How Unusual Was the 21st Century Drought in Mongolia? Placing Recent Extremes in an 1100-Year Context

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ABSTRACT

Understanding the connections between climate, ecosystems, and society during historical and modern climate transitions requires annual resolution records with high fidelity climate signals. In the 21st century, Mongolia experienced a rapid transition away from pastoralism as many families lost their herds during a drought and severe winter conditions (*dzuds*). Though the drivers of this transition were likely multi-factorial, many blamed market forces and overgrazing by herders. Because Mongolia's climate is highly variable, it is difficult to place recent climatic extremes and associated social change in context without long records of climatic variability. Here we ask: how extreme was the 21st century drought in the last 1100 years? We developed a 1100 year long tree-ring reconstruction of warm-season drought, derived from live and dead Siberian pine (*Pinus sibirica*) trees growing on a Holocene lava flow in north central Mongolia. Trees growing on the lava today are stunted and widely spaced, occurring on microsites with little to no soil development. These trees are water-stressed and their radial growth is correlated with both soil water availability (scPDSI) and grassland productivity (Normalized Difference Vegetation Index (NDVI)). Our reconstruction, calibrated and validated on instrumental June-August scPDSI (1959-2009) account for >57% of the variability in the regional scPDSI when >70% of the annual rainfall occurs. Our tree-ring data combined with meteorological data suggests that the early 21st century drought was the hottest and one of the most severe droughts in the last 1100 years. These results are consistent with model projections of warming in Inner Asia where rising temperatures will contribute to increased water stress, independent of changes in rainfall. Future warming may overwhelm increases in precipitation leading to similar high temperature droughts, with potentially severe environmental and social consequences for modern Mongolia. Long records of past climate variability can help us understand the relative importance of climate versus land management in catalyzing social change and help prepare societies for the full range of future climatic extremes.

Keywords: drought, tree rings, ecology, past environments.

INTRODUCTION

Semi-arid continental locations like Mongolia are characterized by highly variable moisture regimes even in the absence of human-caused climate change making it difficult to distinguish the long-term consequences of anthropogenic warming from inter-annual variation in moisture. Projections of future drying in Mongolia hinge on expected changes in rainfall – projections that are less certain than those of future temperature. Understanding the connections between climate variability, ecosystems, and society during historical and modern climatic transitions requires annual resolution records with high fidelity climate signals. When combined with climate forecasts, these long records can help us place recent extremes in climate in the context of the last two millennia and help us estimate the range of possible conditions likely to occur in future decades.

During the late 20th and early 21st centuries, Mongolia experienced a major drought, several *dzuds* (harsh winters) and rapid social and economic change (Sternberg, 2010). Following the independence movement of the 1990s, opening markets lead to large increases in total livestock production and a trend towards larger proportions of herds in resource-demanding goats (Liu et al., 2013). A severe drought as well as several *dzuds*, combined to kill off ~30% of the national herd in 1999-2002 and 20% of all livestock in 2010, forcing large numbers of herders and their families to relocate to cities such as Ulaanbaatar (Sternberg, 2010). Informal housing on the outskirts of the capital city and its associated environmental and social consequences continue to challenge Mongolia's ability to adapt to changing conditions.

Though a suite of social, economic, and climatic phenomena are likely responsible for the rapid changes observed in Mongolia's herding economy, the instrumental climate record is insufficient to place recent climatic extremes in context. The purpose of this study is to use an 1100 year record of past moisture conditions and climate model simulations to place the 21st century drought in context. Here we ask: how extreme was the 21st century drought in the last 1100 years?

STUDY SITE

We collected Siberian pine (*Pinus sibirica*) increment cores and cross sections from a Holocene lava flow (Khorgo) in north central Mongolia in 2010, 2012, and 2014. Samples were collected from living and dead trees on thin or absent soils surrounded by dark basalt. Trees growing on the lava flow today are widely spaced, stunted, and appear severely moisture-limited. We measured total ring width to +/- 0.001 mm and crossdated samples using standard procedures. Our chronology extends from 900 CE to 2011 CE and maintains a minimum sample depth of 25 series between 228 and 2009 CE (Table 1). This new chronology includes two more years of the recent drought (2010 and 2011) as well as additional samples collected in 2014 to our existing chronology (Pederson et al., 2014).

