RECONSTRUCTED DROUGHT VARIABILITY ACROSS MONGOLIA BASED ON

TREE-RING RECORDS

by

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ABSTRACT OF THE DISSERTATION

Reconstructed Drought Variability Across Mongolia Based on Tree Ring Records

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Our understanding of climate in Mongolia is hindered by the extremely limited meteorological data in the region. Longer records, and insight into temporal drought patterns could aid greatly in anticipating extreme events and agrarian planning. Tree-ring reconstructions can provide longer, high-resolution records of climate variability in regions where recorded data are limited.

In central Mongolia, streamflow for the Selenge River (1637-1997), the largest river in Mongolia, was reconstructed. Regression models resulted in a reconstruction of streamflow that explains 49 percent of the flow variation. The wettest 5-year period was 1764-1768 and the driest period was 1854-1858. The most extended wet period is 1794-1802 and an extended dry period is 1778-1783. Spectral analysis, a method for identifying periodicities within a time series, indicated significant variation in the frequencies common to Pacific Ocean variations (PDO and ENSO) and also some quasi-solar and lunar-nodal periodicities.

In the far west, a grid cell of the Palmer Drought Severity Index (PDSI) was reconstructed (1565-2003) and explains 41 percent of the total variance in the instrumental PDSI. The reconstruction shows that starting in the 20th Century and continuing into the 21st Century there was a large-scale regional increase in growing-season moisture conditions compared to the prior centuries, a trend not seen in central or eastern Mongolian tree-ring reconstructions. Spectral analysis shows significant periodicities at approximately 22 (99% significance level), 11 (90%), 7 (99%), and 5 (99%) years.

Also presented is a summer drought reconstruction for all of Mongolia, based on a network of 34 tree-ring chronologies that span the country. The PDSI model explains 61% of the variance over the most replicated period (1703-1993) and nested model methods were used to create the longest reconstruction possible (1520-1993). The reconstruction shows that droughts from 1999-2002, felt across central and eastern Mongolia, were extreme compared to the past 500 years. Significant periodicities are found at 40 (90%), 19.3 -25 (99%), 11.6 (95%), 6.4-7.2 (95%), and 2.8 years (99%).

These high-resolution drought reconstructions supplement and extend the sparse meteorological data in Mongolia and allow for a long-term perspective of drought across Mongolia. As temperatures continue to rise in Mongolia, and much of the Northern hemisphere, drought may be an increasingly dire issue for human and environmental well

being. Future predictions of drought and forecast capabilities are summarized, as are current climate risk management program.

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CHAPTER 1. INTRODUCTION AND REGIONAL CLIMATE OF MONGOLIA

1.1 Introduction

a. Context

Roughly half the people of Mongolia (~3M) are nomadic herders (Figure 1.1) and survive by raising livestock such as sheep, goats, horses, camels, and yaks, frequently moving these animals over long distances to find better grazing pastures for them. In fact, a common greeting of Mongolian nomadic herders is "Mal sureg targan tavtai yu", meaning, "I hope that your animals are fattening up nicely". This greeting typifies the importance of herd health on the survival and wellbeing of the traditional nomadic lifestyle. In recent time (1999-2000, 2000-2001), summer temperatures reached record highs (Batima 2006), and there was widespread drought and devastating livestock mortality rates in much of the country (Orfinger 2002, Helminen IFRC 2002). Severe winter weather following these droughts caused more loss, forcing many families to abandon the traditional nomadic lifestyle and move to more urban areas. The nomadic people are particularly vulnerable to climate change and climate extremes because they are directly dependant on animals and the health of the grasslands, and have no reserves in place when extreme climate events occur.

Understanding of drought is limited by the length, spatial coverage and completeness of the meteorological station records. Few Mongolian stations started recording data prior to the1940s and are therefore not adequate to help us to fully understand climate cycles and trends. Often months and sometimes entire decades of data are missing from the meteorological record, further limiting their usefulness. This is particularly true during social hardships such as war or political instability. For example, very few stations recorded data during the collapse of the Iron Curtain in 1989.

Tree-rings can be used to supplement and extend the limited instrumental records. They are a unique proxy for reconstructing and extending climate records because they can record climate within their annual rings for every year that they are alive. In Mongolia, it is possible to find very old living trees (300-800 yrs.), and also preserved dead trees that died hundreds of years ago (D'Arrigo et al. 2001). Thus it is possible to create climate records that are hundreds to thousands of years old. These reconstructions can be used to fill in and extend station records and to more fully represent the range of natural variation, extremes, and trends, which may be much larger than what is captured in limited instrumental records. They also place recent trends into a long-term context and allow for evaluation of past climate variability, forcings and possible teleconnections.

To this end, there has been much success using tree-rings to reconstruct drought in North America (Cook et al. 1999), China (Li et al. 2006), and Southeast Asia (D'Arrigo et al. 2006, Sano et al. 2008). Developing tree-ring records in Mongolia will provide a better understanding of the climate system and possible cycles of drought and moisture and will enable the people of Mongolia to better manage current and future climate risks.

b. Objective

The main objective of this research is to evaluate drought in Mongolia on much longer time scales than is possible with the limited instrumental data available. By developing a large-scale network of tree-ring width records across the country, it is possible to create a drought history for Mongolia. This tree-ring network is used to better understand drought trends, extremes and possible cycles, and the spatial complexities of drought for nearly half a millennium.

To do so, it must first be established that:

1. The trees are sensitive to climate conditions and are capturing the climate history of a given region.

Then it is possible to determine:

1. If there are identifiable and significant climate trends, possible cycles and extremes.
2. How drought varies spatially and temporally across Mongolia.
3. If there are significant teleconnections with oceanic periodicities.
4. If drought and moisture patterns have changed in the 20th century.

1.2 Regional Climate of Mongolia

Mongolia has an area (1,564,116 sq km) roughly smaller than Alaska, and is landlocked in the central Asiatic continent, bordered by Russia and China. The topography of Mongolia is mainly a plateau (914-1524 m) with the Altai Mountains in the west, the Khoridol Saridag range in the North, and the Gobi Desert in the South (UNEP 1998) (Figure 1.2). Land-cover mainly consists of grasslands and steppe (70-80%), due to the semi-arid to arid climate and about 10% forests (Figure 1.3). Other land-cover consists of barren lands, and agriculture (UNEP 1998). Steppe is typically too dry for agriculture, therefore, livestock (goats, sheep, horses, yaks) is the primary source of livelihood for rural people. Roughly 80% of Mongolia's land area is used for pasture (Batima 2006).

a. Ecology and Biogeography

Distribution of trees in Mongolia is problematic for dendroclimatological studies because the extreme climate, long harsh winters and very little precipitation over much of the country, limits the distribution of trees. There is also low species diversity. In many areas the upper treeline species are the same as the lower forest border species, often mainly Siberian larch (Larix sibirica). Scots pine (Pinus sylvestris) can be found at lower elevations in eastern Mongolia. Siberian pine (Pinus sibirica) is found at upper treelines throughout the country, but seldom at lower elevations where moisture may be the limiting factor for tree growth. In certain situations even the higher-elevation trees show enough response to moisture to contribute some information to the climate/tree growth models. For the purpose of reconstructing past drought conditions, samples mainly come from the lower forest border, where the trees are most sensitive to moisture stress (Discussed more in Chapter 2). It is possible to find birch (Betula spp.), poplar (populous spp.), and spruce (Picea spp.) but they do not often achieve enough age to be useful for dendroclimatic studies.

Mongolia is regarded by many as a country with low human impact of the terrain. This is partially true but there have been nomadic herdsmen throughout the country for millennia. Much of the best grazing land is in the upper grasslands where there is a little more precipitation near the lower forest border. Due to this grazing, the lower forest border may not be the actual ecological lower limit to tree distributions. Cutting of trees in these areas, for construction of shelter and transportation, moves the lower forest border upwards and the grazing prevents seedlings from surviving. Optimally the true ecological lower forest would be the best location to look for drought sensitive trees. However, old-aged trees, necessary for long-term reconstructions, are absent in many places due to human activities and fire (Discussed more in Chapter 2). These conditions led to extensive travels to seek out locales where stands of lower elevation, moisture-stressed trees have survived to reach centuries old age.

b. Weather

Mongolia has extreme continental climate: short, warm summers (~20°C) and long, extremely cold winters (-20°C). The majority of precipitation falls in the summer (June-August), although total precipitation is relatively low, roughly 100-200 mm a year in the dry south and 200-350 mm a year in the mountain regions (Sato et. al. 2006). Snowfall is fairly minimal (contributing less than 20% to annual PPT) due to high anticyclone dominance in winter (Batima 2006). Figure 1.4 (from Morinaga et al. 2003) shows average monthly precipitation, snow depth, and temperature in (a) Underkhaan, which is central eastern Mongolia and (b) Khovd, which is central western Mongolia. Both regions show similar temperatures, with a maximum near 20°C in July, and minimum of less than (–) 20°C in January, and similar snow depth, starting in October maxing in January at about 4cm and ending in April. Precipitation is highest during the summer in both regions.

c. Climate Risks

The main climate risk for the people of Mongolia, particularly for the agrarian nomads is when prolonged or consecutive summer droughts are followed by a particularly cold winter. Even light snowstorms and ice can blanket pasturelands making it nearly impossible for animals to get access to the already drought-impoverished grass underneath, resulting in widespread starvation. This phenomenon is commonly referred to as the "Zuud" (sometimes spelled Dzud or Zud). However, there is no formal definition of Zuud and no index of Zuud.

Devastating Zuud conditions occurred in the winter of 1999-2000 and 2000-2001 (Swift & Bass 2007, Begzsuren et al. 2004). The 1990s had three of the hottest years on record; 1997, 1998 and 1999 (Batima 2006), and were followed by consecutive summer droughts of 1999, 2000, 2001, and 2002, affecting 50-70 percent of Mongolia territory (Batima 2006). When snow covered pasturelands during the winter of 1999-2000 and 2000-2001 there was widespread livestock loss - as much as 40% of the nation's livestock (Helminen 2002). This widespread devastation led to international support for climate readiness programs and climate risk assessment (described in Chapter 6)

d. Climatology

Mongolia and much of continental Asia have extreme continental climate with somewhat limited ocean influence (Aizen 2001). The Siberian anticyclone circulation (SH), a semi-permanent high-pressure system, is responsible for stable, sunny weather through most of the year, less summer. In summer there is a northward migration of the westerly polar jetstream, development of convection and strengthening of unstable atmospheric stratification. This allows for warm moist air mass influxes from the west resulting in a summer maximum of precipitation (Aizen et al. 2001). Other moisture influences include; (1) the strength of the North Atlantic Oscillation (NAO) (described below), as it determines the location of the westerlies and mid-latitude disturbances within the westerlies (National Weather Service 2002), (2) continental evapotranspiration and evaporation from oceans and (3) the Asian Monsoon (Aizen et al. 2001, Yamanaka et al. 2007). Li et al (2009) find that there is more moisture in Mongolia when the Asian Monsoon is strong and less when it is weak.

Synoptic-scale climatological studies in Mongolia are minimal due to limited meteorological data and a lack of studies that attempted to quantify observed regional climate with atmospheric forcings in the mid-latitudes of Asia. What follows is a summary of research on this topic.

A study by Aizen et al. (2001) evaluates the influence of atmospheric circulation patterns on regional precipitation at the mid-latitudes of Asia; however, Mongolia is excluded due to the lack of meteorological data. The Tien Shan Mountain region is part of this study and is located near the Altai region in western Mongolia, so it may be possible to infer information from this study. They find that westerly airflow is the most influential atmospheric variable in the middle and upper troposphere in middle Asia and is a main source of moisture. The strength and location of westerly airflow over Europe and Asia is influenced by the NAO. When there is a negative difference of anomalies of SLP between Azores and Iceland, more moisture occurs in the Tien Shan region and likely the Altai region. During a positive phase of the NAO, the strong westerlies shift, resulting in a decrease in winter precipitation in the Tien Shan region (and likely the Altai region) (Aizen et al. 2001).

Sato et al. (2007) focused specifically on regional climatology of Mongolia by analyzing isotopes (Delta O18) in precipitation during 2003. They found that summer (JJA) precipitation is supplied by mid-latitude synoptic-scale cyclones because the country is in the westerly-dominated zone. Delta O18 decreased over the Altai and Sayan mountain region as moisture was dropped over the mountains. Lighter moisture was then advected to eastern Mongolia by the prevailing westerly winds. Delta O18 showed that the origin of water vapor is not only local evapotranspiration, but also moisture from central Asia and western Siberia. Eastern Mongolia and NE China are bordered between westerly wind transport and southerly wind transport of the Asian Monsoon.

The National Weather Service (NOAA) Climate Prediction Center's Special Assessment Report about regional climatology of China and Mongolia shows that Mongolian precipitation is related to mid-latitude disturbances propagating within the cyclonic shear side of the jet stream along the poleward flank of the Asian monsoon ridge (Figure 1.4), and that the seasonal variations in rainfall are associated with quasi-persistent, large-amplitude circulation anomalies within the westerlies. In fact, persistent height anomalies (200 hPa) correlate with large seasonal departures in precipitation at 0.5 over Mongolia, over the 1979-2002 time span (National Weather Service 2002).

To better understand large-scale circulation patterns, they evaluated the drought year 2002 (Figure 1.5). Figure 1.5 shows that this drought was related to a persistent upper-level ridge through the depth of the troposphere over the western half of the country and southward shift in major cyclogenesis events to central China and complete disappearance of the low-level trough and southerly flow of moist air.

Climate feedbacks may also play a major role in prolonging and/or amplifying a drought. For example, dry conditions in Mongolia may lead to warmer temperatures and higher pressure. This high pressure can lead to continued dry conditions and more heat and higher pressure, thus a positive feedback of drought leading to more drought. High pressure also leads to clear skies, for example, the semi-permanent Siberian high pressure system results in clear skies in Mongolia for most of the year. In summer, anomolous high pressure results in clear skies that allows for an increase of solar flux at the surface which further enhances evapotranspiration, thus dessication.

It is not clear how the high-pressure anomalies described above are related to drought. Do the drier conditions lead to warmer temperatures that in turn cause higher than normal pressure (a positive feedback loop), or do anomalous high-pressure systems in the atmosphere lead to prolonged drought? It is possible that each scenario is true, that an anomalous pressure system leads to drought and that drought is prolonged/accentuated by feedbacks, however, at this time it is not possible to know for sure.

There are two complicating factors for understanding seasonal climate variations. First, increasing global temperatures may have significant impacts on precipitation (patterns, dynamics and evapotranspiration rates) and the associated economies in Mongolia. In an arid region like Mongolia, large variations in moisture could have significant impacts on the livelihood of people. Adjusting to warming-induced, amplified variation could be difficult. Second, warming temperatures could amplify land degradation from grazing and development, which could lead to further altering of regional climate and reduction in rainfall (based on GCM experiments) (Xue 1996).

e. Instrumental Data:

NOAA's Global Historic Climate Network shows that in Mongolia there are forty-five meteorological stations recording precipitation, ranging from 1862-2008 (Figure 1.6) and fourteen temperature stations ranging from 1943-2008. The majority of these stations do not begin recording data until the 1940s or later and have many missing values (more in-depth information about station data used in this study is in each research chapter). Several studies have evaluated these instrumental records (1940-2001) and found that Mongolia is undergoing significant climatic change. Temperatures have been steadily increasing (Yatagai & Yasunari, 1994, Batima et al. 2005, Endo et al. 2006), particularly in the high mountain regions (Christensen et al. 2007), such as the Altai in the west (Batima et al. 2005). A 1738-year record of Mongolia temperature, inferred from tree-ring variation, (D’Arrigo et al. 2001, Jacoby et al. 2008 in press) shows that temperatures are increasing and that the late 20th century is the warmest time of the entire record (Figure 1.7).

Batima et al. (2005) evaluated sixty individual stations (1940-2001) and found that there are regional precipitation patterns. Spatial patterns of precipitation are complicated because they can vary due to differences in elevation, topography, and storm tracks. These lead to differences in precipitation, even in neighboring areas. They find that annual precipitation has been decreasing in central Mongolia and increasing in eastern and western Mongolia. The majority of these decreases have been seen in winter and spring, when other studies show increasing temperatures. Summer and autumn remain unchanged, although none of these changes are statistically significant

Dai et al. (2004) used the principal component of the first empirical orthogonal function (EOF) of global Palmer Drought Severity Index (PDSI) (Palmer 1965), which suggests a drying pattern over the majority of Mongolia. However, subsequent analysis of PDSI over China and Mongolia (Li et al. 2008) finds no significant moisture trend in the PDSI (1951- 2005) record over central and western Mongolia. Although, in eastern Mongolia there is an overall drying trend (statistically significant at the 0.01 level.), particularly beginning in the early 1990s.

1.3 Dissertation Justification

Although evaluating instrumental data is valuable, many questions are left unanswered. The instrumental record cannot tell us the full range of climate variability or if, for example, drought in the recent decades is truly anomalous or something that happens episodically. Additionally, if there are significant multi-decadal climate variations they may not be captured by a limited instrumental record. Of all the above studies, at best, 60 years of data are evaluated, far too short a period to be able to fully understand trends or periodicities. The focus of this dissertation is to create meteorological data from tree-rings that can then be used not only to extend station records, but also to add data to regions where no observations were ever made.

Synoptic-level studies have not been possible in Mongolia, mainly because of the sparse meteorological data. The Zuud, a climate phenomenon that can cause widespread livestock loss, is not well understood and is the main climate risk for the people of Mongolia. This study will create meteorological data based on tree-rings that can be used to supplement and extend the human-observed meteorological record. These tree-ring records will put the recorded meteorological data in a long-term context and allow for evaluation of trends, extremes and periodicities, and further our understanding of drought mechanisms and overall climate of Mongolia.

