki, 2007) were calculated as follows:

$$N_{i,100} = \frac{N_i}{i \times n} \times 100 \tag{1}$$

where $N_{i,100}$ is the number of droughts for a timescale i in 100 years; N_i is the number of months with droughts for a timescale i in the n-year set; i is the timescale (1, 3, 5 and 17 months) and n is the number of years in the data set (37).

2.3. Methods

Precipitation data for the period 1970–2006 were obtained from the Mongolian Institute of Meteorology and Hydrology. Precipitation data were examined, using SPI software from the U.S. National Drought Mitigation Center (2006) for drought occurrence at four timescales – 1, 3, 5 and 17 months – to identify spatial and temporal drought dynamics at five meteorological stations. Because of Mongolia's short (90–130 frost-free days) vegetation growth and intensive grazing season, the SPI was calculated through the end of September to monitor drought during the critical summer plant growth season (Begzsuren *et al*., 2004; FAO, 2006). This season matches the peak precipitation period because ≥80% of precipitation falls between May and September (Figure 2) (Hilbig, 1995). In this ecosystem, rainfall and the coefficient of variation (CV) data confirm substantial precipitation variability over the study period, particularly in the key summer months (Figure 3(a), Table II). Such high precipitation variability implies a non-equilibrium environment as noted in prior studies (Begzsuren *et al*., 2004; Retzer and Reudenbach 2005; Munkhtsetseg *et al*., 2007).

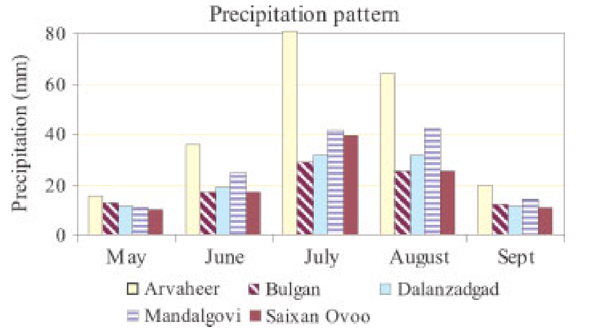

Figure 2. Precipitation distribution in the growing season. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