METHODS

Tree Ring Data

Tree rings contain growth-related trends, unrelated to climate that can be reduced using detrending techniques. To maintain as much low frequency information as possible, we used conservative techniques in the program ARSTAN to detrend and standardize the raw ring width series (Cook, 1985). We used either a negative exponential curve or straight line with slope ≤0 (typically samples containing or close to pith), straight line with slope ≤0 (typically non-strip bark samples without early growth), or straight line with slope > 0 (typically strip-bark samples). Three samples with unusual growth trends were standardized using the Friedman SuperSmoother (alpha = 9), a flexible piecewise, smoothing technique (Friedman and Silverman, 1989). Median series length was 512 (range 300 – 1193 years) (Table 1).

Climate Data

Mongolia's climate stations are sparse and at times incomplete, particularly since 1980. We instead chose to use the gridded self-calibrating Palmer Drought Severity Index (scPDSI) derived from CRU 3.20 precipitation and potential evapotranspiration fields (van der Schrier et al., 2013).

Tree Ring Reconstruction of scPDSI

The average correlation between tree-ring series (rbar) included in the chronology is 0.65, indicating that tree growth is responding to a common environmental signal. The average expressed population signal (EPS), a metric that quantifies how well a chronology based on a finite number of trees represents a hypothetical perfect or 'true' chronology, is >0.90 (possible range 0-1.0) beginning in 900 CE, indicating adequate sample size during the period of analysis (900 to 2011 CE).

Calibration/Validation

We reconstructed average June to August scPDSI for north central Mongolia using a linear regression model relating June to August scPDSI from a grid box (46-49N, 99-109E) to the mean of our detrended ring width chronologies over the 1959 to 2012 period (Fig. 1b). Gridded climate data for Mongolia prior to 1959 are based on few stations and exhibit unstable variance. We then validated our model and estimated prediction error using a split-period cross-validation approach by partitioning our time series into two 27-year periods (1959-1986; 1987-2012). We then compared the recent drought (1996 to 2012) in Mongolia to time spans of the same length sampled from our reconstructed scPDSI record.

Model Simulations

We used the long unforced control run of the GFDL CM2.1 climate model (Wittenberg, 2009) to contextualize the severity of the 21st century drought within the scope of natural climate variability in Central Asia. We extracted model simulated monthly precipitation and temperature from the half degree gridcells corresponding to central Mongolia, and calculated the Palmer Drought Severity Index (PDSI). These were compared to the empirical estimates of PDSI generated from the tree ring reconstruction from Khorgo (Pederson et al., 2014) and summer temperatures from the Asia2k reconstruction (Cook et al., 2012).

We compared past and recent droughts with those predicted using climate models. Our chronology has a strong, significant, and stable correlation ($r=0.76$, $p<0.01$, 1959-2011) with June through August scPDSI (van der Schrier 2013). This reconstruction permits a direct comparison to the future scPDSI projections developed by Cook et al. (2014) using 36 simulations from the historical and RCP8.5 experiments from CMIP5. We extracted the model simulated June to August scPDSI corresponding to our reconstructed region, as well as evaluating the relative contributions to total scPDSI from changes in precipitation and potential evapotranspiration.

RESULTS

Reconstructed scPDSI

Our reconstruction accounts for 56.5% of the variance in the observational scPDSI from 1959-2012 and faithfully represents the range of decadal changes from the late 20th century through the early decades of the 21st century (Figure 1). Split calibration and verification statistics indicate that the reconstruction is reliable over the full calibration period and that the model yields significant skill over a null model (Pearson r >0.70 for all calibration and verification periods). Reduction of error (RE) and coefficient of efficiency (CE) statistics exceed 0.60 and 0.45, respectively for both calibration and verification periods indicating a robust model.

The tree-ring record of growing season moisture (June to August) suggests that the 21st century drought actually began in 1996 and continued until at least 2011 (Figure 1b), interrupted by only two non-adjacent years that were slightly above the mean (1999 and 2008). Similarly, the instrumental record of June to August scPDSI suggests the drought began in 1996, with only one year, 1998, recording a positive scPDSI value between 1996-2013. Cumulative reconstructed scPDSI during this period (1996-2012) was -27.4. Randomly selecting 10,000 16-year periods from the reconstruction of scPDSI suggests that the recent drought exceeds the 95% confidence limits and nearly exceeds the 99.9% confidence limits of the distribution of these draws (Figure 1c).

Model Simulations

Comparison of decadal-scale drought simulated by the long control run of the GFDL CM2.1 shows that the 21st century droughts fall outside the range of the simulated drought severity and associations with temperature. The 21st century drought falls just outside the simulated decadal drought severity distribution, but is associated with elevated decadal average temperatures not observed in the unforced control run.

