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Is eastern Mongolia drying? A long-term perspective of a multidecadal trend

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[1] Temperatures in semiarid Mongolia have rapidly risen over the past few decades, and increases in drought, urban development, mining, and agriculture have intensified demands on limited water resources. Understanding long-term streamflow variation is critical for Mongolia, particularly if alterations in streamflow are being considered and because of the potential negative impacts of drought on the animal agriculture sector. Here, we present a temporally and spatially improved streamflow reconstruction for the Kherlen River. We have added 11 new records in comparison with two in the original 2001 reconstruction. This new reconstruction extends from 1630 to 2007 and places the most recent droughts in a multicentennial perspective. We find that variations in streamflow have been much greater in the past than in the original study. There was higher variability in the mid to late 1700s, ranging from severe and extended drought conditions from 1723 to 1739 and again in 1768–1778 to two decadal length episodes of very wet conditions in the mid 1700s and late 1700s. Reduced amplitude is seen in the mid-1800s, and several pluvial events are reconstructed for the 1900s. Although recent droughts are severe and disturbing economic and ecological systems in Mongolia and it appears that eastern Mongolia is drying, the drying trend since the late 1900s might in fact be accentuated by a change from a particularly wet era in Mongolia. The recent drought might be a return to more characteristic hydroclimatic conditions of the past four centuries in Mongolia.

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1. Introduction

[2] Mongolia has a largely semiarid or steppe climate where significant declines in water resources can have devastating socioeconomic impacts [*Batima*, 2006; *Batima et al.*, 2008; *Sternberg*, 2010]. Nomadic herders that are dependent on the health and productivity of the grasslands for their herds are particularly sensitive to variation in water resources. Drought in Mongolia has been frequent and extreme over the past decade. Harsh droughts occurred from 1999 to 2001 and in 2005 and 2009 over most of the country [*Batima*, 2006; *Davi et al.*, 2010] and resulted in devastating livestock losses [*Sternberg*, 2010]. Recorded mean streamflow from the Kherlen River in eastern Mongolia decreased by more than half from 2000 to 2008 when compared with prior decades (Figure 1), and a study by *Brutsaert and Sugita* [2008] also shows a decline in average area-wide underground terrestrial water storage in the Kherlen River basin since the year 2000. *Li et al.* [2009] evaluated drought across China and Mongolia (1951–2005) and found a significant trend in large-scale drying across eastern Mongolia and northeastern China. Thus, the recent decline in moisture and its impact on economic systems in eastern Mongolia has become a cause for concern for future water resource sustainability.

[3] Mongolia is currently undergoing rapid warming [*Ministry of Nature, Environment and Tourism*, 2010; *World Wildlife Fund* (*WWF*), *Mongolia Programme Office*, 2011], and how that warming will affect limited water resources is of grave concern. Warming likely contributes to increased water supply issues through increased evapotranspiration [e.g., *Weiss et al.*, 2009]. In addition, changes in land use, such as pastoral practices (e.g., more cashmere goats), mining [*Byambaa and Todo*, 2011; *WWF, Mongolia Programme Office*, 2011], and irrigation [*WWF, Mongolia Programme Office*, 2011], also have the potential to affect ecosystems and water resources negatively.

[4] This study aims to place the recent droughts into a long-term context to understand if recent events and trends are unusual and to get a better sense of hydrological variations on climate scales. Tree-ring data have improved our understanding of the natural variability of critical water

All Supporting Information may be found in the online version of this article.

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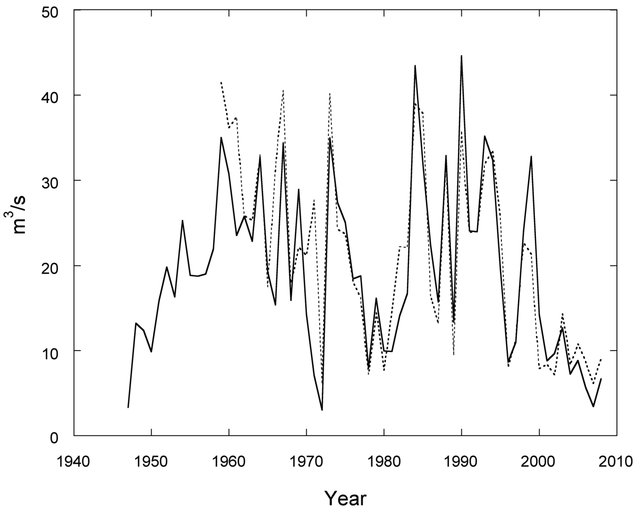

Figure 1. Annual averaged streamflow data from Choibalsan (solid line) and Undurkhaan (dashed line) stations. Mean flow from 2000 to 2008 is less than half of the mean flow prior to that time.