With the intensity of recent droughts in Mongolia and the uncertainty of drought variability in the context of rapidly increasing temperatures (Christensen et al. 2007), long-term tree-ring reconstructions are imperative to fully understand the full range of past drought variability and the spatial and temporal scales of drought and moisture patterns.

1.4 Dissertation Organization

The following chapters are broken down as follows:

- **Chapter 2** focuses on principles and methods of dendrochronology. Focusing on why it is possible to use tree-rings as a proxy for climate, the field methods for collection of samples and general laboratory methods for creating climate models.

There are three-research chapters (Chapter 3, 4 and 5) and each of these chapters has a distinct methods section due to variation in methods in each region.

- In **Chapter 3,** streamflow (1637-1997) for the Selenge River Basin in central Mongolia is reconstructed based on five tree-ring chronologies. The Selenge is the largest river in Mongolia and a major input into Lake Baikal in Siberia.
- **Chapter 4** focuses on reconstructing a grid-cell of Palmer Drought Severity Indices (PDSI, Dai et al. 2004) in western Mongolia (1565-2001) based on three tree-ring chronologies.
- In **Chapter 5** all drought sensitive tree-ring data developed for this study (34 chronologies) are used to develop a drought index (1520-1994) for all of Mongolia. This model reconstructs the average summer PDSI, of 44 grid cells across Mongolia, and puts the droughts from 1999-2002 into a long-term perspective.
- **Chapter 6** is discussion chapter that evaluates the spatial patterns of moisture and discusses the main climate risks in Mongolia, the prediction capabilities to date and some of the steps the Mongolian government and international institutions have taken to try to lessen the impacts of climate change on the people of Mongolia.

- **Chapter 7** is a concluding chapter that summarizes the research and discusses possible future uses of the data network developed for this dissertation.

1.5 Dendroclimatology in Geography

Dendroclimatology, the study of climate using tree-ring chronologies, fits into the discipline of geography on many levels. Dendroclimatology focuses on variations of tree-growth in relation to climatic change and has strong spatial and temporal components, making it inherently geographic. In this dissertation, annual tree-ring records are used to evaluate drought patterns through time and across space and are used to evaluate possible connections to large-scale atmospheric/oceanic climate forcings (i.e. NAO, ENSO).

Geography, like dendroclimatology, has a long tradition of studying human/environment interactions. Recent work in dendroclimatology has used long-term paleoclimatic reconstructions to place into perspective possible anthropogenic impacts on the environment, such as global warming. More recently, tree-ring reconstructions have been used to document the impacts that natural climate variation and natural disasters can have on culture and people (i.e. the lost colony in Roanoke, and the Jamestown droughts). Tree-ring records developed for this dissertation, can be used to better understand the severity of recent drought that occurred across much of Mongolia.

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FIGURES

Figure 1.1. Nomadic man on horseback herding sheep and goats.

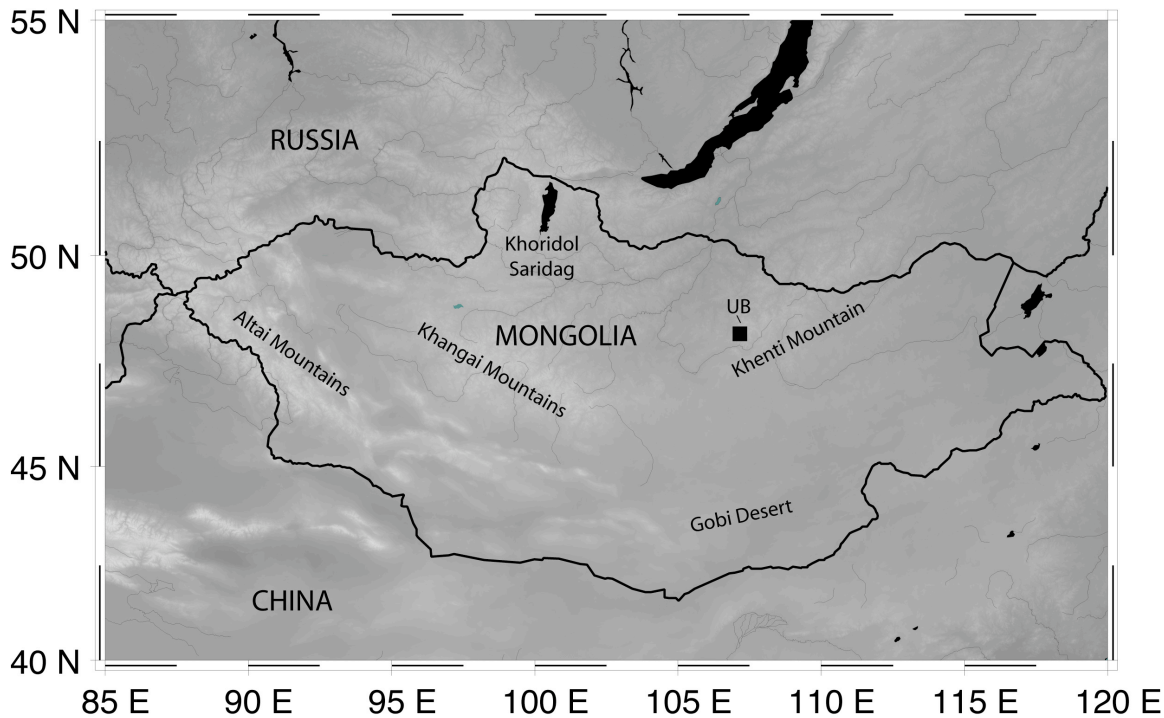

Figure 1.2. Topographic map of Mongolia showing, lakes and streams, mountain ranges, Ulaan Baatar (UB), and the Gobi desert.

Figure 1.3. Typical Mongolian steppe landscape with larch and pine trees growing on the northern slopes.

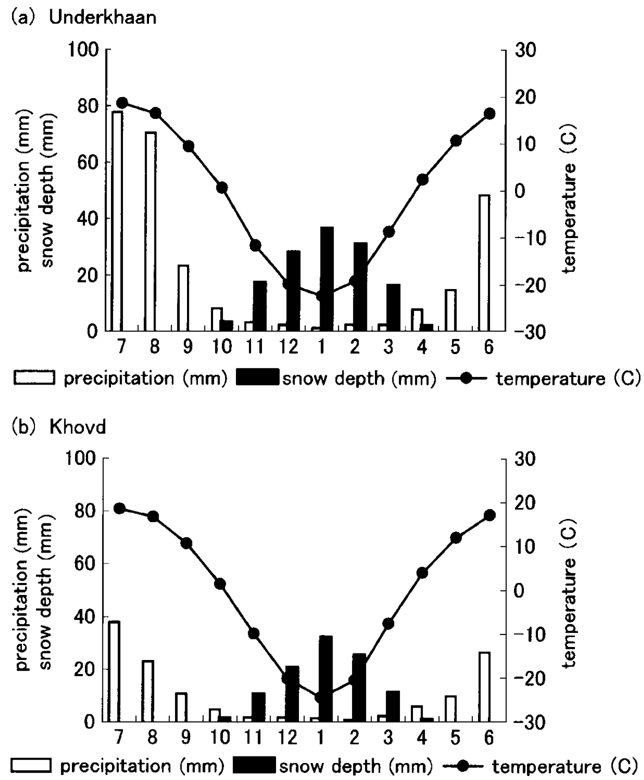

Figure 1.4. Average precipitation (mm), Snow depth (mm) and temperature (°C) from a) Underkhan and b) Khovd station (Figure from Morinaga et al. (2003)).

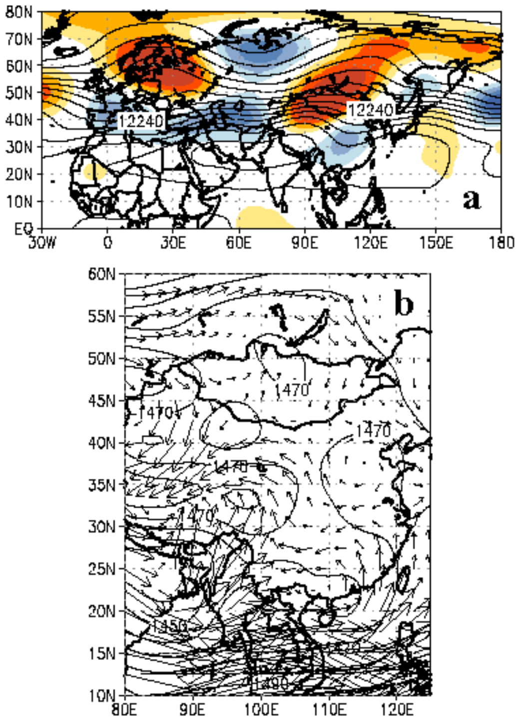

Figure 1.5. From NOAAs Climate Prediction Center put out a Special Assessment Report (Figure 4). 'July-August 2002 mean (a) 200hPa height (contours, interval is 60m) and anomaly (shading), and (b) 850- hPa height (contours, interval is 10m) and vector winds. Height anomalies are departures from the 1979-1995 base period means.'

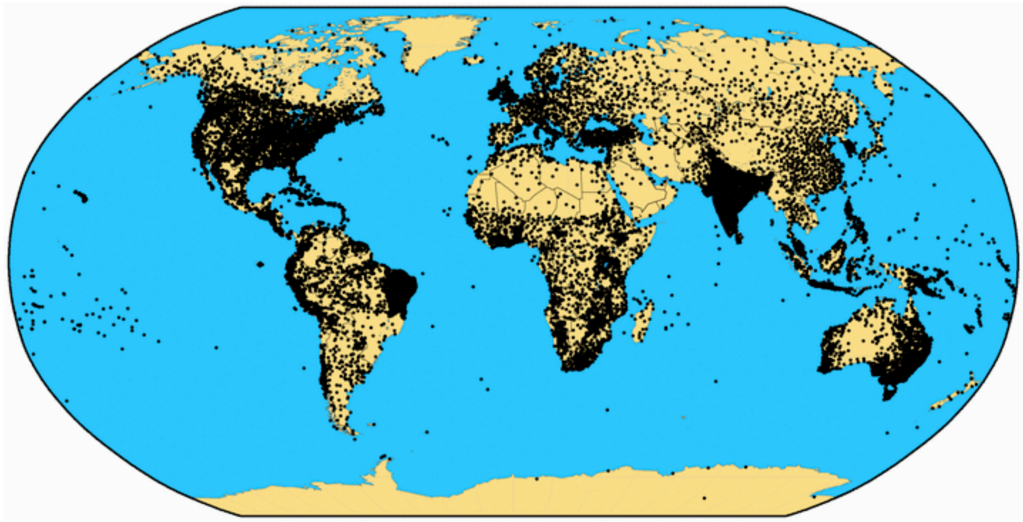

Figure 1.6. Global locations of all precipitation stations from Global Historic Climate Network.

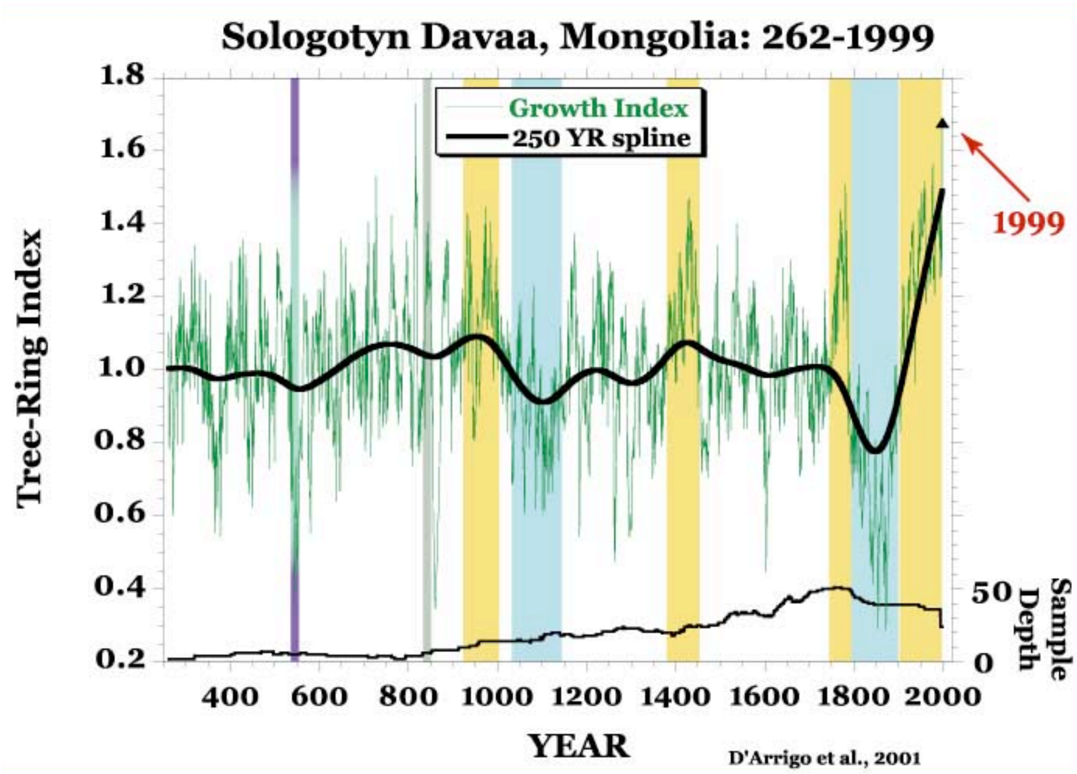

Figure 1.7. A 1700 -year temperature inferred from tree-ring data showing that the 20th century is unusually warm (1999 the warmest year) Although there is a problem with the smoothing spline I think. It is trending up too much at 2000. Typical Northern Hemisphere trends can be observed (such as LIA episodes) D'Arrigo et al 2001.

CHAPTER 2. PRINCIPLES AND METHODS OF DENDROCHRONOLOGY

2.1 Proxy Data and Principles

a. Proxy data

Most of what we know about global and regional climate on long-term time scales comes from “proxy” data. For the purposes of understanding climatological patterns, recorded meteorological records in general are short, typically pertain to only the past century or so. They are also regionally limited, for example, developing nations may not have the infrastructure to support meteorological stations. It is also possible that meteorological data may include trends created by human influence rather than natural variability. Therefore, we must rely on proxy data to foster our understanding of climate variability.

In this study, annual tree-ring widths are used to reconstruct moisture conditions in Mongolia over the past several centuries. However, it is important to note that there are many different types of proxies, including, but not limited to, pollen, ice cores, and sediments. Each proxy uses different statistical methods to understand the climate "signal" therein, and come from different locations with very different climates. Fundamental to all proxy records is that they are indirect information about climate variations from biological and/or geological evidence. These proxies are affected by changes in the surrounding environment, which affect the growth or composition of the proxy, and are recorded sequentially through time. By understanding how variability in the environment affects the proxy, it becomes possible to reconstruct climate conditions through time.

Proxies are limited spatially by the location where the proxy can be found. For example, trees that are old and sensitive enough to record climate are not widespread and can only be sampled in regions where they grow, the same with coral records. And, both tree-ring and coral records are limited by the life span of the organism. Although there are trees that can live several thousands of years, it is not common. With the spread of human population, many forests were cleared for agriculture or timber, making it difficult to find trees that are over 300 years. Tree growth and thus the climate records that are reconstructed based on that growth, is also typically limited to the growing season. During northern latitude winter, trees are not growing, and are therefore not recording climate conditions.

Another thing to consider is that a tree is a living organism, responding to its environment individualistically and does not respond solely to one single climate variable, such as precipitation. Dendroclimatology as a science depends on there being a dominant climate variable to reconstruct, such as precipitation in an arid environment, there will always be influences from other climatic and non-climatic sources (discussed further below). Our understanding of past climate is limited to our understanding of the proxies recording the climate and the inherent strengths and weaknesses of each, such as resolution, spatial extent, modeling methods, seasonality, and disturbances. Tree-rings are by far the most heavily relied on proxy for understanding climate on timescales of 100s to 1000s of years due to their high-resolution (annual to seasonal), their relative spatial abundance, and the ability to calibrate and verify the models against recorded meteorological data.

b. Principles of Dendrochronology

There are several principles of dendrochronology that make it possible to create valid climate reconstructions. A basic principle in the science of paleoclimatology and Dendrochronology is the **Uniformitarian Principle**, which states that the natural process that links climate with tree-growth today had to be in operation in the past (Fritts 1976, Cook 2002). Therefore, present day processes can be used, through paleo-data, to interpret past climate patterns. In other words, "the present is the key to the past." Then, by understanding past climate, we are better able to understand the range of natural variability and to predict possible future climate trends.

Is it possible that proxies, such as trees, have responded differently to climate through time? There is some evidence of non-stationarity in tree-rings in some high-latitude areas of Alaska and Yukon Territory. In this region tree that are presumably limited by temperature, and normally thrive under warmer conditions, are showing a negative relationship with warm temperatures in recent decades (Jacoby et al. 1995, Barber et al. 2000). It is hypothesized that under higher than normal warming, seen in the 1990s, there is a threshold where the environment starts to dry and the trees are subject to moisture stress, causing annual growth to respond negatively (Barber et al. 2000, D'Arrigo et al. 2004). The implications of widespread divergence, as it is called, would cast much uncertainty on the ability of trees to capture the true range of climate variability, which would mean that there is a limit to the information trees can yield during warm periods at particular regions. As temperatures continue to rise it is imperative to test tree-ring chronologies for divergence. However, as it turns out, divergence is not a widespread problem, as it is limited to some northern, high latitude areas (although not ubiquitous there) (D'Arrigo et al. 2004, Jansen et al. 2007). There is no evidence of divergence in any chronologies used for this dissertation or in Mongolia in general. However, it must be considered when evaluating tree-ring proxies, particularly high-elevation or high-latitude, temperature-limited trees.