Comparison of our scPDSI reconstruction to future simulated drought and pluvial (wet) trends suggests a highly uncertain future. Model predictions through the end of the 21st century encompass a range of possible future moisture conditions that include both pluvial and drought conditions outside the range of the last millennium. There is no model consensus on future moisture trends in north central Mongolia. Analysis of the influence of the simulated precipitation and potential evaporation terms over the 21st century reveals that this uncertainty arises from the balance between the tendency toward wetter conditions associated with increased precipitation and greater evaporative demand associated with rising temperatures. The diverse range of possible future moisture trajectories reflects the relative influence in each model of these two opposing trends.

DISCUSSION

Multiple failures in the steppe ecosystem of Mongolia during the early 21st century have been attributed to a variety of factors including: livestock privatization, reduced government support for herders, and changes in traditional livestock herding techniques including decreased mobility, a focus on commercial production, and increase in proportion of goats (Liu et al., 2013; Sternberg, 2008). However, these changes in policy and culture occurred during a period of unprecedented drought relative to the last 1100 years, exceeding the 99.9% confidence intervals of 10,000 replicated reconstruction segments of the same length as the recent drought. Elevated temperatures during the drought further suggest the anthropogenic warming contributed to the severity of this event (Pederson et al., 2014). The ecological, social and economic challenges experienced by herders over the last two decades must be placed within the context of this severe and possibility unprecedented drought. Modeled projections of drought for central Mongolia suggest a highly uncertain future with increasing variability in moisture likely to result in both pluvials (wet periods) and droughts that exceed those of the last 1000 years (Figure 2).

IMPLICATIONS

Results from this study provide a long context for recent environmental conditions in Mongolia. Though policy changes and an emphasis on commercial livestock production undoubtedly had negative impacts on rangeland quality during the late 20th and early 21st centuries, these impacts coincided with a drought of great magnitude given the context of the last 1100 years. This drought presented Mongolia with a set of environmental conditions that would challenge most livestock management approaches. Modeled drought conditions for Mongolia over the next 100 years indicate a wide range of extremes including droughts of similar or larger magnitude to the 21st century drought as well as wet conditions that meet or exceed those of the recent past. Our results indicate that a key challenge for Mongolia in coming decades will be to adjust policy in the face of widely varying forecasts of drought and moisture. Policy makers can use the recent drought as an example of future extremes, but should also consider the social, economic, and environmental implications of increased frequency and severity of drought and pluvial (wet) conditions beyond those experienced in recent decades.

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Table 1. Summary statistics of the Khorgo (KLP) tree ring chronology from north central Mongolia including number of series, median, minimum, and maximum segment length, and total number of rings in each chronology. R-bar is the average correlation between series.

Site Id	First Year	Last Year	# Series	Median Segm.	Min Segm.	Max Segm.	r-bar (std)	EPS>0.9
KLP	900	2011	127	492	302	1192	0.713 (0.04)	900 - 2011