resources, such as streamflow and precipitation, through the reconstruction of centennial-length to millennial-length hydroclimatic records [e.g., *Stockton and Jacoby*, 1976; *Cook and Jacoby*, 1983; *Hughes and Brown*, 1992; *Stahle and Cleaveland*, 1992; *Pederson et al*., 2001; *Woodhouse et al*., 2010; *Büntgen et al*., 2011; *Maxwell et al*., 2011; *Cook et al*., 2010]. Due to limited meteorological data in Mongolia spatially and temporally, the use of tree-ring-based reconstructions of hydroclimate have been necessary to get a full sense of the frequency, magnitude, and duration of such droughts from multidecadal to multicentennial time scales [*Pederson et al*., 2001; *Davi et al*., 2006, 2009, 2010]. A history of long-term streamflow variation, developed here, is critical information for resource managers and for understanding and predicting the impact of natural and altered flow regimes on the people and biota that depend on it [*Olden and Poff*, 2003].

[5] Here, we update and improve on the previous reconstruction of the Kherlen River by *Pederson et al*. [2001]. We accomplish this through increased spatial and temporal tree-ring replication and the use of nested model methods [e.g., *Meko*, 1997; *Cook et al*., 2002, 2003] that adds 40 years to the original *Pederson et al*. [2001] reconstruction. We also update the *Pederson et al*. [2001] reconstruction, as the Choibalson streamflow data that the model was based on had a decimal point error that has been corrected here (e.g., streamflow in the original meteorological data ranged from 0 to 500 m^3/s, but should have ranged from 0 to 50 m^3/s). Most importantly, the updated tree-ring network is composed of 13 records that cover substantially more of the Kherlen River headwater region than the original reconstruction (Figure 2). The original annual reconstruction was based on only two tree-ring chronologies. Seven new chronologies were collected since 2009, and three previously unpublished records were updated after *Pederson et al*. [2001]. The updated network for the Kherlen River reconstruction not only includes nearly seven times the original chronology replication but also includes five records at 1680 and three back to 1651. The inclusion

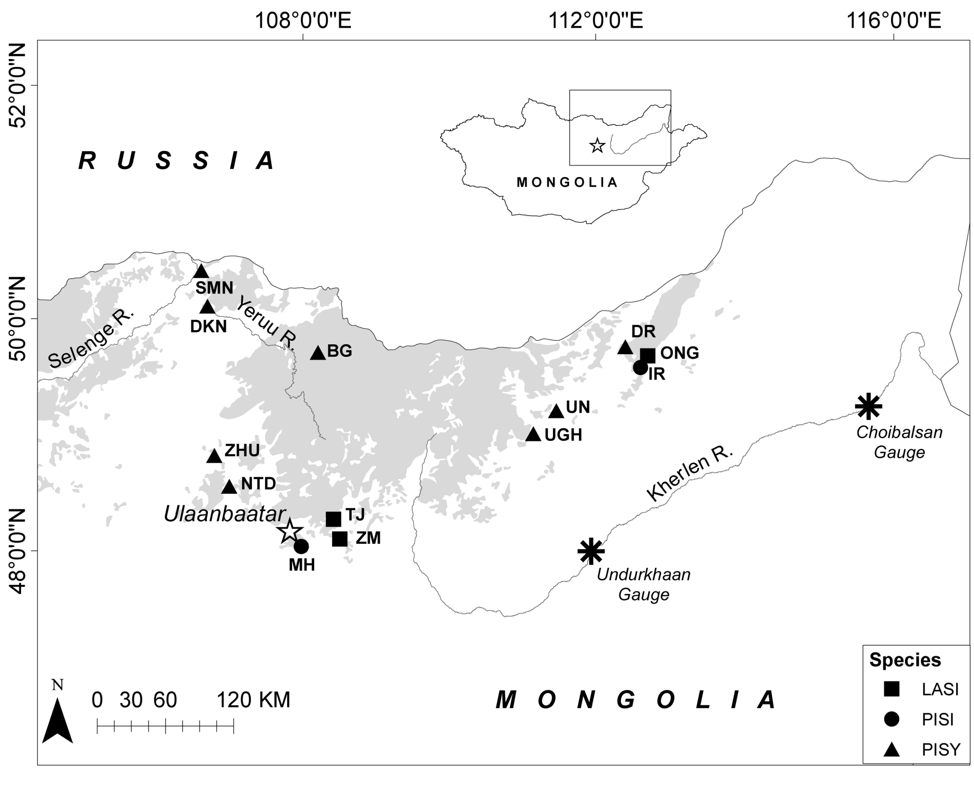

Figure 2. Map of study region showing tree-ring sampling site locations and species used (see key) from Kherlen River streamflow gauge stations at Choibalson and Undurkhaan. Prior study based on Urgun Nars (UN) and Zuun Mod (ZM) [*Pederson et al*., 2001].