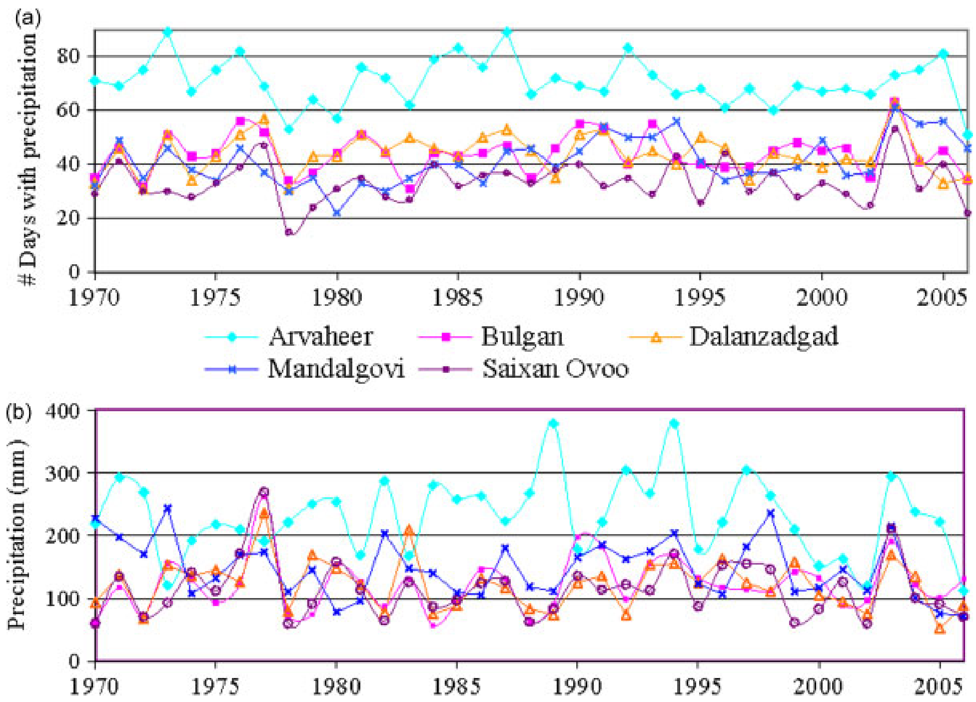

Figure 3. (a) Annual number of days with precipitation by site, 1970–2006; (b) yearly precipitation (mm) at all sites, 1970–2006. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Drought and the annual number of days with precipitation (Figure 3(b)) were compared to explore the strength of the relationship. Temperature is important as the combination of drought and extreme winter cold creates a condition identified as *dzud* when due to heavy snow or ice cover, livestock are unable to forage and thus starve to death (Shinoda and Morinaga, 2005; Sternberg *et al.*, 2009). Additionally, Mongolia's great winter–summer temperature range of over 80 °C in the survey period can create severe summer heat episodes and high evapotranspiration rates that impact pasture quality (Figure 4). SPSS 14.0 (Chicago, IL, USA) was used for statistical comparison.

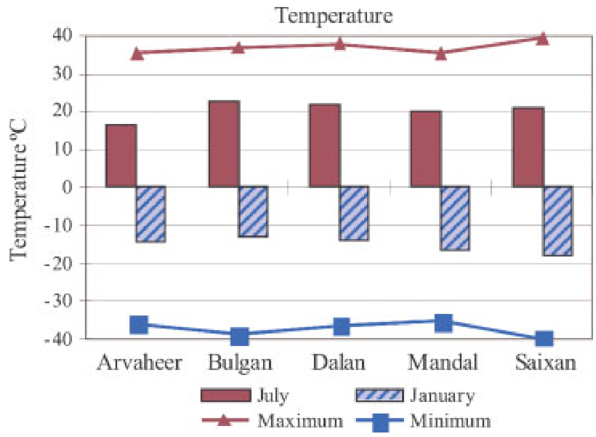

Figure 4. Average January and July and maximum/minimum temperature (°C) at each station, 1970–2006. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

3. Results

A concise drought record from 1970 to 2006 was established across the Mongolian Gobi region using the SPI. Results showed cyclical fluctuations with broadly wetter conditions in the 1970s and 1990s, a notably drier period in the 1980s and alternating wet–dry episodes in the 2000s, with 2006 a particularly dry year. Drought events had similarities, exemplified by patterns at the 5-month timescale, representing one growth season and the 17-month timescale reflecting two growth seasons (Figure 5). Episode rates varied within and between sites and at different timescales. In general, drought measured at the end of September was less prevalent than cumulative probability would predict, with drought lowest at the 1-month timescale and highest at 17 months. Site drought records fluctuated, with Arvaheer and Mandalgovi below estimated probability at each measurement, and Dalanzadgad was in drought greater than expected at 5- and 17-month timescales. Severe droughts exceeded expected frequency more often than at moderate or extreme levels. Months in drought at each location and timescale and the predicted number of droughts (Equation 1) for a 100-year period are shown in Table III.

Nine extreme SPI 17-month drought events occurred from 1970 to 2006 with 2005–2006 the driest period

Table II. Precipitation and CV records, 1970–2006.

	Precipitation		CV	
	Mean	Minimum–Maximum	Annual	Summer
Arvaheer	231	119–378	27.3	60.1
Bulgan	122	57–261	35.0	87.8
Dalanzadgad	122	51–235	33.5	71.8
Mandalgovi	147	72–243	31.6	60.8
Saixan Ovoo	115	59–268	39.5	76.2