Divergence, if present, can be fairly striking. In a region where it has been established through the meteorological record that temperatures are increasing, you would expect to see annual tree-growth accelerating in temperature sensitive trees (discussed further in below). In these trees, ring growth in the most recent decades would be relatively large. However, when the growth appears to be small or stunted, compared to the prior several centuries (again, temperature sensitive trees is key here), then it is reasonable to suspect divergence. Such trees could be compared to other nearby temperature sensitive chronologies to see if there are similar patterns. It is possible that divergence can be limited to regions. However, if all trees show divergence over large areas one would have to look at other proxy records, if available, to see how the trees have responded to warmer temperatures through time and to establish if divergence has happened in the past.

Site Selection is another principle of dendrochronology. Without proper site selection it is possible that no clear climate signal would be found. Dendrochronological analysis uses a tree's growth history (expressed in the radial growth of annual rings) from old-age trees that are strongly influenced by climate to provide information about past environments (Fritts 1976, Cook 2002). It is possible to reconstruct temperature and moisture conditions using tree-rings because trees are sampled only in areas where they are environmentally stressed or sensitive (i.e., growing near the limit of their range in latitude or altitude, or growing on a steep slope or well drained substrate.) (Figure 2.1 & Figure 2.2). Therefore, the presumed "limiting factor" is often fairly well understood by knowledge of the site ecology.

The lower-elevation, arid-climates such as the Mongolian steppe receive relatively low moisture (200-300 mm/year, the bulk of which of which falls during the warm season); therefore variability in summer moisture conditions will very likely be reflected in the annual growth rings of the trees. During a wet year, a tree will grow more, resulting in a wider ring; conversely, during a dry year, the ring would be much narrower (Figure 2.3). It is important to note that an understanding of both site conditions and limiting factors are essential when choosing an appropriate sampling site. No less important is finding trees that are relatively undisturbed not only by human influences such as forest cutting and grazing, but also by infestation, disease, fire, and other disturbances.

It is never possible to totally isolate a single climate variable, because trees are living organisms responding to both climatic and non-climatic variables, including; light availability, fire, competition, seed dispersion, infestation, human influence, and reproduction strategies. It is impossible to avoid the influence of variables such as gap dynamics and competition on tree growth because trees will age and die, or be blown over by a storm, and the remaining trees will have more sunlight then they used to. These types of growth influences are kept to a minimum, however, by selecting open canopy forests (Figure 2.1 & 2.2). Sometimes there are regions where it is not possible to infer the limiting factor with much certainty, therefore the growth-climate relationship is always statistically modeled by calibrating annual tree-growth against recorded meteorological data for the same year (described below). This allows us to better understand and quantify the full extent of the climate/tree growth relationship.

The most striking non-climatic influence on tree growth is age-related growth trends (Figure 2.4). As a tree ages, the amount of annual wood attained is distributed around an increasing circumference, causing negative exponential trends in ring widths that have nothing to do with climate. As a result, trees growth series are conservatively detrended or "standardized" in order to remove growth trends and yet retain low-frequency information presumably from climate. Figure 2.4 demonstrates detrending. The top figure shows increased growth and amplitude beginning at about 1250 until about 1500. The bottom figure (2.4b) shows the same tree-ring series only now this growth trend has been removed. Other variables that may influence tree growth are microclimates, tree-to-tree competition, human disturbance, grazing, disease, insect infestation, fire, soil chemistry, the genetic makeup of each tree species, or on a larger scale, factors such as changing CO_2, O_3 and UV-B levels (Briffa et al. 1998, Jansen et al. 2007). The influence of many of these variables may be minimized through careful site selection.

The Principle of Aggregate Tree Growth (Cook 2002) decomposes tree growth into an aggregate of environmental factors.

$$\mathbf{R_t = A_t + C_t + \hat{O}D1_t + \hat{O}D2 + E_t}$$

Where tree growth in a given year is a function of age related growth trends (A), climate (C), endogenic disturbance (D1), exogenic disturbance (D2), and random error not accounted for (E). In order to get the strongest climate signal, the other variables need to be minimized. This is possible by removing age related trends, by selecting appropriate tree-ring sites where trees do not show signs of disturbance (discussed above) and are growing near the border of their natural range so that they are very sensitive to climate variation.

It is possible that a large-scale event, such as an earthquake or insect-outbreak, could affect the entire stand and be misinterpreted as a climate event. However, earthquakes, fires, and insect outbreaks often have a signature ring pattern that is identifiable (Figure 2.5). Usually following the event, depending on how badly the tree was affected and on the time during the growing season the event took place, there is a severely stunted ring, followed by 5-10 years or more of stunted growth. There may also be traumatic cells or fire scars (burnt wood). Trees are inspected for damage before coring and sites are inspected for evidence of fire, earthquakes and insects. Additional information can be learned from local people living near the sampling sites. These people often have in-depth knowledge about forest history, health, or unusual events. Following these guidelines, described above, prevents such misinterpretation.

Tree-rings are a unique proxy for reconstructing past environmental conditions because each tree ring can be matched to an exact calendar year, thus providing very accurate information about annual to seasonal climate for as long as the trees are old. Annual resolution also allows for calibration with recorded meteorological data (when available) and verification of tree-ring models to understand the strength of the climate/ tree growth models. Once the relationship between instrumental data and tree ring variation is defined, tree rings can then be used to reconstruct and extend climate records well beyond the period of instrumental observations.

2.2 Methodology

a. Field Methods

Once a sampling site has been carefully selected (as described above) the forests are explored on foot, by car, or horseback to get a sense of the ecology of the area and what is contributing to the growth of the forests, and also to assess the forests for disturbance. Typically, several days are spent at each sampling area exploring the region and collecting samples. Cores are taken from trees using 5mm increment borers (Figure 2.6). At least two cores are taken from each tree from all mature trees (est. over 200 years). Ultimately, sample size at a site is determined by the number of mature trees without heartrot that yield good quality cores. An old rule of thumb is a target of 10-20 trees, but often the real limit of good trees within a site may be smaller. Heartrot is very prevalent in Siberian Larch trees in Mongolia and Siberia; sometimes over 50 percent of the trees will have rot. Where there is a single, strong, growth-limiting factor, reliable chronologies can be developed using five to seven trees (Schweingruber 1990).

All tree-ring sites are scoured for dead trees. Often in harsh climates, such as the upper treeline in Mongolia, trees die but do not rot. These ‘relict’ trees are extremely valuable because they have the potential to extend tree-ring based climate records back several 100 years past the age of living trees. These trees are sometimes cored with increment borers or sampled by taking a chainsaw section from them, or ‘cookie’. Once cored, samples are labeled by site and inserted into plastic “drinking” straws to protect them from breaking. Cookies are duck taped to protect them during transport. Further preparation and analysis of samples occur in the laboratory.

b. Laboratory methods:

The Conventional techniques of dendrochronology are employed in dating and chronology development (Fritts 1976, Holmes 1983, Cook and Kairiukstis 1990). In the laboratory samples are removed from straws, glued onto wooden mounts, air-dried, and sanded up to either 400 or 600 grit for optimal viewing. Cookies (cross-sections) are glued to boards and sanded similarly. Individual samples are examined under the microscope and marked with one pencil dot on decades, 2 pencil dots for 50 years, and 3 pencil dots for centuries (Fritts 1976). Unless dead trees were sampled, the last year of tree-growth is known, so it is possible to count backward from the year the sample was taken and mark the decades and centuries appropriately.

Dendrochronology requires great care and precision and afford higher temporal resolution and absolute dating accuracy than other proxy methods. In general, every year of an annual tree-ring is known and there are minimal mistakes in the final chronologies. Great strides are taken to ensure that each individual ring from every core of every tree is dated correctly. This includes, dating each ring by eye (as described above and below) and using quality control programs to statistically evaluate the series.

Individual series from each site are cross-dated (matching patterns of wide and narrow rings between trees) visually by comparing marker years to ensure that each tree ring was dated to the exact calendar year of growth. In drought years, it is possible that an annual ring will be locally absent in some trees, where an annual ring does not form uniformly around the bole of the tree and is "missing". Unique seasonal conditions can also cause what appears to be an extra ring. A tree may begin to go into dormancy in the fall and form a dark late wood band of cells, but if conditions become optimal for growing again (i.e. warm and wet) the tree will continue to put on new growth. The result is what looks like a double ring. Without careful cross-dating and experience in identifying both missing and extra rings, it is possible to introduce dating errors throughout the chronology. These types of mistakes are easily identifiable when checking the series with quality control programs (described below), and can be easily corrected.

Samples are then measured on a linear-encoding measurement stages (Velmex systems) and are measured to the nearest 0.001 mm. Once measured, dating of samples is checked for quality assurance using COFECHA software (Control de calidad de fechado y medicion), a publicly available quality control program (Holmes 1983). COFECHA tests to verify cross-dating by comparing segments within each series to a master series (the mean of all other series) and flagging problem areas. Dating problems and periods of low correlation are then identified and fixed when applicable.

Next, samples are detrended to correct for a biological age-trend (as described above). A curve is fit to each individual tree-ring series to model the biological growth trend. Conservative detrending methods (negative exponential or straight-line curve fits) are used to fit each series, and then the measured values are divided by the “growth” curve values to produce a detrended and standardized series. This method maximizes the amount of low-frequency information in the resulting chronologies (Cook 1985, Jacoby and D’Arrigo 1989, Fritts 1976). Ring-width chronologies are calculated using a mean-value function (combining the detrended tree-ring series), and the mean of each year is computed as a biweight robust estimate. These chronologies contain the common variations among the individual tree-core series and retain low through high frequency common variance, presumably in response to climate (Cook 1985). This method removes the growth trend, stabilizes the variance, and turns absolute ring width values to dimensionless indices with a common mean of 1.0 (Cook 2002).

The overall signal strength of all the trees used in a chronology are evaluated using the interseries correlation, mean sensitivity, Rbar and Expressed Population Signal (EPS) (Wigley et al. 1984) statistics. Average mean sensitivity is a measure of the relative change in ring-width from one year to the next in a given series, and is determined from COFECHA output. EPS is a measure of chronology reliability and evaluates the relationship between the sample size of a chronology and the common variance or "signal" within a chronology. A generally accepted cut-off level is 0.85. Rbar is the running mean correlation coefficient (25 year window) between all tree ring series used in a chronology.

If all of the statistics are strong, it can be assumed that the trees are all showing the same signal, and that there is a strong climate forcing, given that the sampling site was chosen carefully in order to minimize non-climatic factors. The climate signal in the trees can be verified by comparisons to local recorded meteorological data if the independent data is of high quality. Otherwise, globally gridded data, such as precipitation or drought indices can also be evaluated. The annual resolution of tree rings allows for calibration with recorded meteorological data and verification of tree-ring models to understand the strength of the climate/tree growth relationship. Once the relationship between instrumental data and tree-ring variation is defined, tree-rings can then be used to reconstruct and extend climate records (through linear regression, and rigorous calibration and verification) well beyond the period of instrumental observations (Cook and Kairiukstis 1990).

In the grand scheme of dendroclimatology, tree-ring models generally explain anywhere from 30-65% of the variance of the variable being reconstructed. In some cases, when the meteorological data is very poor or non-existent, it is not possible to create a climate model. This does not mean, however, that there is no climate information to be extracted from the trees. This was the case in the D'Arrigo et al. 2001 study, where high elevation trees in Mongolia were used to infer information about temperature for nearly two thousand years, but the meteorological data was too sparse to calibrate a model. It is worth noting, that many other proxy records (pollen, sediments, corals) typically do not have the annual resolution that tree-rings have (although there are exceptions) and cannot be calibrated to recorded data and thus the amount of variance explained by such proxies cannot be ascertained.

In this dissertation, the variance explained in the reconstructions ranges from 41% to 61%. Although 41% of the variance of a given variable might not seems to be enough to be of much value, one must consider that this region, far-western Mongolia, has extremely limited and incomplete meteorological records. The tree-ring reconstruction developed there adds significantly to our long-term understanding of climate and climate forcings.

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FIGURES

Figure 2.1. Khorgo Lava study site (used in Chapter 3 to reconstruct Selenge River streamflow) showing Siberian Larch trees growing on an old lava flow. This substrate does not hold water well and therefore leaves the trees extremely sensitive to variation in precipitation.

Figure 2.2. Zuun Mod study site (used in chapter 7) demonstrating a lower-elevation, open canopy Siberian Larch stand (photo credit: Brendan Buckley).

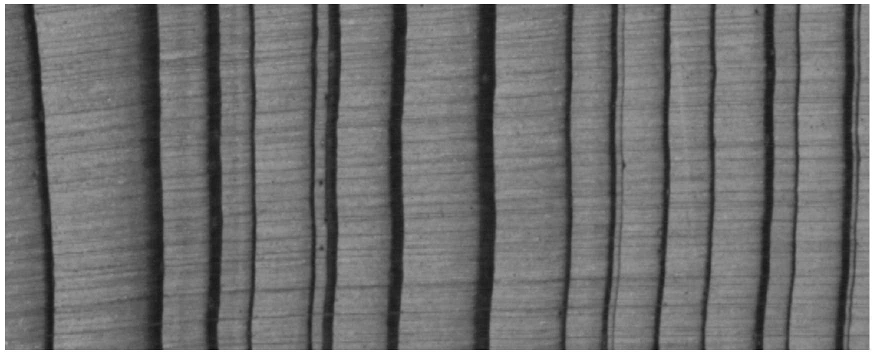

Figure 2.3. Variation in annual tree-ring width from a Siberian Larch tree. Narrow rings are associated with dry summer conditions and wide rings are associated with wet summers.

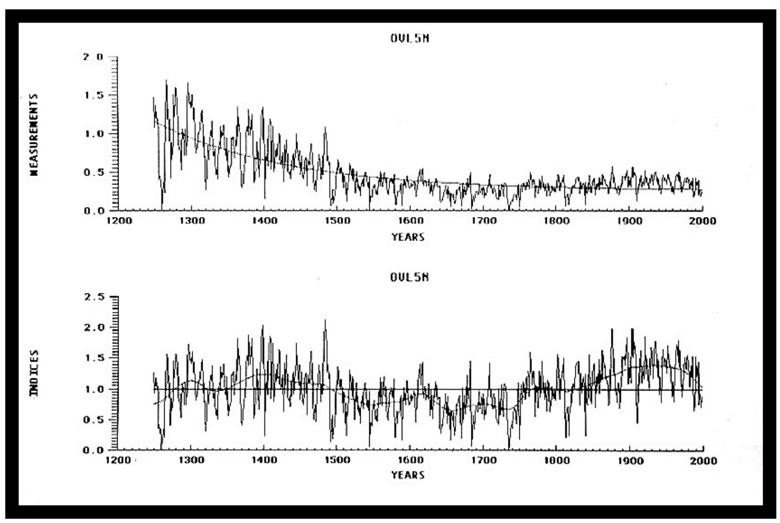

Figure 2.4. Raw measurements from a tree-ring core (top) that demonstrates age trends. At the beginning of the tree's life, at about 1250 to 1500 there is much more growth variation then following centuries. This trend is removed, as described in the text, and the resulting series is show (bottom)

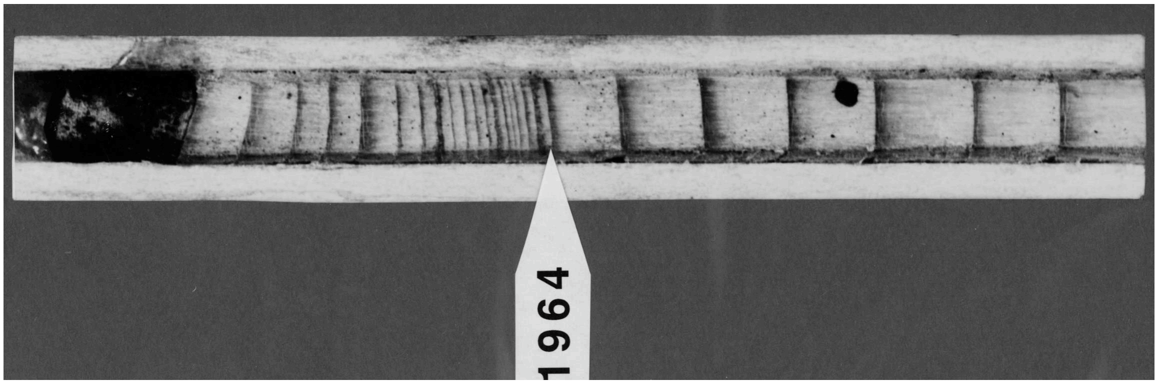

Figure 2.5. A Sitka spruce (Picea sitchensis) tree-core taken from about 240 km east of the epicenter of an earthquake in Alaska in the year 1964. This earthquake was one of the largest historical earthquake in America. The tree was shaken violently during the earthquake and caused damage to the root system. This resulted in stunted growth for a decade. The core is 5 mm in width.

Figure 2.6. An increment borer cores a nearly dead Siberian Larch tree at Khorgo Lava site (used in Chapter3), in Mongolia.