Table 1. Study Sites: Chronologies Used and Their Statistics for Kherlen Gol Streamflow Reconstruction

Site	Species	Number of Cores	Chronology Span	EPS (Tree)[a]	EPS > 0.85[b]	Year EPS > 0.85[c]	Median Segment (years)	Chronology Used
Bugant	PISY	34	1730–2008	0.970	1815	1793	210	ARS
Dadal	PISY	22	1704–2001	0.968	1735	1716	259	STD
Dulaankhan Nars	PISY	44	1653–2008	0.981	1675		281	STD
Inferno Ridge	PISY	35	1692–1996	0.980	1750		175	ARS
Manzhir Hiid	PISI	25	1505–1994	0.985		1787	183	ARS: 1 tree prior to 1784
Narstyin Davaa	PISY	20	1740–2008	0.972		1802	181	ARS
Onon Gol	LASI	25	1576–2001	0.952	1680		201	STD
Shaamar Manhan Nars	PISY	17	1770–2008	0.965		1786	208	ARS
Terelj	LASI	28	1590–2002	0.980		1622	288	STD
Uglugchiin Herem	PISY	16	1705–2009	0.924	1770		171	ARS
Urgun Nars	PISY	33	1651–1996	0.984		1664	189	STD
Zurkh Uul	PISY	22	1714–2009	0.971		1737	192	STD
Zuun Mod	LASI	51	1582–2001	0.993		1582	332	STD

[a]Between-tree EPS.
[b]Segment where between-tree EPS > 0.85.
[c]Year when between-tree EPS > 0.85 if earlier than segment EPS.

of the new records and the use of forward reconstruction nests allow us to update the reconstruction to 2007.

2. Data and Methods

2.1. Streamflow Data

[6] In this study, we tested average monthly streamflow data from two gauges on the Kherlen River: the Choibalsan gauge (1947–2008, 747 m) and the Undurkhaan gauge (1959–2008, 1032 m). The Kherlen River is located within the Dahurian Steppe Ecoregion, which contains three subregions [*WWF, Mongolia Programme Office*, 2011]. Choibalson and Undurkhaan stations are located within the Mongol Manchurian Grassland subregion. This grassland region occupies more than a million square kilometers of temperate grasslands and is located on the inland side of Manchuria's coastal mountain ranges and river basins. Much of the lower elevation regions contain lakes and wetlands habitat. The Kherlen region is characterized by low precipitation, high evaporation, and limited water resources. Average summer temperatures (June to August) at Undurkhaan and Choibalsan stations from 1961 to 1990 are 17.2°C and 19.2°C, respectively. Total precipitation for June to August at Undurkhaan and Choibalsan stations from 1961 to 1990 is 192 and 178 mm, respectively. Average monthly streamflow for these stations peaks from July to August. Flow patterns can be seen in Figure S1 in the Supporting Information.

[7] The *Pederson et al.* [2001] Kherlen reconstruction was calibrated and validated using streamflow data from the Choibalsan hydrological station, which is located in the middle of the drier Gobi steppe and far downstream from sampled stands of drought-sensitive trees (Figure 2). Although the new reconstruction presented here uses the shorter Undurkhaan meteorological record, this record is closer to the trees used for reconstruction.

2.2. Tree-Ring Data

[8] Urgun Nars and Zuun Mod were the basis of the original Kherlen reconstruction. Eleven additional chronologies were used in the new network here (Table 1, Figure 2, and Figure S2). Chronologies are composed of *Larix sibirica*, *Pinus sylvestris*, or *Pinus sibirica*. Many of the sites collected since 2009 came from classical drought-sensitive sites, south to southwest-facing, thin-soiled slopes, or well-drained sites on deep, sandy soils (Dulaan Khan Nars, Onon Gol, Shaamar Manhan Nars, Terelj, Tujyin Nars, and Zurkh Uul); however, some sites came from less-typical sites: closed-canopy forests on steep, rocky ridges or sites with fairly thin soils at elevations above the forest-steppe ecotone (e.g., Bugant and Narstyin Davaa).