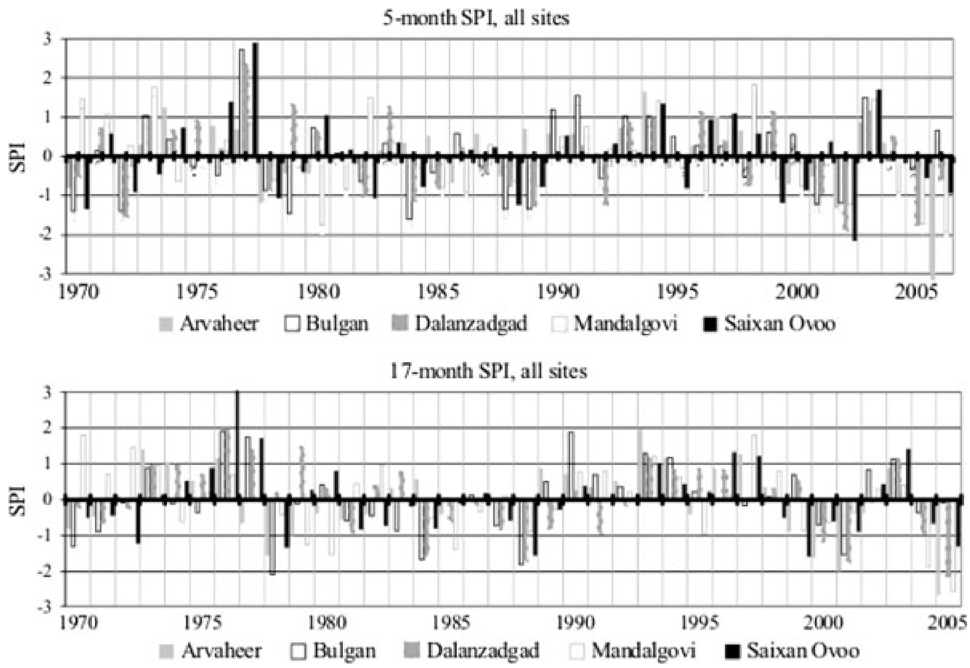

Figure 5. SPI at 5 months (a) and 17 months (b) computed through September for five stations, 1970–2006.

Table III. Months in drought, 1970–2006 (predicted number of episodes over a 100-year period).

SPI	Months in drought (% time in drought)			
	1	3	5	17
Arvaheer				
Moderate	37 (8.3)	32 (7.2)	32 (7.2)	28 (6.3)
Severe	9 (2.0)	18 (4.0)	10 (2.2)	23 (5.1)
Extreme	3 (0.6)	9 (2.0)	12 (2.7)	14 (3.1)
Total	49 (11.0)	59 (13.3)	54 (12.2)	65 (14.6)
Bulgan				
Moderate	36 (8.1)	32 (7.2)	45 (10.1)	37 (8.3)
Severe	16 (3.6)	23 (5.1)	18 (4.0)	23 (5.1)
Extreme	5 (1.1)	10 (2.2)	11 (2.5)	9 (2.0)
Total	57 (12.8)	65 (14.6)	74 (16.7)	69 (15.5)
Dalanzadgad				
Moderate	19 (4.3)	31 (7.0)	48 (10.8)	48 (10.8)
Severe	17 (3.8)	19 (4.3)	19 (4.3)	18 (4.0)
Extreme	3 (0.6)	10 (2.2)	8 (1.8)	12 (2.7)
Total	39 (8.8)	60 (13.5)	75 (16.9)	78 (17.6)
Mandalgovi				
Moderate	33 (7.4)	37 (8.3)	38 (8.6)	39 (8.8)
Severe	6 (1.4)	25 (5.6)	23 (5.1)	15 (3.4)
Extreme	4 (0.9)	4 (0.9)	7 (1.6)	15 (3.4)
Total	43 (9.7)	66 (14.8)	68 (15.3)	69 (15.5)
Saixan Ovoo				
Moderate	25 (5.6)	49 (11.0)	42 (9.4)	47 (10.6)
Severe	9 (2.0)	23 (5.1)	10 (2.2)	22 (4.9)
Extreme	2 (0.4)	3 (0.6)	13 (2.9)	0 (0)
Total	36 (8.1)	72 (16.2)	65 (14.6)	69 (15.5)

Table IV. Extreme SPI 17-month drought events.