CHAPTER 3. EXTENSION OF DROUGHT RECORDS FOR CENTRAL ASIA USING TREE RINGS: WEST CENTRAL MONGOLIA[1]

[1] This chapter is based on the following publication- Davi NK, Jacoby GC, Curtis AE, Nachin B (2006) Extension of drought records for central Asia using tree rings: west central Mongolia. J. of Climate 19: 288-299. The original manuscript was drafted by N. Davi although co-authors improved the manuscript significantly with edits and suggestions or by other contributions such as fieldwork. All samples for this study were processed by N. Davi, with the exception of site Telmen Hövöö, which was processed by N. Pederson, a technician at that time.

3.1. Introduction

Drought across central Asia has devastated many regions over the last few years and many times in the past. Much of Mongolia was especially hard hit with 4 years of extensive drought between 1999-2002. The paucity of long-term records interferes with efforts to anticipate probable occurrence and extent of future droughts in central Asia and in particular Mongolia. Traditional knowledge and historical records provide partial estimation of drought recurrence (e.g., Mijiddorj and Namhay 1993) but better quantitative information is needed to define long-term drought variations in means, extremes, and trends; and to test for evidence of cyclical variations. Human observations leading to hypotheses of drought variations need to be supported by quantitative reconstructions and analyses of temporal and spatial patterns that may hopefully lead to understanding of probable future events.

Mongolia typifies the steppe terrain and semi-arid to arid continental climate that extends across much of central Asia (Zhang and Lin 1992). Mongolia also typifies large areas of Asia in another way, in that there are few long records of hydrometeorological data. Most records barely extend beyond 50 years. A previous study demonstrated that tree-ring analysis can be used to reconstruct precipitation and streamflow in eastern Mongolia (Pederson et al. 2001) and that there was evidence supporting quasi-solar and lunar-nodal variations in drought for that region. The streamflow of the Kherlen River and precipitation for part of the region were reconstructed back to 1651. Spectral analysis is a method for identifying periodicities within a time series and is often used to establish possible connections with forcing factors. Spectral analysis showed quasi-solar and lunar-nodal variability: and the extreme drought of 1999-2002 fit the long-term pattern caused by the combination of solar (22 & 11 yr.) and lunar-nodal (18.6 yr.) variations (Pederson et al. 2001). Testing of the spatial consistency of such patterns is needed to evaluate their importance.

The precipitation models and streamflow reconstruction presented here are based on annual ring-width variations of moisture-stressed, old-aged trees. Trees were sampled nondestructively at several lower-elevation sites where precipitation appears to be the major factor limiting to growth. Trees were also sampled at one slightly higher-elevation site where the highly-permeable rock substrate produces an edaphic desert. The tree-ring data were tested against individual precipitation stations and regional averages of precipitation for the central region of Mongolia (Figure 3.1). Significant correlations were found and models developed to estimate seasonal precipitation using the tree-ring data. An independent streamflow reconstruction was also developed for the Selenge River. The resulting reconstruction, based on five tree-ring chronologies, forms a 360-year (1638-1997) record for streamflow variations of the Selenge River. The Selenge river basin is a relatively densely populated area and is the major source of fresh water for Mongolia, as well as the major input to Lake Baikal (Ma et al. 2003).

3.2. Tree-Ring Data

a. Site Information

The Zuun Salaa Mod (ZSM) site (Figure 3.1, Table 3.1) was named for a “hundred-branched tree” of old-aged appearance just to the east of the site. It is greatly revered by people and draped with cloth and other items placed there for religious purposes. This tree was not sample nor any nearby trees. There is a major road about 100 meters to the east of the site but little evidence of other disturbance. ZSM is gently sloped (~5°) to the East and sparse grass grows between each tree. There was substantial heartrot in some of these trees, which frequently occurs in larch trees throughout Asia, even in dry sites.

Telmen Hövöö (TH) (Telmen Beach) (Figure 3.1, Table 3.1) was the only stand of trees for several tens of kilometers in this area. This small forest grows on part of a sand dune complex located next to Telmen Lake. Local residents indicated that there had been some logging (very few stumps seen), no fires, and no dramatic change in lake levels over the past 60 years.

The Khorgo Lava (KL) site (Figure 3.1, Table 3.1), located in the Khorgo-Terkhiin Tsagaan Nuur National Park, is on a geologically young basaltic lava flow with very little soil development. There has been previous success in reconstructing drought using trees from such sites (Grissino-Meyer 1997). The extreme dryness of the site likely reduces the prevalence of heartrot in these trees, resulting in great longevity (1340-2002). Although near a small town, the rugged and rocky terrain appeared to reduce the cutting and disturbance of the site.

Undur Ulaan (UU) (Red Hill) (Figure 3.1, Table 3.1) is on a steep hill, about 200 meters north of a main road. Hillside grazing was the only evidence of disturbance. Trees had substantial heartrot.

Suulchyin Medee (SM) (Last Statement) (Figure 3.1, Table 3.1) is on the north and west facing slopes of a dry ridge with very sparse vegetation. A lot of dieback, attributed to insect infestation, was seen in the canopy, however, there was no evidence of decrease growth due to infestation in the growth rings. This indicates that the severe infestation is very recent. Presently, insect infestations are very common in Mongolian forests and the stand of trees may not survive many more years. We tried to sample healthy trees to exclude effects of recent insect infestation.

b. Methods

Standard tree-ring methods were used for chronology development and climate analysis (Fritts 1976, Cook and Kairiukstis 1990). Ring-widths were measured to the nearest 0.001 mm using a Velmex system. Individual series measurements and dating were checked using COFECHA software (Holmes 1983) and standardized using ARSTAN software (Cook 1985). Conservative detrending methods (negative exponential and straight line curve fits) were used to generate the ring-width index chronologies. The purpose of standardization is to reduce the effects of age and other non-climatic factors on the resulting series. The standard chronologies were used in order to preserve low frequency variations that would be removed by prewhitening. All the stands were open canopy and the standard chronology is more appropriate than the arstan chronology for such sites (Cook 1985).

Autoregressive properties of the tree-ring and meteorological data were tested for the common period (1945-1998). The meteorological data are autoregressive order one based on the Aikaike criteria and three of the five chronologies are order one. The other two are order zero. Thus the data are compatible. The model is not prewhitened in order to preserve low-frequency variation in the reconstruction.

Individual chronology information and statistics are shown in Table 3.1. The Expressed Population Signal (EPS) statistic, a measure of chronology reliability (Wigley et al. 1984), is greater than 0.89 over the entire length of each chronology, with the exception of the early portion of KL (Table 3.1). A level of 0.85 is considered indication of satisfactory quality for a chronology. The R_{BAR} statistics, the mean correlation coefficient for all tree-ring series in each individual chronology, are shown in Table 3.1. Average series intercorrelation between the 5 chronologies is 0.51 over the 1638-1990 common period. Correlations for each individual chronology pair are shown in Table 3.2.

The five tree-ring chronologies loaded similarly in a principal component analysis (PCA) (Table 3.3). The chronologies were combined using PCA to reduce the number of predictors and create one series representing common regional variations. PCA was calculated using a correlation matrix because the data are standardized. The first eigenvector (EV1) contains 55% of the total variance.

3.3. Hydrometeorological Data

a. Precipitation

Monthly instrumental precipitation and temperature records from Mörön (1941-2003), Uliastai (1937-2003), and Khujirt (1943-1996) (MUK) were obtained from the Global Historic Climate Network (www.ncdc.noaa.gov/oa/climate/research/ghcn/ghcngrid.html) (Table 3.4). These stations are the closest to the tree-ring sites with continuous records. There are other stations in the region but they either have much shorter records or have many missing values. There is also a precipitation station near the Khorgo Lava site with a short (1971-1983) record called Mongolian Station, N. Han. (Station ID 2184423701). Although there are only 13 years of record, it is uncommon to find a meteorological station adjacent to a sampling site (See Tables 3.1 & 3.5). This record is too short to include in the regional precipitation series but is useful to further test the precipitation signal in the long Khorgo Lava chronology. Average mean monthly precipitations for the three stations (Mörön, Uliastai, and Khujirt,) shows that most (72%) of annual precipitation falls during June, July, and August (Figure 3.2). The sum of annual precipitation averaged for the three stations is 252.3 mm. The growing season in Mongolia, at our lower elevation sites, is roughly June to Late August. Average monthly temperatures from Mörön, Uliastai, and Khujirt are above freezing starting in May and drop below freezing starting in October. Average annual temperature for West central Mongolia based on the three stations is –1.9° C over the 1943-1996 common period.

b. Hydrological Data

Streamflow data for the Selenge River at the Hutag streamflow measuring station (1945-2002) was obtained from the Hydrometeorological Institute of Mongolia, and was updated by B. Nachin (personal communication). Most of the runoff comes from precipitation in the mountains surrounding Lake Hövsgöl and the mountains to the northwest. Most streamflow discharge occurs over a longer season (April through October) than precipitation, with the highest discharge in July and August (Figure 3.2). Spring streamflow comes from melting winter snowpack and much of the late season streamflow comes from infiltration and bank storage after the direct precipitation runoff decreases. The June-August precipitation averaged over the three stations used for modeling (Mörön, Uliastai, and Khujirt) correlates with April-October streamflow ($r=0.68$, $p= 0.01$) data over the common period 1945-1996.

3.4. Analysis and Results

a. Precipitation

The five individual tree-ring chronologies were tested with three local meteorological stations; Mörön, Uliastai, and Khujirt (MUK). We tried to include more stations but using records with many missing values estimated or shorter records detracted from the results. Correlations with monthly precipitation for individual MUK stations varied from site to site. The most consistent positive correlations were with current season June. Correlations improved when using the EV1 from the five chronologies with average monthly precipitation from MUK. The EV1 shows positive significant correlation with prior September, current season February-March and June-July (Figure 3.3). February-March correlations do not have any ready explanations. Liang et al. (2001) also found significant correlation between Meyer spruce growth and February precipitation in Inner Mongolia. We found that there are no significant intercorrelations of precipitation with temperature for these months. The ring-width EV1 correlates highest with an average of

June, July and August precipitation from MUK (r=0.52) (p=0.01) over the 1943-1995 common period (Figure 3.4).

Regression between the Khorgo Lava trees and the local precipitation record (1971-1983) at Mongolian Station N. Han showed strong significant correlations between the tree-ring indices and April and July precipitation, 0.57 (p= 0.05) and 0.80 (p=0.01), respectively. The ring-width indices from the standard chronology and the April-July total precipitation have a simple r of 0.69 (p=0.01) and the r-squared, adjusted for degrees of freedom lost due to the regression, is 0.43. Although the N (13) of the recorded precipitation data is low, the correlations are significant and confirm the precipitation signal in the Khorgo Lava chronology shown in Figure 3.5.

Temperature station data were also tested using the same three local meteorological stations (Muren, Uliastai and Khujirt). These temperature data show a consistent negative relationship with the 5 chronologies for previous July and current season April and June. This relationship strengthened when data from the three temperature stations were averaged and then correlated with ring-width EV1. The consistent negative correlation for the current warm season months ranged from April (r=-0.471) to July (r=-0.239). April is a month of low precipitation and warm springs may increase an already high rate of evapotranspiration (Ma et al. 2003). This may further lessen water availability for the growing season and explain the high negative correlation for April.

b. Streamflow

Each individual chronology was tested with Selenge streamflow data for the current year (T) and prior year (T-1) (Table 3.3). Three of the five chronologies show significant correlations with prior year streamflow. Site UU (Table 3.1) shows a positive, but not significant, correlation with prior year streamflow (Table 3.3). This may reflect the downstream distance from the Selenge streamflow gauge to the UU site (Figure 3.1). Khorgo Lava is a precipitation-sensitive site that has a high degree of agreement between trees, but does not have a prior year signal. The main differences between the Khorgo Lava site, and the others, is the low moisture retention of the lava substrate and the site elevation. It is the highest elevation of the five sampling sites (Table 3.1).

The regionalized EV1 based on 5 chronologies shows positive significant correlations with current season April through October and prior year September and October (Figure 3.6). Based on these correlations, principal component regression (which recreates EV1) is used to develop an April-October tree-ring based model (using EV1 for year T and year T+1 to predict streamflow for year T) for Selenge streamflow over the 1638–1997 time period (Figure 3.7). The climate/tree-growth reconstruction (Figure 3.8 a & b) accounts for 49.3% of the streamflow variance (variance explained from tree-ring models typically range from roughly 30%, the lower side, to 60% or more, which would be considered quite high) and demonstrates valid calibration and verification statistics (Table 3.5). Additional eigenvectors were tested, but they did not improve the model.

Most streamflow models using tree-ring data are linear. However in some circumstances the relationships can be nonlinear (e.g., Fritts 1976). With increasing amounts of precipitation (and resulting streamflow), levels are reached that do not cause ring widths to increase at the same rate that they do for the increases at lower levels because the trees experience other growth restraints such as nutrient supply or internal biochemical limitations. Plotting the estimated and recorded values can reveal whether "..a curvilinear model is more appropriate." (Fritts 1976). Previously a log-model improved results in a reconstruction of the Virgin River in Utah, USA (Hereford et al. 1995). Nonlinear models were tested in Pederson et al. (2000) but showed no improvement (This negative result was not included in that publication). In this Selenge model the plots suggested a nonlinear relationship between the tree-ring data and streamflow (Figure 3.8a). The nonlinear model improved the explained variance from 42.1% to 49.3%, therefore the nonlinear model is used (Figure 3.8 a & b).

Selenge streamflow variability was evaluated using the top-ten wet and dry five-year intervals (Table 3.6). The wettest 5-year period was 1764-1768 and the driest period was 1854-1858. The 1800s show reduced variability in general with two periods of extended low flow. Streamflow was low from roughly 1854 to 1867 (14 years) and again from 1809 to 1830 (22 years). The most extended wet period is 1794-1802 and an extended dry period is 1778-1783. From the beginning of the reconstruction through the mid-1800s the reconstruction shows a high degree of variability in streamflow. This trend is also seen in the Kherlen River reconstruction but ends around 1850 (Pederson et al. 2001). The severe extended droughts during the 1800s (Figure 3.7) are more extreme than those found in Pederson et al. (2001). The 20th century looks wetter than prior centuries but is within the range of long-term variability (also seen in Pederson et al. 2001). The strongest regional difference is in the very late 1700s. The eastern region was dry while this central region was very wet.

c. Spectral Analysis

The streamflow reconstruction, the five chronology EV1, and the chronology from Khorgo Lava site were processed through multitaper method (MTM) spectral analysis (Mann and Lees, 1996) and cross-spectral analyses with climatic series; specifically the Southern Oscillation Index (SOI) and Pacific Decadal Oscillation (PDO) for the season having the strongest climatic signal. We describe the EV1 and Khorgo Lava results (EV1 and the streamflow reconstruction have the same spectral characteristics). Spectral analysis is a method for identifying periodicities within a time series. The MTM plots (Figures 3.9 a & b) show that both the series have spectral power in an ENSO range of about 4 years (99% significance) and 5-6 years (90% significance). There is also spectral power in a quasi-solar range of about 22-24 years (95%) and for Khorgo Lava there is some power in the lunar-nodal range of about 16-19 years (90-95%). Evidence of power in the range of PDO variation 35-50 years is also present (99%). Differences between the EV1 and Khorgo Lava results are not unexpected because the latter had no lag effect of prior year's precipitation and it is a substantially longer series by 238 years.

The amount of variance explained by the quasi-solar and lunar-nodal frequencies is estimated by using single spectrum analysis (SSA) (Vautard and Ghil 1989). The frequencies included are 22 and 11 year (solar) and 18.6 (lunar nodal). Summing the variance explained by these frequencies gives an estimate of about 27%. One must regard this estimate with caution as the SSA is very sensitive to changes in input parameters.

Spectral coherency between the tree-ring series and SOI and PDO are also checked. The SOI results show coherency in the 3-4 and 6-8 year ranges between SOI and both EV1 and Khorgo Lava. There is spectral coherency between PDO and both series in the 32-year range and 3.8-3.9 year range (Figure 3.10 a & b). Between 4 years and 21 years there are differences between the coherencies of the PDO with the two tree-ring based series.

3.5. Discussion

Streamflow can be a better indicator of regional water resources than individual station precipitation records. Streamflow integrates the areal effects of precipitation input and evapo-transpiration losses. This system of moisture balance is more similar to the hydrologic environment of trees than precipitation alone. Hence a closer relationship between ring-width data and streamflow is not surprising. A precipitation reconstruction with the EV1 was not made because the variance explained was only about 25% whereas with the streamflow it was almost 50%. The reconstruction extends beyond the season of cambial (ring) growth to better represent the longer season of streamflow, and the longer season of cambial activity, April through October. The correlations between the EV1 and September and October streamflow, after the end of the season for cambial growth, are caused by streamflow for these months reflecting the precipitation input of the prior months and river basin storage components (e.g. bank storage and subsurface infiltration). The earlier precipitation directly benefits the tree growth. The precipitation results confirm the primary influence on the tree's growth. In addition the results for Khorgo Lava site alone support the value of this series for analyses of longer-term spectral properties. The large difference between the eastern (Pederson et. al. (2001)) and the west-central (herein) reconstructions in the late 1700s is an example of the high spatial variability that can occur in Mongolia. This type of regional difference was also found by Yagatai and Yasunari (1995).

Spectral periodicities found in Pederson et al. (2001) are similar to some of the properties found in the west central Selenge River reconstruction. Differences may be due to the more mountainous topography of the West as well as regional differences due to circulation shifts. The spectral properties similar to Pacific Ocean spectra suggest teleconnections in agreement with previous findings. Evidence for these types of oceanic teleconnections have also been presented by Kripalani and Kulkarni (1999) and Morinaga et al. (2003), although they focused on winter conditions. Possible mechanisms for summer precipitation variations are described in Yagatai and Yasunari (1995) based on analysis of recorded precipitation from 1951-1990.