2.3. Core Processing and Chronology Development

[9] All cores were visually crossdated and measured to thousandths of a millimeter. The program COFECHA was used to check visual crossdating and calculate interseries and intersite correlations [*Holmes*, 1983]. Cores processed were standardized using the software program ARSTAN [*Cook*, 1985; *Cook and Kairiukstis*, 1990; *Frank et al*., 2006; *Cook and Krusic*, 2011]. We used conservative detrending methods, including straight line and negative exponential curve fits, or the Friedman Super-Smoother [*Friedman*, 1984] to retain as much low-frequency information as possible in open-canopy and closed-canopy forests [*Cook and Peters*, 1981; *Jacoby and D'Arrigo*, 1989; *Pederson et al*., 2004]. As many collections came from classic, open-canopy forests with minimal canopy competition, the standard chronology was used for reconstruction (Table 1). However, some samples from several collections came from closed-canopy forests or showed evidence of abrupt changes in growth that strongly resembles a release from tree-to-tree competition or declines in ring width related to nonsynchronous crown disturbance [e.g., *Lorimer and Frelich*, 1989; *Lafon and Speer*, 2002]. In these cases, the ARSTAN chronology was used instead of the standard chronology, in which autoregressive modeling pools and retains the common autoregressive properties of the sample collection to reduce the individual or stochastic variation in ring width. Effectively, the final ARSTAN chronology reduces endogenous disturbance and retains exogenous factors of tree growth that is likely representative of climate [*Cook*, 1985]. All chronologies were truncated at the earliest year at which the expressed population signal (EPS) fell below 0.85 (Table 1) [*Wigley et al*., 1984].

[10] Signal-free methods of standardization [*Melvin and Briffa*, 2008] were also tested to see if we might better

capture the recent drought (1999–2007). Signal-free standardization was developed to reduce trend distortion that reduces retention of medium and low frequencies at the end of a time series, an issue that is not uncommon with data-adaptive detrending [*Melvin and Briffa*, 2008].

2.4. Modeling

[11] The Kherlen steamflow model was created using principal component regression on the 1960–1993 common period and validated using a split-calibration verification scheme [*Cook and Kairiukstis*, 1990] that is calibration from 1977 to 1993 and verification from 1960 to 1976 and vice versa (Table S1). We use a probability level for screening correlations of $p = 0.1$, with one-tailed test (positive only) and an eigenvalue selection criterion of 1.0 or greater. We tested previous and current year tree-ring indices as candidate predictors because tree growth can be influenced by both prior and current year growing conditions. A nested model approach was used to fully use the oldest chronologies and most recent samples (Table 1). Nest length was determined by the EPS strength (0.85 or greater) of each additional chronology used for nesting. We evaluate the fit of the regression model for each nest using r^2, coefficient of efficiency, and the reduction of error statistics [*Cook and Kairiukstis*, 1990] (Table S1). Each individual nest was normalized and rescaled (mean and variance) to match the most replicated period (1815–1993) to avoid artificial variance due to the number of chronologies used within each nest.

[12] The new Kherlen streamflow reconstruction is evaluated for drought characteristics, including duration, magnitude, and intensity using runs analysis [*Salas et al*., 1992; *Biondi et al*., 2002; *Gray et al*., 2011]. Magnitude is calculated as the cumulative departure from the median for each event, 3 years or greater, and intensity is calculated as the mean cumulative departure for each event [*Gray et al*., 2011], 3 years or greater.

3. Results

[13] The variance explained from the regression model based on the Undurkhaan data over the period of 1960–1993 was significantly greater than the same period versus Choibalsan (∼76% versus ∼60%, respectively). In addition, as the Undurkhaan station is closer to the tree-ring sampling sites, we henceforth focus on the Undurkhaan model. Thirteen tree-ring chronologies (Table 1) were used as predictors over the common period of 1815–1993 in a principle component regression analysis of streamflow data from the Undurkhaan station. We found that the strongest model was produced when using the dendroclimatic year from prior August to current July, with one lag over the common period of 1960–1993, which is the same dendroclimatic year used in *Pederson et al*. [2001]. The common period of 1815–1993 nest explains 76% of the variance in the recorded streamflow of the dendroclimatic year variance from 1960 to 1993 (Figure 3), an improvement of 28% versus the model in *Pederson et al*. [2001]. Additional 12 nests were stepped back in time, and four nests were stepped forward in time. The number of predictors used for each nest and nest statistics are shown in Table S1.

[14] The forward nests pass statistical tests for modeling and show that streamflow was low since 2000; however, even though the tree-ring models capture the nineteenth-century droughts well, the tree-ring models overestimate streamflow from 2001 to 2007 (Figure 3). We believe that the overestimation of the drought by the trees since the year 2001 is a function of trend distortion at the end of the tree-ring series [*Melvin and Briffa*, 2008]. We found that signal-free methods of standardization improve the relationship between the trees and the streamflow data since 2001 (not shown); however, the additional nests based on signal-free methods explain less of the variance (49.3% to 70.4%) when compared with the conventional methods (57.3% to 76.4%). Therefore, we consider only the conventional reconstruction for further analyses.