Station	Extreme droughts, 17 months					
	Intensity peak	Onset		End		Duration months
		Year	Month	Year	Month	
Arvaheer	−3.75	2006	6	Ongoing	–	7+
Mandalgovi	−2.77	2005	6	Ongoing	–	19+
Arvaheer	−2.49	1978	12	1980	11	12
Bulgan	−2.46	1978	12	1980	4	17
Dalanzadgad	−2.44	2005	11	Ongoing	–	14+
Arvaheer	−2.4	2002	1	2003	6	18
Bulgan	−2.2	1985	2	1985	12	11
Mandalgovi	−2.09	1980	10	1981	11	14
Bulgan	−2.04	1989	3	1990	1	11

on record (Table IV). The most serious in magnitude, −3.75 (Arvaheer), and longest duration, 19+ months (Mandalgovi), were ongoing at the end of the study period. Arvaheer and Bulgan experienced more extreme droughts, whereas Saixan Ovoo did not have extreme events. At this timescale, there were no extreme events from February 1990 to January 2002; only twice did extreme droughts take place simultaneously at multiple sites (1978 and 2005–2006). Examination of drought at other timescales and intensity found that 1- and 3-month droughts were short in duration, not exceeding 2 months and 5 months, respectively, with the exception of longer drought episodes in Arvaheer in 2006. At 5 months, drought length did not exceed 9 months and the most serious droughts were ongoing at all sites at the end of the study. Further emphasizing the acute drought in 2006 was that all sites reached extreme drought status at the 5- or 17-month timescale during the year and all except Bulgan were in drought at the year's end.

At 1 month, SPI values were correlated across all sites (Figure 1), but at the 5-month timescale only Saixan Ovoo SPI values were significantly related to the other sites, whereas Bulgan and Mandalgovi were related to half of the sites ($P = 0.05$) (Table V). Patterns emerged: centrally located Saixan Ovoo was correlated with all other sites, whereas Mandalgovi appeared to follow latitude-influenced relationships with Arvaheer and Saixan Ovoo, and Bulgan's relationships were proximal to Dalanzadgad and Saixan Ovoo, the two nearest sites. Arvaheer's distribution was consistent with all but Bulgan, whereas Dalanzadgad was not correlated with Mandalgovi. Correlations increased at the 17-month timescale with only Mandalgovi and Bulgan unrelated.

The magnitude and occurrence of drought events fluctuated between meteorological stations and highlights how drought varies both by the timescale measured at a site and location within the region. Evaluation of different drought timescales through September 2006 identified Arvaheer experiencing drought at all periods (severe at 1 month, extreme at 3, 5 and 17 months), whereas Bulgan was unaffected. At the same time, Mandalgovi encountered moderate (1-month), severe (5-month) and extreme (17-month) droughts. Saixan Ovoo faced moderate (1- and 17-month) drought, whereas Dalanzadgad had an extreme (17-month) event. Examining drought coverage through June, a key month for forage growth, at decadal intervals found drought at one site in 1975, four sites in 1985, two sites in 1995 and four sites in 2005. Findings stress that drought distribution was not spatially consistent across sites nor were there uniform patterns

Table V. Between-site correlations at 1- and 5-month timescales with significant correlations in bold text ($P = 0.05$).

1-month SPI	Arvaheer	Bulgan	Dalanzadgad	Mandalgovi	**5-month SPI**	Arvaheer	Bulgan	Dalanzadgad	Mandalgovi
Bulgan	**0.013**	–	–	–	Bulgan	0.124	–	–	–
Dalanzadgad	**0.027**	**0**	–	–	Dalanzadgad	**0.030**	**0**	–	–
Mandalgovi	**0.027**	**0**	**0**	–	Mandalgovi	**0.001**	0.179	0.063	–
Saixan Ovoo	**0.002**	**0.002**	**0.001**	**0.001**	Saixan Ovoo	**0**	**0**	**0**	**0.026**

Table VI. 2006 Average SPI time series at all timescales.

Site	Timescale			
	1	3	5	17
Arvaheer	−1.53	−2.88	−3.12	−1.76
Bulgan	−0.50	−0.53	−0.36	−0.32
Dalanzadgad	−0.33	−0.48	−0.77	−2.15
Mandalgovi	−0.48	−0.95	−1.33	−2.32
Saixan Ovoo	−0.41	−0.80	−0.78	−0.91

Table VII. Significance of SPI values and number of days with precipitation ($P = 0.01$, 0.05).

Site	Days			
	3	6	12	24
Arvaheer	0.05	0.01	0.05	–
Bulgan	0.01	0.01	0.01	0.05
Dalanzadgad	0.05	0.01	0.01	–
Mandalgovi	–	0.05	0.05	–
Saixan Ovoo	0.01	0.01	0.01	–

over time, and that within the same year drought identification and coverage were site and timescale dependent (Table VI).