3.6. Conclusions

This Selenge River streamflow model in west-central Mongolia increases the knowledge of drought and wet periods. The spectral properties (in agreement with Peterson et al. (2001)) are strong enough to infer some significant predictability and also suggest teleconnections with Pacific Ocean variations.

Figure 3.7 shows that there is decadal scale variability, much more decadal information than the limited record of measured precipitation and streamflow. It also shows that there were extended periods of very low streamflow. The 1800s in general showed reduced flow and the period from 1854 to 1867 (14 years) and again from 1809 to 1830 (22 years) were extended low flow intervals. This new reconstruction provides an important extension of the input flow to Lake Baikal, by more than 300 years. Thereby providing information about past, and the range of possibilities for future, variations in water availability in central Mongolia.

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TABLES

Table 3.1. Tree-ring site information table.

TREE-RING SITES	Lat. (N)	Lon. (E)	Alt. (m)	No. trees	Years	species	EPS[1]	RBAR[2]
Undur Ulaan (UU)	48°59'	103°14'	1400	15	1473-2002	*Larix sibirica*	>0.96	0.50-0.77
Suulchyin Medee (SM)	49°29'	100° 50'	1800**	15	1573-2002	*Larix sibirica*	>0.97	0.68-0.84
Khorgo Lava (KL)	48°10'	99°52'	2060	39	1340-2000	*Larix sibirica*	>0.92*	0.54-0.78
Telmen Hövöö (TH)	48°46'	97°07'	1841	16	1638-1998	*Larix sibirica*	>0.93	0.41-0.69
Zuun Salaa Mod (ZSM)	48°09'	100°17'	1900	20	1513-2001	*Larix sibirica*	>0.89	0.45-0.85

*KL Rbar is >0.92 except for pre-1400s where EPS is 0.81.

** Estimated from map.

[1] Expressed Population Signal statistic.

[2] Rbar = the mean correlation coefficient between all tree ring series used in a chronology.

Table 3.2. Five-chronology correlation matrix over common period 1638-1990.

	UU	SM	KL	TH	ZSM
UU	1	0.56*	0.27*	0.31*	0.37*
SM		1	0.42*	0.43*	0.50*
KL			1	0.45*	0.62*
TH				1	0.46*
ZSM					1

*Significance level (0.05)

Table 3.3. Ring width loadings on the first eigenvector from principal component analysis for the five chronologies. Current year (T) and current year with prior year (T-1) correlations with recorded Selenge streamflow data.

Site	Eigenloading	T	T-1
UU	0.394	0.435*	0.124
SM	0.473	0.358*	0.264*
KL	0.452	0.501*	-0.011
TH	0.425	0.578*	0.359*
ZSM	0.485	0.539*	0.300*

*Significance level (0.05)

Table 3.4. Hydrometeorological data.

Precipitation Station	Lat. (N)	Lon. (E)	Alt. (m)	Years
Uliastai	47° 45’	96° 51’	1751	1937-2003
Khujirt	46° 54’	102° 46’	1650	1943-1996
Mörön	49° 38’	100° 10’	1283	1941-2003
Mongolian Station N. Han	48° 12'	99° 54'	2010*	1971-1983
Hydrological Station	**Lat. (N)**	**Lon. (E)**	**Alt. (m)**	**Years**
Selenge	49° 14’	101° 21’		1945-2002

*estimated

Table 3.5. Calibration and verification statistics for Selenge River streamflow reconstruction.

	1945-1970 Calibration	**1971-1997 Verification**	**1971-1997 Calibration**	**1945-1970 Verification**
Adjusted r^2	0.356	----	0.543	-----
RE	0.382	0.411	0.561	0.282
Sign test	$20^+/6^-$ (0.005)	$22^+/5^-$ (0.001)	$22^+/5^-$ (0.001)	$19^+/7^-$ (0.01)
P	0.618 (0.001)	0.685 (0.001)	0.749 (0.001)	0.536 (0.002)

Adjusted r^2 is the variance accounted for by the calibration model, adjusted for degrees of freedom; RE is the reduction of error statistic, P is the Pearson correlation coefficient. Levels of significance are indicated in parentheses.

Table 3.6. Wettest and driest five-year periods for Selenge streamflow reconstruction.

RANK	DRY	WET
1	1854-1858	1764-1768
2	1779-1783	1990-1994
3	1736-1740	1797-1801
4	1737-1741	1763-1767
5	1863-1867	1796-1800
6	1901-1905	1798-1802
7	1641-1645	1765-1769
8	1696-1700	1917-1921
9	1855-1859	1794-1798
10	1778-1782	1795-1799

FIGURES

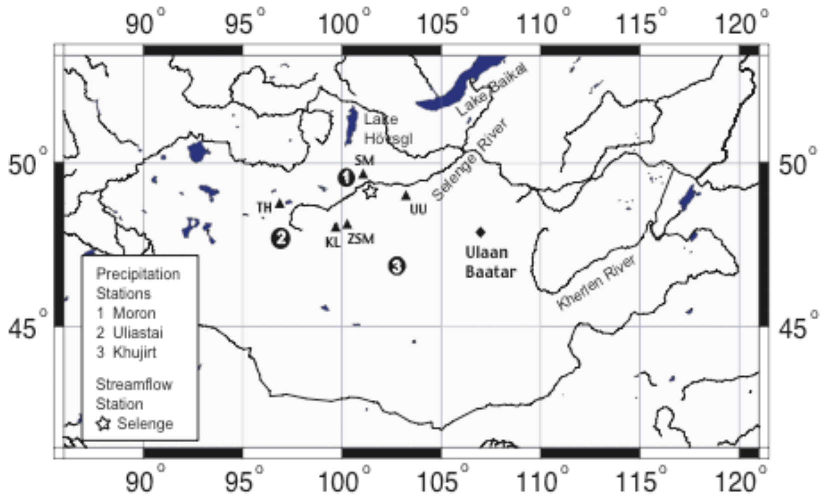

Figure 3.1. Map of Mongolia showing tree-ring sampling sites (triangles), precipitation stations (numbered), and streamflow gauge station (star).

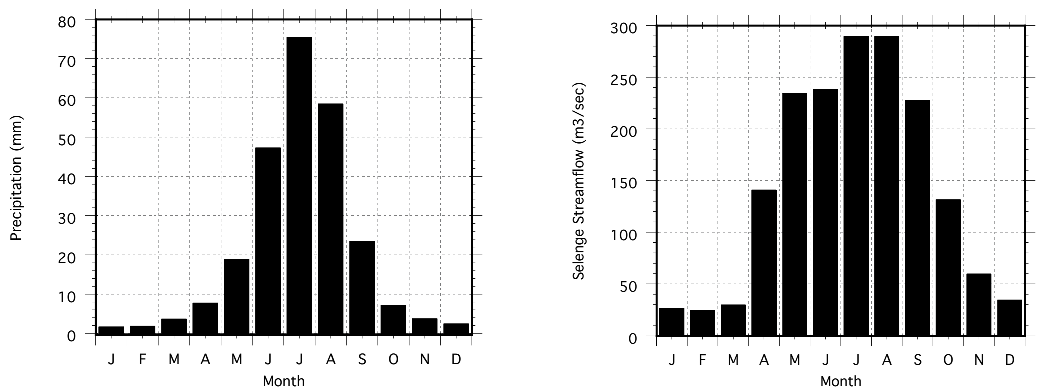

Figure 3.2. Average monthly precipitation (mm) for Mörön, Uliastai, and Khujirt EV1 (left) over the 1943-1996 time interval and average monthly streamflow (m^3/sec) for Selenge-Hutag (right) over the 1945- 2002 time interval.

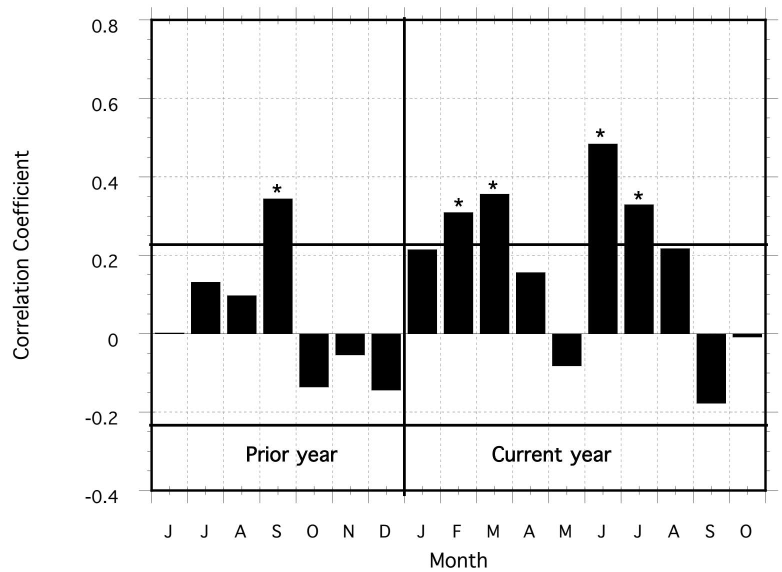

Figure 3.3. Correlation plot comparing average monthly precipitation from Mörön, Uliastai and Khujirt with the first principal component of the five ring-width chronologies over the 1943-1995 common period. Horizontal lines indicate 95% significance level.

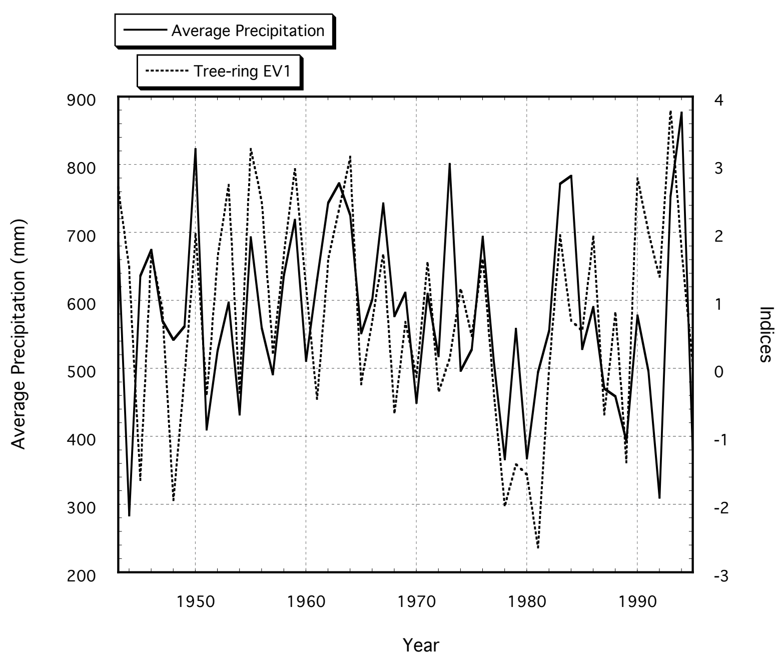

Figure 3.4. Average June-August precipitation from Mörön, Uliastai and Khujirt with the first eigenvector (EV1) from PCA based on the five ring-width chronologies over the 1943-1995 common period.

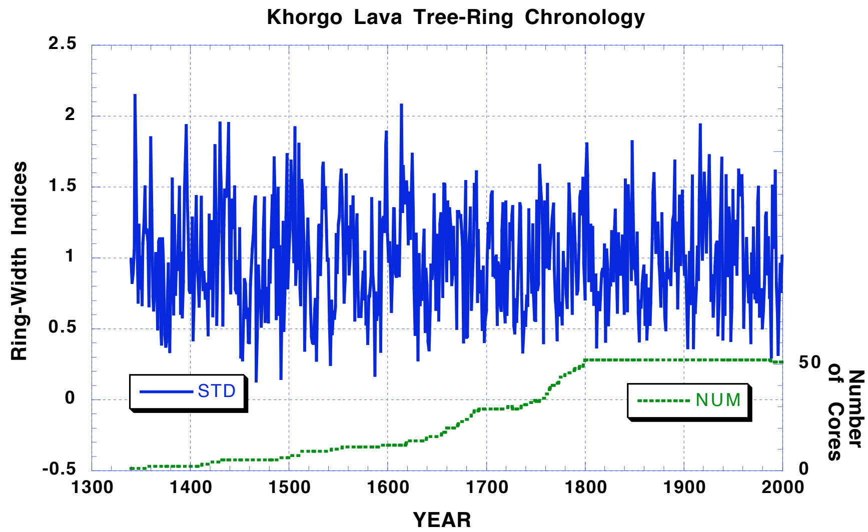

Figure 3.5. Khorgo Lava (1340-2000) Standard chronology of ring-width indices and sample size. Correlations with meteorological data show that this chronology is sensitive to moisture variation, however a precipitation reconstruction is not created due to the short length of the meteorological data closest to the station (as described in the text).

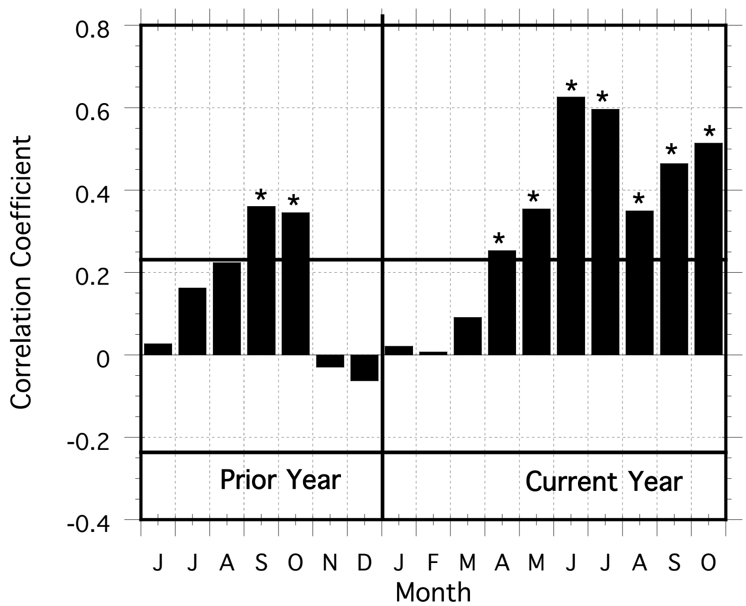

Figure 3.6. Monthly correlation coefficients for Selenge at Hutag streamflow station with 5-chronology EV1 over the 1945-1997 common interval. Horizontal bars indicate 95% significance level.

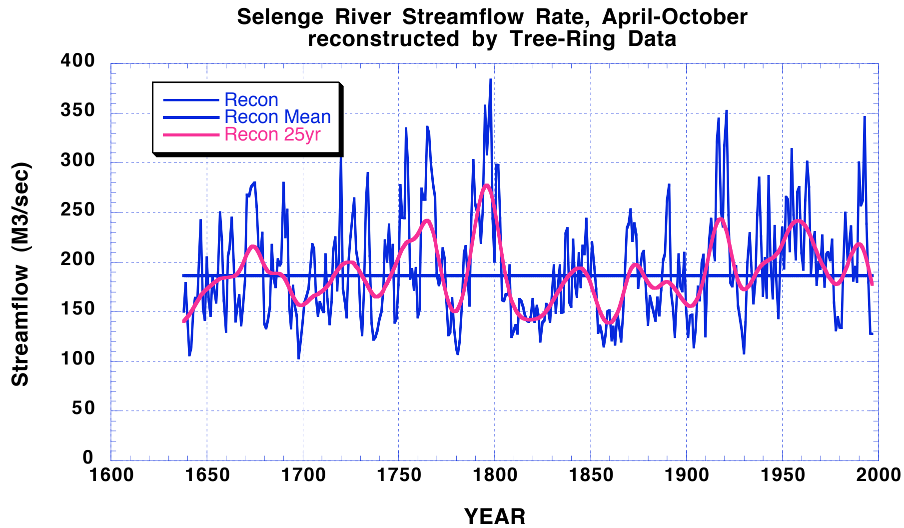

Figure 3.7. Tree-Ring based reconstruction of Selenge River streamflow. The fine line is the average streamflow rate for the months April through October, 1637-1997. The thicker line is a 25-year moving average.

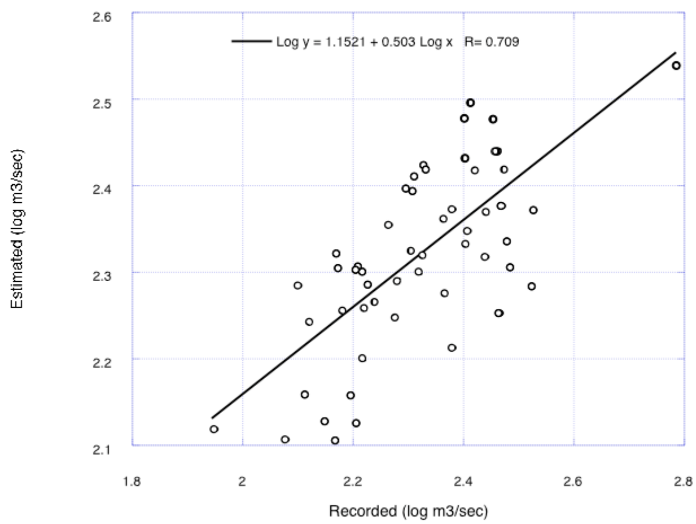

Figure 3.8a. Scatterplot of reconstruction model results using the log of streamflow.