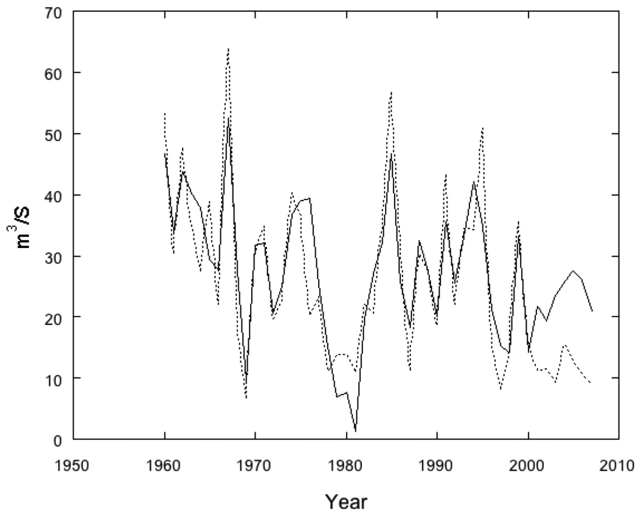

Figure 3. Dashed line shows seasonalized Kherlen River streamflow data, and solid line shows streamflow estimated from tree rings.

[15] We include both forward and backward nests in the reconstruction, and we have graphed the recorded streamflow data along with the reconstruction for comparison (Figure 4). The final reconstruction (1583–2007) was truncated to 1630 so that there was a minimum of two chronologies with EPS values > 0.85 in the earliest part of the reconstruction. Variance explained for the common period and each nest, and the calibration and verification statistics are shown in Table S1.

[16] Despite a loss of variability in the reconstruction of streamflow data using tree rings, the most recent drought, based on instrumental data, is not substantially different than the 1723–1739 reconstructed drought or other reconstructed individual years (Figure 4). Based on recorded data, the most recent drought lasted 9 years from 2000 to 2008 (the record ends in 2008) and had an average flow of 11.57 m^3/s. Of the top 10 most significant droughts reconstructed (Table 2), all lasted 5 years or longer. The longest duration droughts began in the 1720s, the late 1760s (17 and 11 years, respectively), and in the mid-1670s (11 years). The lowest flow events (1723–1739 and 1977–1982) averaged less than half of the mean flow of the entire reconstructed period (1630–2007). An intense 17 year drought occurred from 1723 to 1739 and was the largest magnitude drought of the entire record (Figure 5 and Table 2). This severe drought was followed by three consecutive pluvial

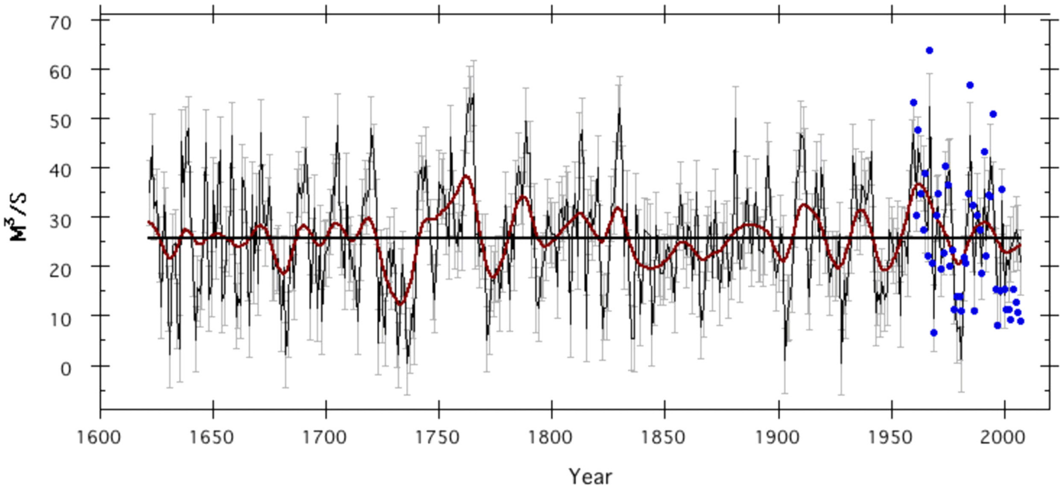

Figure 4. Reconstructed Kherlen River streamflow spanning 1630–2007, with a 20 year moving average (thick line). Recorded streamflow for the Kherlen River (prior August to current July) has been included since 1994 (dashed line) to aid in comparison with prior droughts. Because of nested model methods, each nest has been rescaled to the mean and standard deviation of the common period nest (1815–1993).

events from 1740 to 1746, 1749 to 1753, and 1759 to 1767. The 1760's pluvial is ranked the second in the top 10 highest flow events (Table 2). Other substantial pluvial events are as follows: 1958–1968 (first), 1784–1790 (third), and 1826–1831 (fourth). Importantly for the Undurkhan region, the 1900s contained three large-scale pluvials from 1907 to 1912, 1933 to 1942, and 1958 to 1968 (Figure 5 and Table 2).