Comparing the number of days of precipitation per year with SPI values through August found that at 3- and 5-month timescales there were significant relationships between the number of days of precipitation and the drought level at most sites. Arvaheer also had correlations at 1 and 17 months (Table VII). There was no link in Mandalgovi. An evaluation of the relationship between the number of days with precipitation and amount of precipitation per year found no association in Arvaheer and Mandalgovi, but a significant relationship in Dalanzadgad ($P = 0.01$), Bulgan and Saixan Ovoo (both $P = 0.05$).

4. Discussion

Drought, a regular feature in the Mongolian steppe and desert-steppe landscape, varies in multiple ways: historically, at different timescales and intensities, in duration and between sites within the region. There are several implications for human populations and pastoral livelihoods: unpredictability of pasture quality and resources, the danger of drought exacerbating extreme winter (*dzud*) conditions, climatic limitations on potential agricultural production in the steppe zone and the ongoing threat to livelihoods dependent on the natural environment for sustenance and survival. This study establishes a drought record applying SPI indices for south-central Mongolia where knowledge of regional drought conditions is essential information for herder decision making; similar assessments could be undertaken throughout the country. Beyond documenting historical patterns, such an index can serve as a predictive tool for both the immediate future, by identifying precipitation shortfalls at selected timescales and generating drought probability perspectives for the long term (Cancelliere *et al.*, 2007).

Examining between-site data showed SPI values were associated over the long term, particularly between Saixan Ovoo (perhaps due to its central location) and the other sites. However, drought episodes were site specific with intensity and duration reflecting local climate anomalies; even concurrent dry conditions varied widely. Although the meteorological stations assessed cover a broad region, geographical variation was limited. This may be due to stable steppe-zone weather patterns across the area, its inland continental location and a lack of local physical features, such as orography or bodies of water, to influence climate.

Across the sites, longer timescales identified a greater number and extent of droughts than events at shorter time periods of more limited duration. It is essential to monitor drought over different timescales for identification of trends enabling them to be placed within a longer perspective. To examine drought only at short timescales would miss broader implications clarifying whether a drought was an isolated event or part of an ongoing dry episode.

Results highlighted the topicality of current drought research with the most extreme (Arvaheer) and longest (Mandalgovi) droughts in progress at the survey's end in increasing frequencies and severity of drought over the 1970–2006 record. The year 2006 suggests greater climate variability today than previous periods of the examined record. Further expanded research could identify national patterns and strengthen interpretation of how a warming climate may further impact the Mongolian environment (Nandintsetseg *et al.*, 2007).

In this study, two causal factors stand out – great interannual precipitation variability, more than a factor of 3 at each site, and a high rainfall CV, especially in the key summer plant growth season (Bohannon, 2008). Thus, climatic unpredictability dominates not only annual precipitation totals but also monthly patterns. The ocillating nature of the rainfall graph line (Figure 2) highlights the dependence and susceptibility of the region to a volatile climate system. This study shows that diligent tracking of rainfall impact through an index such as the SPI can be an effective, low-cost management tool to provide up-to-date information that could improve pastoralists' assessment and decision making as regards migration patterns, potential need for fodder, herd numbers and composition and livestock off-take. If the government promoted further studies, it would lead to an increase in drought understanding and an improvement in policy and planning for drought as well as hazard preparedness and mitigation and relief efforts.

5. Conclusion

Drought, though normal in the Mongolian steppe, becomes socially and economically disruptive as impact spreads beyond physical systems (Sonmez *et al*., 2005). Continued fluctuations in precipitation, its amount, timing and magnitude, coupled with temperature increases due to global weather trends create an environment where variability and extreme events conspire to affect drought occurrence in Mongolia (Gong and Wang, 2000; Tebaldi *et al*., 2006). In the steppe, recurring drought events and the implied randomness of weather factors in this non-equilibrium ecosystem challenge climate-dependent pastoral livelihoods, a major concern where potential mitigating forces, such as government support, access to emergency fodder and transport, are limited (Fernandez-Gimenez, 1999). Documentation and up-to-date assessment of drought are important for pasture management, herder livelihoods and livestock productivity practiced in Mongolia's highly variable environment.

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