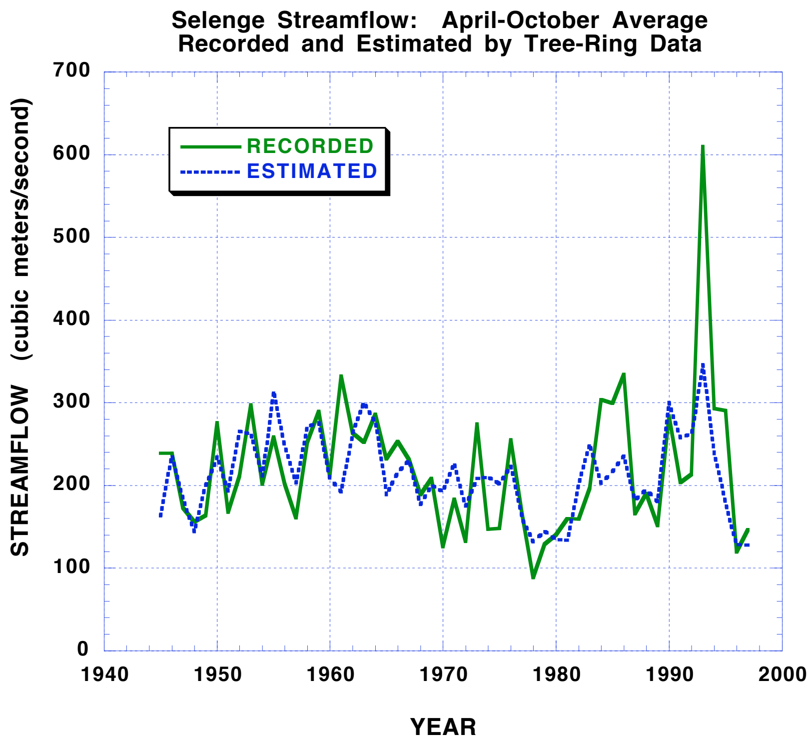

Figure 3.8b. Estimated and recorded Selenge River streamflow rate converted back to cubic meters per second. Note that even with a log model the tree-ring data still underestimate the extreme flow of 1993.

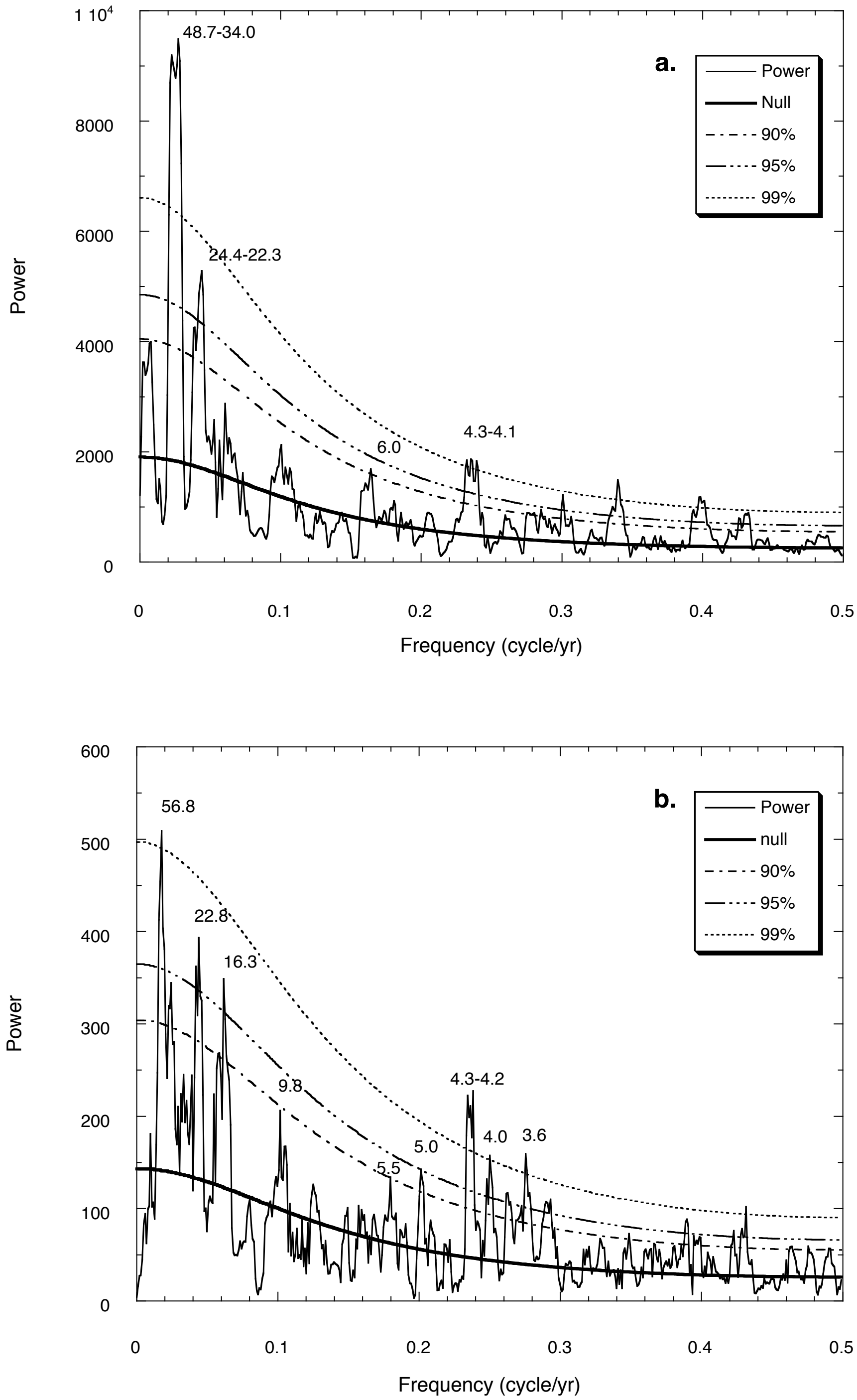

Figure 3.9. Multitaper Method (MTM) spectral frequencies of (a.) the five chronology EV1 (1638-1997), and (b.) Khorgo Lava site (1400-2000).

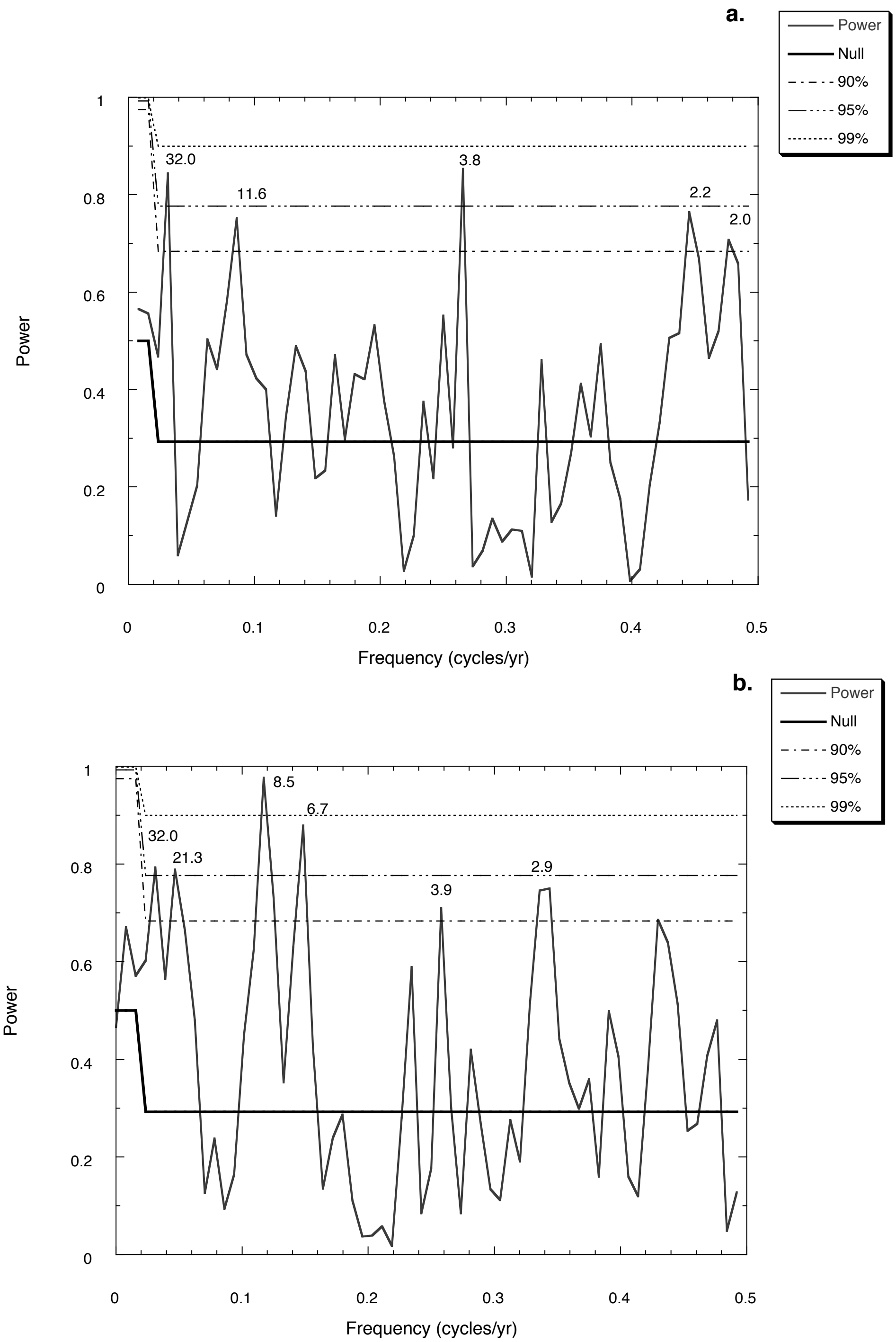

Figure 3.10. Cross-spectral analysis of (a.) the five chronology EV1 with PDO, and (b.) Khorgo Lava site and PDO, over the 1900-1997 common period.

CHAPTER 4. A TREE-RING BASED DROUGHT INDEX RECONSTRUCTION FOR FAR-WESTERN MONGOLIA: 1565-2004[2]

[2] This chapter is based on - Davi N, Jacoby G, D'Arrigo R, Baatarbileg N, Li J, Curtis A (2009) A Tree-Ring Based Drought Index Reconstruction for Far Western Mongolia: 1565-2004. Int. J. of Climatology 29 (3), 1508-1514. The original manuscript was drafted by N. Davi, although co-authors improved the manuscript significantly with edits and suggestions or other contributions such as fieldwork. Tree-ring samples were processed either by N. Davi or by A. Curtis, a laboratory technician at that time.

4.1 Introduction

Climate and climate change is very relevant to society in Mongolia. Changes in climate patterns such as prolonged drought can translate into degradation of pastureland and loss of livestock and have serious economic effects. These effects could threaten the pastoral and nomadic lifestyle of much of the population of Mongolia. With the intensity of recent droughts over parts of Mongolia during 1999-2000 and 2000-2001 (Helminen 2002), and the uncertainty of future moisture variability in the context of rapidly increasing temperatures; long-term, high-resolution proxy reconstructions are critically important for understanding how the climate varies on decadal to centennial scales. This understanding is important for evaluating the spatial and temporal variability of moisture patterns in Mongolia, and other remote regions of central Asia and the globe.

Much of what is known about climate patterns in Mongolia is based on very limited instrumental station records, often only beginning in the 1940s or later, with many missing values. Western Mongolia is a particularly data sparse region. It is not uncommon for whole decades of information to be absent. At Ulgii (1959-2005) (Figure 4.1) the closest station to our study, average temperatures are 15.5 °C in the summer (June-Aug.) and –15.3 °C in the winter (Dec-Feb). Average annual precipitation is 93.4 mm, the majority falling in June, July and August. The instrumental record shows that Mongolia is undergoing significant climatic change, with temperatures rapidly increasing (Yatagai & Yasunari, 1994, Batima et al. 2005, Endo et al. 2006), particularly in the high mountain regions, such as the Altai in western Mongolia (Batima et al. 2005).

Spatial patterns of precipitation can be complicated because they vary regionally due to variations in elevation, topography and storm tracks, which can lead to great differences in precipitation, even in neighboring areas. Dai et al. (2004) use the principal component of the first empirical orthogonal function (EOF) of the global Palmer Drought Severity Index (PDSI), to suggest a drying pattern over the majority of Mongolia. Batima et al. (2005) evaluate sixty individual stations (1940-2001) and find that there are different regional precipitation patterns. Annual precipitation has been decreasing in central Mongolia and increasing in eastern and western Mongolia. The majority of these decreases occur in winter and spring (when other studies show increasing temperatures), while summer and autumn remain unchanged. However none of these changes are statistically significant (Batima 2005).

Temperatures are predicted to continue to warm throughout Asia and Mongolia through this century (Batima et al. 2006, Sato & Kimura 2006, Christensen et al. (IPCC) 2007). The rate of the increase depends upon which emission scenario is followed (Christensen et al. (IPCC) 2007). Precipitation is predicted to increase throughout Mongolia as a consequence of a general intensification of the global hydrological cycle (Christensen et al. (IPCC) 2007), however, JJA, the time when there is the most precipitation in Mongolia, shows the largest variability and uncertainty (Batima et al. 2006, Christensen et al. (IPCC) 2007). A dynamical downscaled model (using a regional climate model) of Mongolia shows that precipitation will be lower during the June-August, particularly where the sources of major rivers are located in central Mongolia (Sato & Kimura 2006).

Tree-ring reconstructions of hydrological variations have supplemented and extended the limited meteorological records in eastern (1651-1995) (Pederson et al. 2001), and central (1637-1997) (Davi et al. 2006) Mongolia and Inner Mongolia, China (1627-2001) (Liu et al. 2007). Here, tree rings are used to reconstruct and extend the record for a grid point ((2.5°x2.5°, at 48.75N and 88.75W) of the Palmer Drought Severity Index (PDSI), based on the Dai et al. (2004) global data set, for western Mongolia where very little work has been done.

PDSI is a standardized estimate of meteorological drought, derived from both recorded precipitation and surface-air temperature (Palmer 1965, Dai et al. 2004). PDSI ranges from approximately +10 (wet) to –10 (dry), where > +3 is considered very wet and < -3 is considered very dry. PDSI can also be a good indicator of streamflow and warm-season soil moisture content (up to 1 meter depth). In western Mongolia the correlation coefficient for monthly anomalies of observed soil moisture content with PDSI is 0.50 (5% level) (Dai et al. 2004). There has been much success using tree rings to reconstruct PDSI in North America (Cook et al. 1999; Fye et al. 2003), China (Li et al. 2006, Li et al. 2007, Fan et al. 2008), and Southeast Asia (D'Arrigo et al. 2006a, Sano et al 2008).

The present reconstruction more fully represents the range of natural and anthropogenic variations and puts recent climate change into a long-term context. It also supplements the sparse instrumental records of precipitation and drought of far-western Mongolia. An integrative approach is used by relating this reconstruction to other proxy records from adjacent areas and lake-level data from Khar-Us Nuur. It is also evaluated for long-term climate trends, extremes and possible forcings.

4.2 Data and Methods:

a. Tree-ring Data

Tree cores were collected from three relatively lower-elevation sites (Figure 4.1, Table 4.1). At these sites, open-canopy trees with sparse vegetation between each tree, an indicator of drought stress, grow on thin, rocky soil. Siberian larch (*Larix sibirica*) are the dominant trees and were the only species sampled. Two cores are typically sampled from each tree using non-destructive, 5.1 mm diameter increment borers. Standard tree-ring methods were used for chronology development (Fritts 1976, Cook and Kairiukstis 1990). Cores were visually cross-dated and measured to the nearest 0.001 mm. Individual series measurements and dating were checked using COFECHA software (Holmes 1983). Series with gaps (due to ring damage or rot) were connected with flags indicating the gaps and thus the standardization process treated them as a single series. After standardization of the series, the indices of the gap portion was deleted from the series of indices to avoid introducing any non-authentic data. Series less than 200 years in length were deleted to retain longer average segment length (Cook et al. 1995). These methods were employed in order to optimize the preservation of low-frequency variations in the final chronologies. The remaining series were standardized and developed into chronologies using ARSTAN software (Cook 1985 and Cook, personal communication 2006). Conservative detrending methods (negative exponential and straight-line curve fits) were used to generate the ring-width chronologies. The Standard version (Cook 1985) of all chronologies was used.

The three chronologies are summarized in Table 4.1. Ankhny Khoton (AK) spans 1469-2004 and consists of 38 samples from 18 trees, with an average high-frequency series intercorrelation of 0.63 and average mean sensitivity of 0.27. The Expressed Population Signal statistic (EPS) (Wigley et al. 1984), a measure of chronology reliability, is above 0.85, a generally accepted level, over the common period used for modeling (1565-2004), and drops to 0.78 prior to 1500 when there are fewer samples. Khoton Nuur (KN) spans 1215 to 2004, and consists of 34 cores from 18 trees, with a series intercorrelation of 0.68 and average mean sensitivity of 0.26. EPS is above 0.85, begining at 1500 when the sample depth increases, but falls to 0.76 prior to 1500. Khovd Gol (KG) spans 1565-2004, and consists of 21 cores from 11 trees with a series intercorrelation of 0.65 and average mean sensitivity of 0.29. EPS is above 0.89 over the length of the series. The three chronologies are similar and correlate well with one another at 0.67 or higher over their common periods (1565-2004).

b. Hydrometeorological data

Monthly 2.5°x2.5° PDSI grid-cell data were obtained from the Dai-Trenberth-Qian Global Land Data Server (Dai et al. 2004). The data have been processed through program DiaTrendPDSI.exe V3, in order to clean up outliers and discontinuities (E. Cook, personal communication 2008). The PDSI grid point centered nearest to the sites was used: 48.75N 88.75W (Figure 4.1), although other points were tested. At this location the PDSI data extends from 1936-2003. Monthly station data for rainfall and temperature used to compute the Dai et al. (2004) PDSI originates from historical data.