[17] The Undurkhaan streamflow reconstruction spans nearly four centuries and shows greater variability historically than what is seen in the recorded streamflow (Figure 4) at both Undurkhaan and Choibalsan. Violin plots of nonoverlapping 50 year periods, using density estimates of streamflow values [*Hintze and Nelson*, 1998], illustrate high variability in the reconstruction (Figure 6). The eighteenth century contains the highest degree of variability. Differences between the seventeenth and eighteenth centuries when compared with the twentieth century are further supported in the violin plots. The violin plots indicate a greater probability of severe drought during the seventeenth and early eighteenth centuries when compared with the latter half of the twentieth century (Figure 6).

Table 2. Flow Table: 10 Lowest Flow Events (Top) and 10 Highest Flow Events (Bottom)

Year	Duration	Magnitude	Intensity	Score	Average Flow (m^3/s)
1768–1778	11	−86.71	−13.40	49	17.54
1723–1739	17	−220.73	−12.40	47	12.44
1676–1686	11	−96.11	−10.67	44	16.69
1943–1948	6	−58.91	−12.98	43	13.84
1847–1855	9	−48.08	−14.85	42	20.08
1928–1932	5	−52.45	−13.25	41	14.94
1977–1982	6	−76.88	−8.74	39	12.61
1641–1645	5	−53.37	−7.88	32	14.75
1630–1635	6	−74.37	−5.77	31	13.03
1902–1906	5	−61.88	−6.11	31	13.05
1759–1767	9	127.34	14.15	48	39.57
1784–1790	7	100.77	14.40	48	39.82
1826–1831	6	91.15	15.19	48	40.62
1958–1968	11	135.73	12.34	47	37.76
1636–1640	5	78.75	15.75	46	41.17
1907–1912	6	89.50	14.92	46	40.34
1812–1814	3	53.14	17.71	44	43.14
1716–1722	7	79.09	11.30	40	36.72
1933–1942	10	93.38	9.34	36	34.76
1687–1693	6	64.07	10.68	35	36.10

[18] The new Kherlen River reconstruction, with the addition of 11 chronologies and improved standardization methods, better captures the variability of the meteorological data than the *Pederson et al*. [2001] reconstruction and shows wetter conditions, especially since the last 150 years (Figure 7). The mean flow in the 2012 reconstruction is nearly 3 m^3/s higher (25.71) than the original reconstruction (22.96). Similarly, the standard deviation (11.22 versus 7.34, respectively), variance (125.90 versus 53.81, respectively), and accounted variance of the instrumental streamflow record (76% versus 48%, respectively) have substantially increased. Differences in variability detected here are easily seen visually. Although the major features of the *Pederson et al*. [2001] record are retained, there are more intense pluvial and drought events reconstructed in the new record.

4. Discussion

[19] Recent droughts, along with other variables [*Von Wehrden and Wesche*, 2007], have had huge negative impacts on the people and economy of Mongolia [*Skees and Enkh-Amgalan*, 2002; *Batima*, 2006; *Sternberg*, 2010; Ministry of Nature, Environment and Tourism, 2010]. Drought not only lowers the productivity of the grasslands [*Kogan et al*., 2004] leaving animals more vulnerable to extreme winter conditions but also has the potential to disturb species diversity, composition, and ecosystem function in grassland environments [*Jiménez et al*., 2011], further compounding the vulnerability of nomads and their livestock. The new reconstruction indicates that the most recent drought is not unusual in the context of the last 400 years