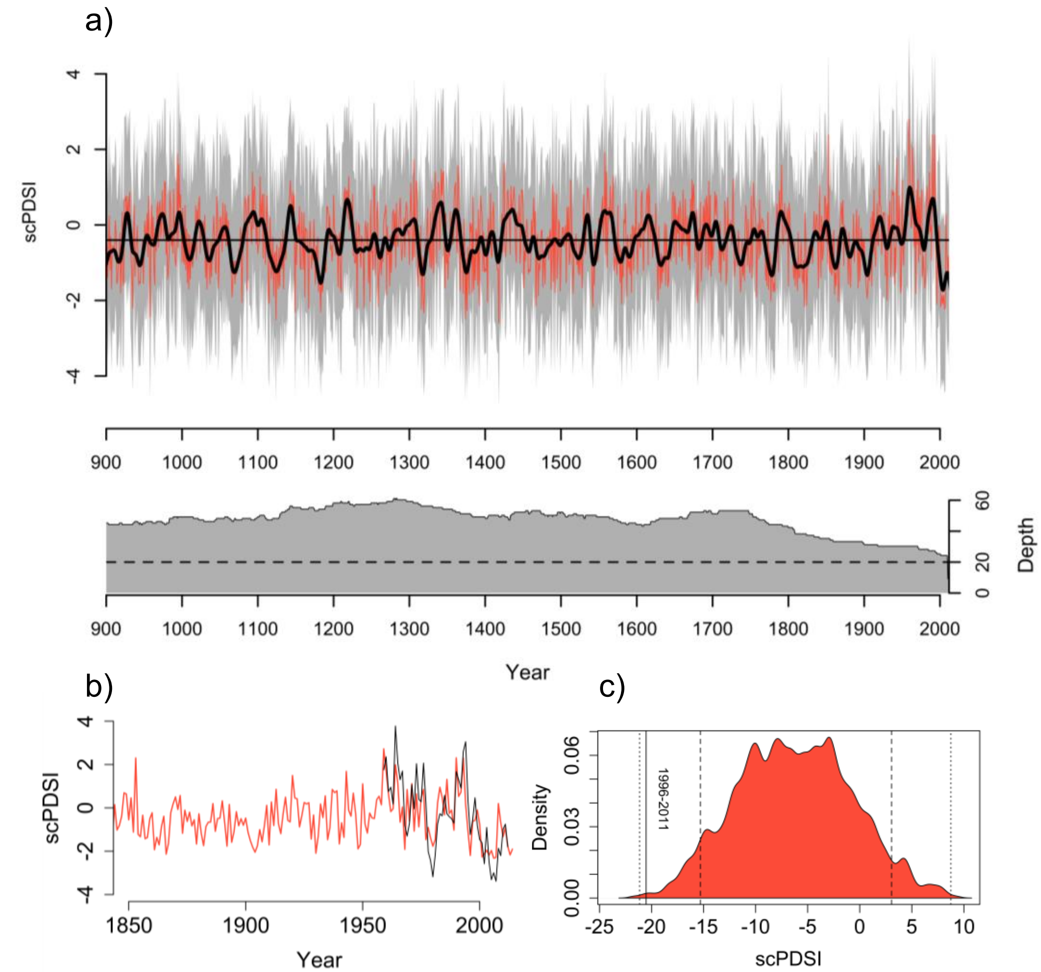

Figure 1. (a) Reconstructed scPDSI from Khorgo from 900 to 2011 CE (red line) with a 15 year spline (black line), 2RMSE of the reconstruction (grey) and sample depth (filled gray area). (b) Inset of reconstructed scPDSI (red line) and instrumental scPDSI (van der Schrier et al. 2013) (black line) from a grid box (46-49° N, 99-109° W) 1850-2012 CE. (c) Kernel density function of cumulative scPDSI derived from 10,000 random samples of 16 year segments from reconstruction (red) with the 1996-2011 drought (black line) and 95% (dashed) 99.9% (dotted) confidence limits.

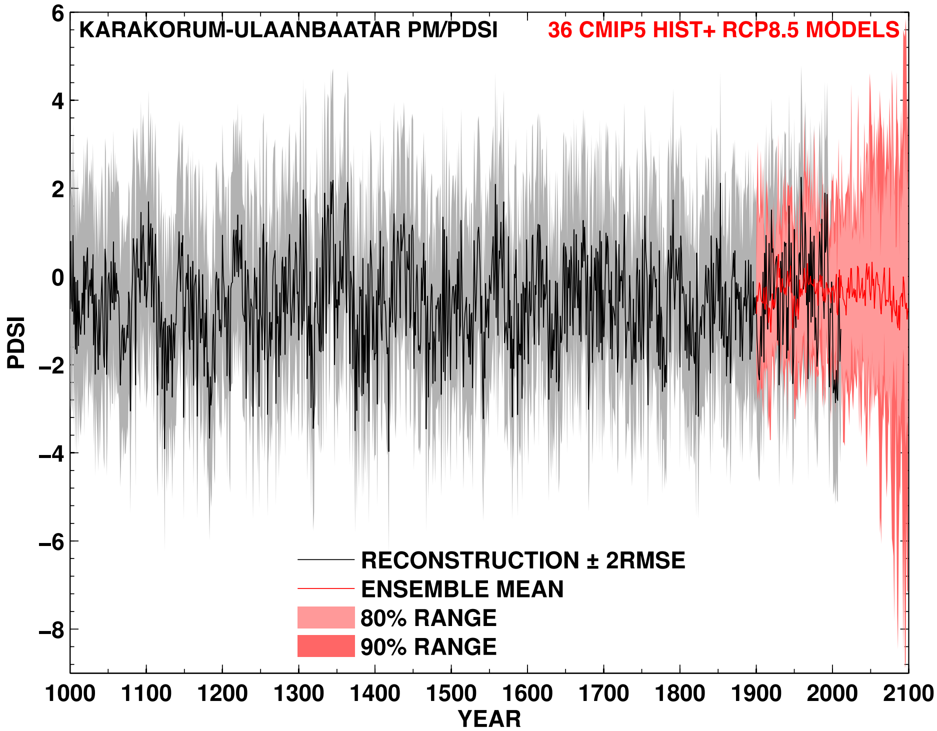

Figure 2. Pederson et al. (2014) tree ring reconstruction of scPDSI for central Mongolia (black) and modeled (red) Palmer Drought Severity Index (PDSI) using CMIP5 Historical and RCP8.5 future climate models.