Ulgii (1959-2005, 1751m) is the closest station to the three tree-ring sites and the PDSI grid point (Figure 4.1). From the Ulgii record, sixty-three monthly values are missing, mostly after 1986. Khovd (1937-2006, 1406m), the next closest station, is missing data for 1984-1991, with many missing values after 1993. Mongolia Station A at Ulaangom (1943-1990, 934m) is more complete, but ends in 1990. Due to the considerable missing values in station data used to create the PDSI, the PDSI record was truncated to the better-replicated period from 1948-1983. The tree-ring series were tested with average monthly precipitation and temperature data from nearby station data.

The reconstruction was compared to lake-level data from Khar-Us Nuur (48.23N, 92.21E) (R. Mijiddorj, personal communication 2006, and G. Davaa, Institute of Meteorology and Hydrology), (Figure 4.1) and a tree-ring based PDSI reconstruction from northwest China (Li et al. 2006).

4.3 Analysis and Results

a. Meteorological Data

In the analyses with average monthly precipitation and temperature data there was correlation with the EV1 of the three chronologies and prior year precipitation; prior-year August (R=0.311, 99% significance level) and Sept (0.327, 99%) at Khovd (1959-1990), and prior-year May (0.225, 95%) and June (0.294, 99%) at Ulgii (1959-1990). The relationship between the tree-ring chronologies and climate data was much improved using PDSI data. PDSI incorporates temperature and precipitation into the index and may better represent the limiting factors of tree growth in this particular region.

b. PDSI model

A principal components analysis (PCA) (Cook and Kairiukstis 1990) was performed on the three tree-ring chronologies for the common period from 1565-2004. The first eigenvector (EV1) explains 70% of the total variance and was positively and significantly correlated with the individual average monthly PDSIs for the current year (T) and prior year (T-1). Correlations remain positive, but were not significant in the third prior year. The strongest consecutive correlations were from June-September of the prior year (T-1). Based on these results, PCA was used to develop a June-September tree-ring based PDSI regression model (using EV1 for year T+1 to estimate PDSI for year T) that spans 1565–2003. This regression explains 41% of the total PDSI variance over the calibration period of 1948-1983 (Figure 4.2). Although this period is short, it produces acceptable calibration and verification statistics (Table 4.2).

Our reconstruction extends the drought history of far-western Mongolia back to 1565 (Figure 4.3). The mid-1700s show extreme variation, 1741-1745 is the wettest 5-year period (1739-1746 is extremely wet) and is followed by the driest period 1755-1759 (Figure 4.3) (and stays extremely dry until 1761). Extreme drought years and extended drought periods occur fairly regularly prior to the 20th century. A trend towards increasing moisture begins in the early 1900s and continues into the 21st Century.

c. Spectral Analysis:

The reconstruction (1565-2004) was evaluated for spectral properties using the multi-taper method (MTM) of spectral analysis (Mann and Lees, 1996). The MTM indicates the spectral power coincides with the 22-year and 11-year solar cycles (Hale 1924) (99% and 90% significance respectively). These combined quasi-solar periodicities account for 12.8 % of the total variance of the PDSI reconstruction. These results suggest possible solar influence on moisture variations in central Asia, although the mechanisms are not well understood (Rind 2002). 22-year spectral peaks were similarly observed in other hydrometeorological reconstructions in Mongolia (Pederson et al. 2001, Davi et al. 2006), and western United States (Cook et al 1996). Periodicities in the 7 and 5.5 year range (99%) are also within the range of variability of the North Atlantic Oscillation (NAO) and ENSO, respectively.

4.4 Discussion

Development of tree-ring reconstructions in remote, mountainous regions such as western Mongolia is difficult due to the lack of meteorological observations, both temporally and spatially. Also, variations in precipitation are often localized over mountainous regions, further hampering development of regional hydrological models (Kimura & Sato 2002, Batima et al. 2005, Sato et al. 2007). The Altai are the highest mountains in Mongolia (Figure 4.1), and local orographic effects, along with synoptic disturbances can cause considerable spatial variability (and sub-anomalies) in precipitation. It is worth noting that Khovd (1406m) and Ulgii (1715m) are two relatively higher-elevation meteorological stations, although all tree-ring sampling sites are over 2000m (Table 4.1). The 300-600m difference in elevations could lead to significant orographic differences in precipitation. Therefore, it is not surprising to find that there are significant differences between meteorological stations and differences between meteorological station records and tree-ring records. Due to these issues, and the short period used for calibration, caution is suggested when interpreting these results.

The model is certainly valid within the calibration range, but may be less certain for the no-analog values where the dry years are outside the calibration range. There are approximately six intervals where the estimated severity of drought exceeds the calibration range. The biggest residual errors within the calibration range are in 1959 and 1960. The year 1959 was also a year that the Asian monsoon brought high precipitation to much of Asia (Li et al. 2009). One explanation for the disparity between the PDSI value and tree-ring growth for that year is that it was too wet. For the years 1948-1983 on average there is some drought every year. For the years 1958, 1959, and 1960 there is no drought at all. For 1960 PDSI never goes below 4.0. The trees-root system may be oversaturated. It appears to be past the threshold for positive moisture response. The trees benefit from some dryness and aeration of the soil (Kramer and Kozlowski, 1979). The first year of excessive moisture, 1958, the trees can respond with positive growth. In the following years of saturation, 1959 and 1960 there may be too much continual moisture. 1961 starts drying out and the trees again show more positive growth. This explanation obviously begs the question: How often has this happened in the past? All the previous extreme wet events were examined. None were as wet as 1958 and the following declines were more persistent, unlike the recovery in 1961. Similar events cannot be totally ruled out but it does appear that this extremely wet interval may be very unusual if not unique.

Lake-level data are also an important large-scale climate indicator because lake levels represent precipitation and evapotranspiration fluctuations over large areas. Khar-Us Nuur has roughly 15,800 square kilometers of surface area and obviously a much larger drainage area. The strong correlation between the tree-ring and lake-level records (R= 0.68) further confirms the moisture signal in the trees. This correlation, although based on a short common period, strongly suggests that PDSI, in this region, corresponds closely to fluctuations in lake-levels (Figure 4.4).

Our results show that there is an increasing moisture trend in western Mongolia in the 20th Century, continuing into the 21st century, and that it is the wettest century of the past four and a half centuries. Evaluation of station records (Batima et al. 2005, Endo et al. 2006) and drought reconstructions in western Mongolia and northwest China (Li et al. 2008) confirm this result. A tree-ring based PDSI reconstruction from northwestern China (1675-2002, Li et al. 2006) also shows an increasing moisture trend in the 20th century that is unusual over the past several centuries. A comparison of the two PDSI reconstructions (this study and Li et al. 2006) shows some similarity (R=0.27) although the study areas are several 100 kilometers apart and use different species. Both show a period of extended drought in the 1820s-1830s, a very dry period in the 1880s, and an increasing moisture trend in the 20th century. PDSI is a combination of precipitation and temperature and the increasing moisture trend seen in both the Altai and Tien Shan Mountain regions may be partly reflecting response to both warming conditions (effects of surface temperature accounts for between 10-30% of PDSI variance (Dai et al. 2004) and increases in precipitation.

Both the western Mongolia and the northwest China PDSI reconstructions show some similarities with a Northern Hemisphere temperature reconstruction (D'Arrigo et al. 2006b) which suggests a relationship between northern hemisphere warming and increased precipitation in this region due to a general intensification of the global hydrological cycle (Christensen et al. (IPCC) 2007). In northwest China, the increasing moisture regime is linked with the early stage Monsoon (April- July) (Li et al. in review) due to global sea-surface temperatures influence on monsoon strength, which can influence moisture variability in the region.

In addition to quasi-solar periodicities (see above), a large-scale study by Dai et al. (2004) shows that the principle component of the second empirical orthogonal function of global PDSI (including central Asia) is highly correlated with ENSO. However, the physical mechanisms that allow for large-scale climate modes, such as ENSO, to be observed in western Mongolia tree-ring records, are unclear. Summer season (JJA) precipitation is largely supplied by synoptic-scale disturbances because Mongolia is in the westerly-dominated zone (*NOAA* Climate Prediction Center *2002,* Sato et al. 2007).

The Kherlen River streamflow and precipitation reconstructions (Pederson et al. 2001) appear to show more frequent extended wet periods in the more recent decades, however these periods are within range of natural variation seen in the length of the record (1651-1995). The 20th century of the Selenge River streamflow reconstruction (Davi et al. 2006) is also within range of natural variation and does not show any strong secular trend.

4.5 Conclusion

It is very likely that the climate of Mongolia has already undergone significant changes that will impact the people of Mongolia and the economy. Evaluation of the instrumental record shows that temperatures are rapidly increasing (Yatagai & Yasunari, 1994, Batima et al. 2005, Endo et al. 2006). It is also clear that warming temperatures are predicted to continue (Christensen et al. 2007).

In western Mongolia, where recorded climatic data are very limited, the PDSI reconstruction described herein puts the climate change of the 20th century into long-term context and allows for the evaluation of climate trends, extremes and possible forcings. Our results show that in far-western Mongolia there is an increasing moisture trend starting in the 20th Century and continuing into the 21st Century and that this is the wettest period of the past four and a half centuries. This large-scale shift in moisture patterns has also been identified in a tree-ring based PDSI reconstruction from the Tien-shan mountain region (Li et al. 2007) and confirmed in station records (Batima et al. 2005, Endo et al. 2006).

The reconstruction shows an extreme wet period from 1739-1746 followed by an extreme dry period from 1755-1761 and an extended wet period in 1993-2003. The reconstruction has spectral periodicities in the 5.5 (99%), 7 (99%), 11 (90%) and 22 (99%) year range. There is a strong correlation between the first eigenvector of the three chronologies and lake-level data from Khar-Us Nuur, which further confirms the moisture signal in the trees.

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TABLES

Table 4.1. Tree-ring site information.

SITES	**Lat. (N)**	**Lon. (E)**	**Alt. (m)**	**Years**	**species**	**EPS[1]**	**RBAR[2]**	**AMS[3]**
Ankhny Khoton (AK)	48°36'	88°22'	2121	1469-2004	*Larix sibirica*	>0.78	0.31-0.51	0.270
Khoton Nuur (KN)	48°30'	88°33'	2145	1215-2004	*Larix sibirica*	>0.76	0.32-0.57	0.260
Khovd Gol (KG)	48°30'	88°48'	2021	1565-2004	*Larix sibirica*	>0.89	0.34-0.69	0.292

[1] Expressed Population Signal statistic.
[2] Rbar = the running mean correlation coefficient (25 year window) between all tree ring series used in a chronology.
[3] Average mean sensitivity from Cofecha output.

Table 4.2. Calibration/ Verification.

	calibration 1948-1965	verification 1966-1983	calibration 1966-1983	verification 1948-1965
Adjusted r^2	0.446	---	0.29	---
RE	0.478	0.336	0.334	0.450
Sign test	15+3- (0.005)	12+ 6- (0.10)	14+ 4- (0.05)	15+3- (0.01)
P	0.692 (0.001)	0.578 (0.002)	0.578 (0.01)	0.692(0.01)

Adjusted r^2 is the variance accounted for by the calibration model, adjusted for degrees of freedom; RE is the reduction of error statistic, P is the Pearson correlation coefficient. The Sign test describes how well the predicted value track the actual data. Levels of significance are indicated in parentheses.

FIGURES

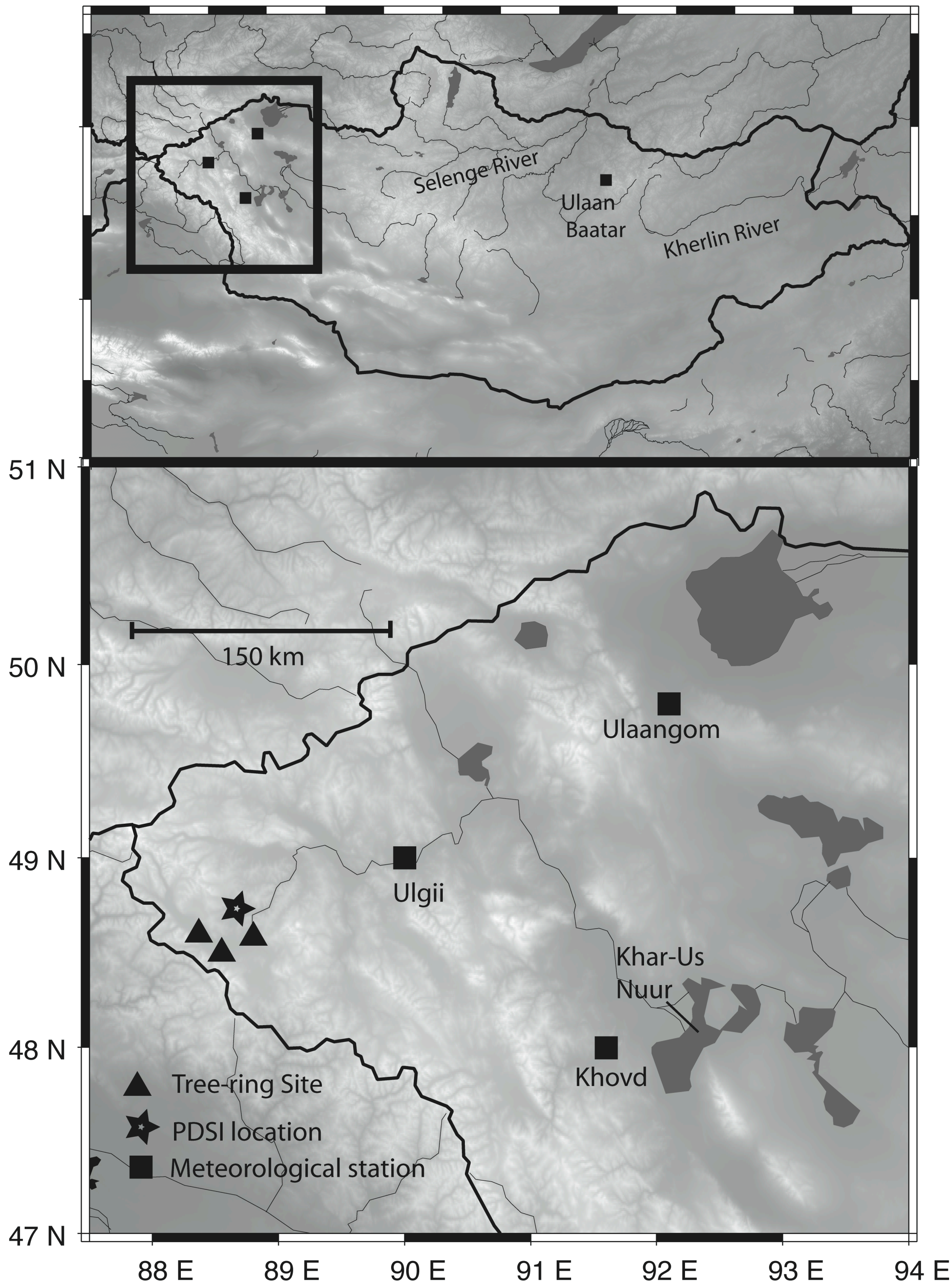

Figure 4.1. Map of Mongolia showing locations of sampling sites (triangles), PDSI grid cell (star), meteorological stations (squares) and topographic relief (lighter is higher).

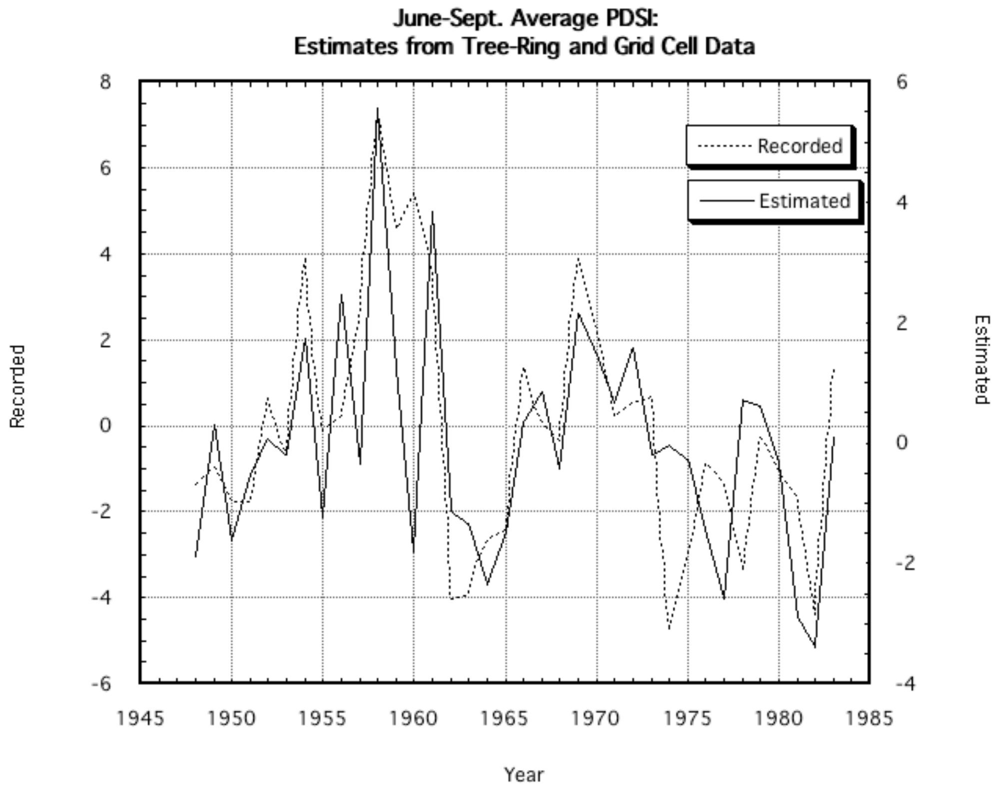

Figure 4.2. June-September PDSI estimated from tree-rings (solid line) and from grid point data (dashed line) over the 1948-1983 calibration period. The largest disparity in the PDSI and estimated (from trees) values is in the year 1959, a very wet year (see text for more detail).