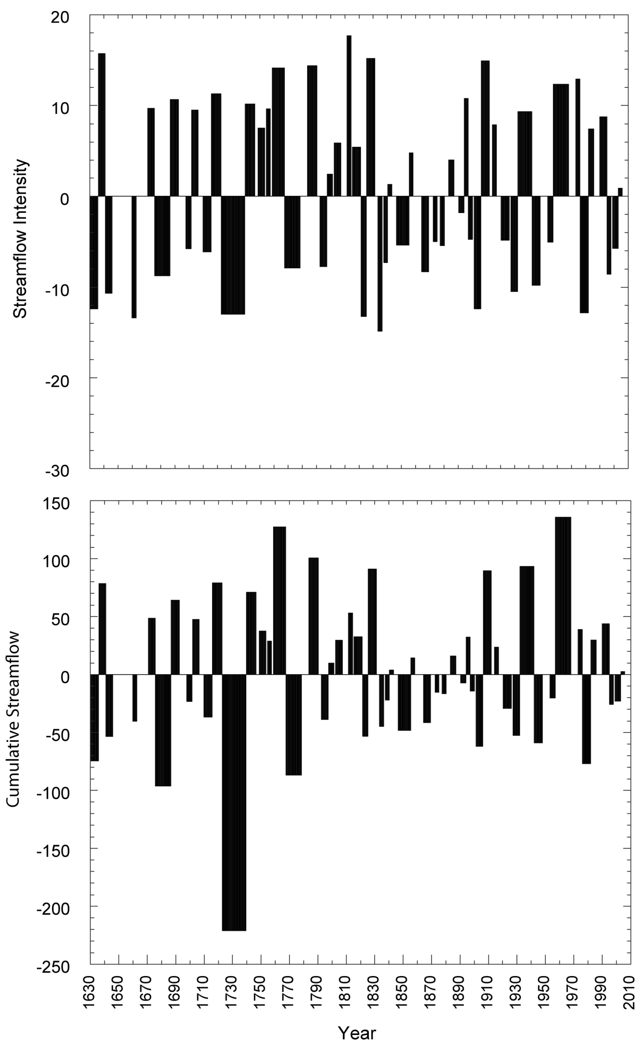

Figure 5. Kherlen River (top) flow intensity and (bottom) flow magnitude of pluvial and drought events for 3 years or greater in duration. Intensity indicates the average severity of each event, whereas magnitude portrays the cumulative severity of each event. Note: The *y* axis scales differ.

and that there were periods that have been more severe and longer in duration than the most recent drought (Figure 4 and Table 2). In fact, the impacts of the most recent drought on the people and herds of Mongolia may have been amplified because it followed three strong pluvials (defined here as a continuous period of above average streamflow) during the twentieth century. Although there has been more severe droughts in the past, the demand for water resources is now greater than it has been in the past [*Ministry of Nature, Environment and Tourism*, 2010]. The recent three strong pluvials could have actually made this region of Mongolia more vulnerable. Societies can become more susceptible to drought if they previously had access to greater amounts of water [*Dahlin*, 2002; *Hornbeck and Keskin*, 2011]. As water demand will increase in the future [*Ministry of Nature, Environment and Tourism*, 2010], it might be best to develop water management plans based more on the long-term range of variability seen here than the instrumental records of the last 50–70 years.

[20] We compared Kherlen River streamflow with the two closest independent streamflow proxies: a Selenge River reconstruction [*Davi et al.*, 2006] and a new reconstruction for the Yeruu River, in a region to the north (Figure 2) [*Pederson et al.*, 2012]. Average flow of the Kherlen River reconstruction is roughly 12% of the flow of the Selenge River and 30% of the flow of the Yeruu River (Figure 8). The new Kherlen reconstruction correlated highest with the Yeruu ($R = 0.65$, $p < 0.05$) and lower with the Selenge ($R = 0.33$, $p < 0.05$). Notably, the Kherlen correlated particularly poorly versus the Selenge reconstruction during the 1800s ($R = 0.07$, $p > 0.05$). However, all three reconstructions show similar intense and extended drought in the 1730s, 1760s, the early 1900s and the late 1920s, and the late 1970s, indicating that these events were regional-scale or extra-basin-scale events. An extended dry period occurred from 1676 to 1686 in the Kherlen and Selenge regions. The 1730s droughts extend into China and may be related to a weakening of westerlies and the East Asian Summer Monsoon [*Fang et al.*, 2013]. Lower hydroclimatic variability is evident from 1850 to 1900 (Figures 4 and 7), a pattern found in *Pederson et al.* [2001], *Davi et al.* [2006], and a drought reconstruction for all of Mongolia [*Davi et al.*, 2010]; however, interestingly, this pattern is not seen in the Yeruu reconstruction. Pluvials occurred in the 1760s and the 1780s in all three rivers and again in the 1910s, 1930s, and 1960s, yet again indicating that the spatial expression of hydroclimatic events occasionally are found at regional scales.

5. Conclusions

[21] The new, 378 year Kherlen reconstruction, with greater spatiotemporal replication and improved tree-ring

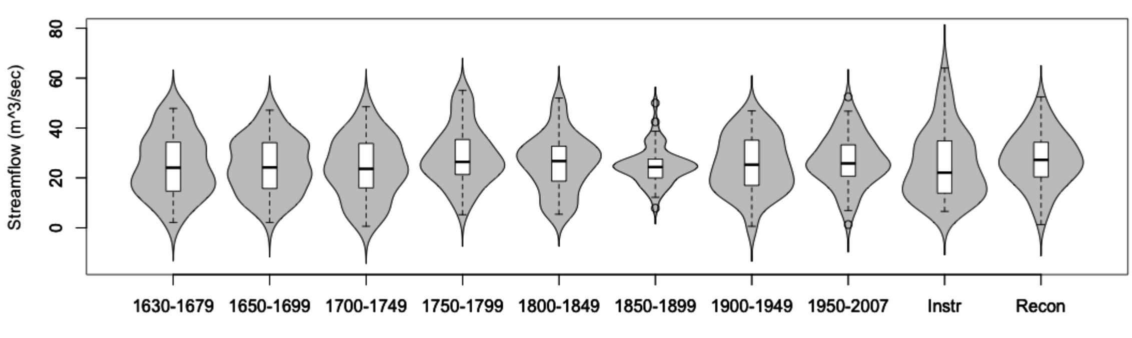

Figure 6. Violin plots for Mongolia, which display probability density estimates (shaded gray areas) for ∼50 year segments, with box-and-whisker plots superimposed on top.

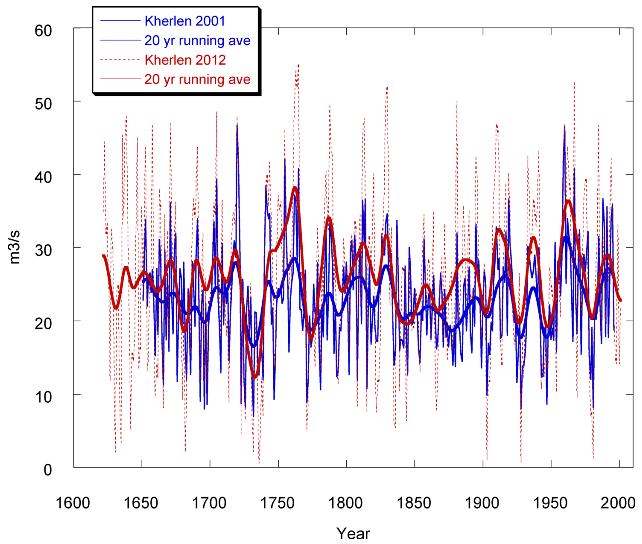

Figure 7. A comparison of the (blue) 2001 and (red) new (2012) reconstruction of Kherlen River streamflow. Thick lines represent a 20-year spline of annual data for reconstruction.

methods, gives us a more complete understanding of the full range of streamflow variability. This information is critical for resource management, especially when alterations in streamflow are being considered for mining or agricultural projects [*Ministry of Nature, Environment and Tourism*, 2010]. The new reconstruction not only shows much greater flow variability than what is captured in limited instrumental data and in the original 2001 Kherlen reconstruction that was based on two tree-ring chronologies but also shows that severe decadal scale droughts and pluvials have occurred historically.

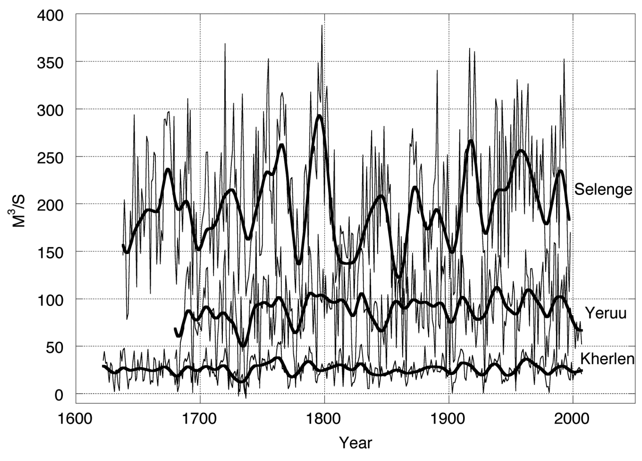

Figure 8. Three tree-ring-based streamflow reconstructions for Mongolia: the Kherlen (this study) on the bottom; the Yeruu River in the middle [*Pederson et al.*, 2012]; and the Selenge River on top [*Davi et al.*, 2006]. The season reconstructed for the Kherlen and Yeruu are the same (prior August to current July) and is current and prior April–October for the Selenge. The 20 year moving average and the mean line for each reconstruction are also displayed.

[22] The new reconstruction indicates wetter conditions and three large pluvials in the twentieth century. We therefore contend that, in the new context of a much wetter century than what was previously known, the recent era of severe droughts likely had a greater societal and ecological impact because of the abrupt transition from unusually wet conditions to a much drier regime. The new reconstruction, however, also indicates that the droughts since the year 2000 might actually be a return to more long-term hydroclimatic variation for Mongolia.

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