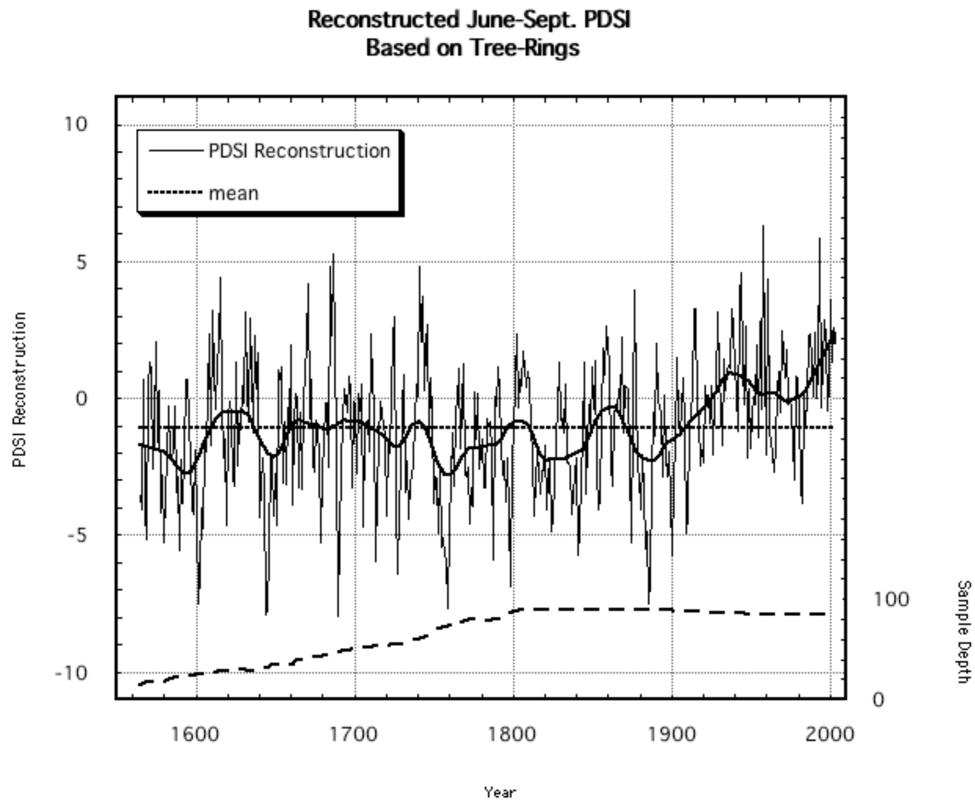

Figure 4.3. Tree-ring based PDSI reconstruction, along with mean (thick dashed line) and smoothed curve that emphasizes low frequency variation. Thick long-dashed line shows sample depth adding all series in all chronologies.

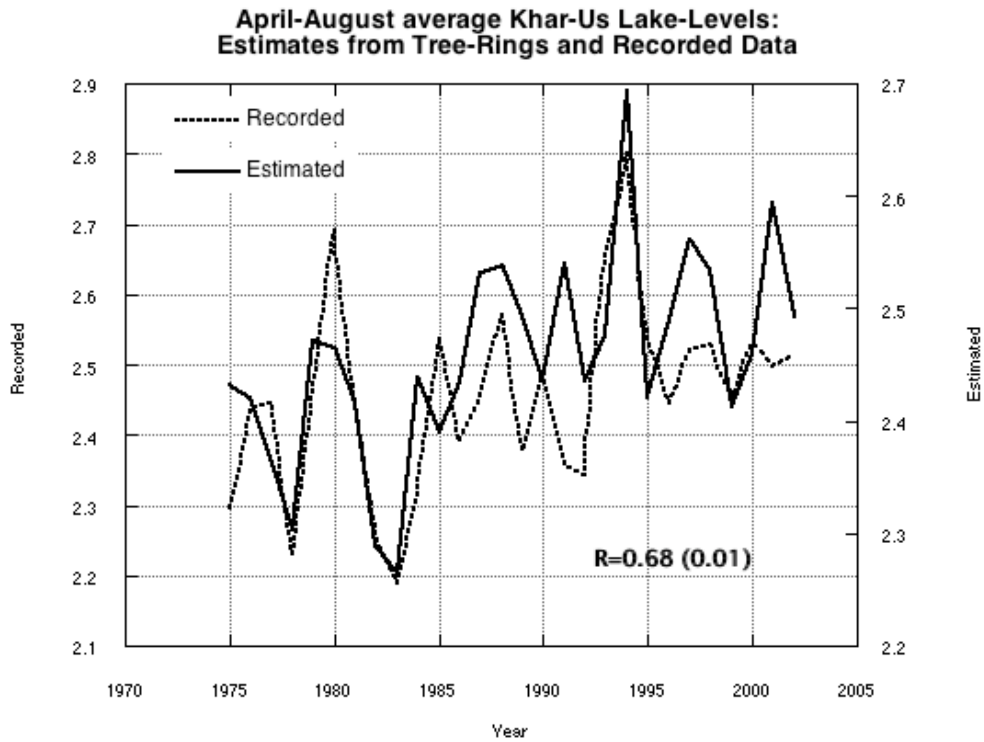

Figure 4.4. Recorded lake-level data (dashed line) graphed with the first eigenvector of the three tree-ring chronologies (solid line) calibrated to lake level.

CHAPTER 5. RECONSTRUCTED DROUGHT ACROSS MONGOLIA BASED ON A LARGE-SCALE TREE-RING NETWORK: 1520-1993[3]

[3] This manuscript, once submitted, will include a list of authors as follows; N, Davi, G. Jacoby, K. Fang, J. Li, R. D'Arrigo, N. Baatarbileg. Although this manuscript was drafted by N. Davi, the co-authors listed above improved the manuscript significantly with edits and suggestions or other contributions such as fieldwork. Tree-ring samples used in this study, collected over a ten-year period (Table 1.), were processed either by N. Davi or by laboratory technicians (listed in acknowledgements).

5.1 Introduction

Evaluation of the instrumental record shows that Mongolia is undergoing significant climatic change (Yatagai & Yasunari, 1994, Batima et al. 2005, Endo et al. 2006). This change includes pronounced warming, consistent with similar temperature increases elsewhere in the Northern Hemisphere and the globe. Warming has been particularly pronounced in the high mountain regions, such as the Altai Mountains in the west (Batima et al. 2005). Millennial length tree-ring width records show that temperatures of the late 1990s to early 2000s were unprecedented in Mongolia (D'Arrigo et al. 2001, Jacoby et al. submitted). How this warming will affect precipitation patterns in the future is difficult to predict (Christensen et al. 2007), as climate forcings in continental Asia and Mongolia are highly complex (Aizen et al. 2001).

Precipitation variability in Mongolia is likely to result from a combination of various forcings, including the Siberian anticyclone circulation (in winter), the northward migration of the westerly jetstream (in summer), synoptic-scale disturbances, the North Atlantic Oscillation (NAO), continental evapotranspiration and evaporation from oceans, orography, and the Asian Monsoon (Aizen et al. 2001, Li et al. 2009). There is only limited understanding of how these various factors impact climate in Mongolia, and much of mid-latitude Asia. This is in part due to limited length and coverage of meteorological data in the region (Aizen et al. 2001).

For the above reasons, tree-ring data have been used to create regional climate reconstructions that supplement and extend the limited meteorological record of Mongolia. These data include reconstructions of drought that reflect spatial and temporal patterns of moisture variability on interannual to centennial time scales (Pederson 2001, Davi 2006, Davi 2009). In western Mongolia (Davi et al. 2009), and also the nearby Tien Shan mountain region of China (Li et al. 2006), positive trends in precipitation have been reconstructed in recent decades. These positive trends may indicate that the influence of the Siberian High pressure system has weakened and/or shifted over the past century and that the influence of westerly airflow has increased, bringing more moisture to mountainous and plain regions of middle Asia (Aizen et al. 2001).

In Central (Davi et al. 2006) and Eastern Mongolia (Pederson et al. 2001), tree-ring records reveal that precipitation levels during the 20th century were within the long-term range (~400 years) and do not appear to be unusual. However, these reconstructions end in 1995 (east), and 1997 (central), just prior to a very hot/dry period spanning 1999-2002.

Prior drought reconstructions were isolated to regions (i.e western Mongolia, Selenge basin), in this study, we use an expanded large-scale network of tree-ring records (34 sites) to reconstruct average June-August (JJA) Palmer Drought Severity Index (PDSI) spanning Mongolia (Figure 5.1). The PDSI is a widely used drought indicator based on a water balance model that considers water supply (precipitation), demand (evapotranspiration) and loss (runoff) (Palmer 1965, Dai et al. 2004). In the Dai et al. (2004) study, the first principal component of an empirical orthogonal function (EOF) of global PDSI (1870-2002) shows global wetting and drying patterns. This EOF suggests a drying pattern over the majority of Mongolia. A subsequent analysis of PDSI over China and Mongolia (Li et al. 2009) found no significant moisture trend from 1951- 2005 over central and western Mongolia. However, in eastern Mongolia there was an overall drying trend (statistically significant at the 0.01 level), particularly beginning in the early 1990s (Li et al. 2009). An average of all monthly PDSI over China and Mongolia (1951-2005) shows a decreasing trend beginning in the 1990s with 2001 being the driest year of that interval (Li et al. 2009). In Mongolia, a multi-year drought, and harsh winter conditions, occurred from 1999-2001 and resulted in large-scale livestock losses (Batima 2006).

The main goal of this study is to extend the drought history of Mongolia, a region where very little is known, by using a network of moisture-sensitive tree-ring records to develop a PDSI reconstruction that reveals the main summer-moisture patterns of the past. The 2001 drought was particularly devastating to the nomadic herding population (Batima, 2006). Tree-ring records can extend the drought history of Mongolia by several hundred years past recorded data allowing for long-term perspective of these droughts. This reconstruction is also used to evaluate trends, extremes and periodicities over the past half millennium.

5.2 Material and methods

a. PDSI data

PDSI values generally range from +10 to –10, where wet years are positive and dry years are negative. Although Palmer (1965) would categorize severe drought or wet conditions as any values over -3 and +3 respectively, interpretations of the moisture severity of a given value depend on the local mean climate condition, as PDSI can mean different things in different regions (Dai et al. 2004). In Mongolia, mean annual precipitation is relatively low, accumulating roughly 100-200mm in the dry south and 200-350mm in mountainous regions (Sato et. al. 2006).

Here, we use the average June-August (JJA) PDSI for forty-eight 2.5° x 2.5° PDSI grid points across Mongolia (Figure 5.1). The Dai et al. (2004) PDSI data has been adjusted using a ‘Queens Case’ method, where any missing values are estimated by interpolating the eight neighboring grids (E. Cook, personal communication, Elobaid et al. 2009). The mean JJA PDSI for Mongolia is –0.81 (1951-2005) and shows extreme drying from 1999-2002 and again from 2004-2005 (hereafter, 2000 droughts). We truncated the Mongolian PDSI beginning in 1951 for this study due to the limited meteorological records before that time in this region. The wettest year on record was 1959 and was also a year that the Asian monsoon brought high precipitation to much of Asia (Li et al. 2009).

b. Tree-ring data

The Tree-Ring Laboratory of Lamont-Doherty Earth Observatory, along with colleagues at the National University of Mongolia’s Department of Forestry, has collected tree-ring samples in Mongolia for the Mongolia-American Tree-Ring Project (MATRIP) since 1995. Results of some of these collections are published elsewhere (Jacoby et al. 1996 and 2003, D’Arrigo et al. 2001, Pederson et al. 2001, Davi et al. 2006, Davi et al. 2009). Of these collections, thirty-four sites showed that they might contribute some information related to moisture availability, based on observations of site conditions and other factors and were evaluated for this study (Table 5.1). Of all the chronologies used for modeling PDSI in this study, six were previously published in regional climate studies (Pederson et al. 2001, Davi et al. 2006, Davi et al. 2009).

All chronologies tested are summarized in Table 5.1. Conventional techniques of dendrochronology were employed in dating and chronology development (Cook and Kairiukstis 1990). Each annual ring from every core of every study site was marked with an exact calendar date and visually crossdated by evaluating marker years (extremely narrow or wide rings). Cores were measured to the nearest 0.001 mm and checked for dating accuracy using COFECHA software (Holmes, 1983). Series were standardized using conservative de-trending methods (negative exponential and straight-line curve fits) and developed into chronologies using ARSTAN software (Cook 1985). We use the Standard version (Cook et al. 1990) of all chronologies for analysis.

Chronologies range from 1403 to 1703 and end from 1994 to 2004 (1703-1994 common period). Chronologies that began with fewer than six individual tree-ring series were truncated to insure reliability of climate signal. For example, Khorgo Lava (Table 5.1) starts in 1340, but has been truncated 1490, when there are at least 6 individual tree-ring series contributing to the chronology. Chronology strength through time was evaluated using the expressed population signal (EPS) and the running mean correlation coefficient (25-year window) between all tree-ring series used in a chronology, or Rbar statistics. All chronologies have an EPS of at least 0.80, (Wigley et al. 1984) although generally higher, and an Rbar of at least 0.3 although generally much higher.

c. PDSI regression model

The PDSI tree-ring model for all of Mongolia (hereafter, all-Mongolia) was created using principal component regression on the 1951-1993 common period. We validated using a split calibration-verification scheme (Cook and Kairiukstis 1990), that is, calibration (1972-1993) and verification (1951-1971), as well as calibration (1951-1971) and verification (1972-1993). Since tree growth can be influenced by climate conditions of both previous and current years, we included tree-ring indices of the previous and current year as candidate predictors in the reconstruction model.

All standard tree-ring chronologies and the PDSI data were prewhitened prior to regression analysis in order to maximum the common signal and minimize the amount of noise (Cook et al. 1999). The pooled autocorrelation (persistence) calculated through this process was added back into the PDSI reconstruction (Cook et al. 1999) to generate an improved reconstruction model with low-frequency information.

In order to develop a statistically reasonable reconstruction that fully utilized the longest chronologies, we used a nested model approach that was stepped back in twenty-year increments (Cook et al. 2002). The reconstruction associated with each nest was rescaled (mean and variance) to match the most replicated model (1703-1993). In so doing, 10 nested reconstruction models were established, extending the model back 174 years past the common period (1703-1993) to 1520. The calibration/verification statistics and variance explained (R^2), for the model (and each amended nest), are shown in Table 5.2. Forward nests were tested using all chronologies that span to 2001 (Table 5.1) and also by limiting the data to regions where the 2000 droughts were the most severe (discussed further below).

d. Spectral methods

To evaluate the reconstruction for periodicities we perform a spectral analysis using multi-taper method (MTM) of spectral analysis (Mann and Lees, 1996).

5.3 Results

a. PDSI reconstruction

Of the thirty-four chronologies tested for the most replicated nest (1703-1993) and 68 candidate predictors (years –1 and 1), 33 predictors were significantly correlated (0.1 level or higher) with the average JJA of forty-eight PDSI cells spanning the entire country of Mongolia. The first six principal components (PCs) of the 38 predictors, which cumulatively explain 65% of the total tree-ring variance, were retained for use in regression. The resulting JJA PDSI model (Figure 5.2) explains 61% of the PDSI variance (a very strong model) and demonstrates valid calibration/verification statistics (Table 5.2). As the model is extended further back in time with each subsequent nest (Figure 5.3 top), the number of predictors declines (Figure 5.3 bottom), as does the variance explained, due to a decrease in the number of chronologies that cover the longer time span. Nests that were tested to extend the model past 1520 failed calibration and verification statistics and therefore were not included.

b. Forward Nest

A forward nest, using all tree-ring chronologies that extend to 2001, was performed. Although the forward nest model captured the general year-to-year variation of the PDSI and correlated quite high (R= 0.88) the model failed because the tree-ring estimates underestimate the actual 1999-2000 PDSI values (Figure 5.4). The actual mean summer PDSI value for 2000 is -5.14 (black line Figure 5.4) and estimates from tree-rings are -1.87 (green line Figure 5.4). Mongolian trees ring chronologies that extend into the 2000s (Table 5.1) and are located within the region that shows extreme drought (Figure 5.5), have extremely narrow rings from 1999-2002, demonstrating that the trees located in the driest regions during that time were sensitive to the these droughts.

A forward nest that includes only the tree rings from the most effected areas (Figure 5.5) resulted in an acceptable forward nest model (1994-2000) that captured the severity of the recent droughts (actual PDSI value for 2000 is -5.14, estimated from tree-ring =-4.27) (Figure 5.4, red line). However, the problem is that regional tree-ring chronologies (the ones that are most sensitive to the droughts) are being used to model a much larger signal (all Mongolia). Although using regional tree-ring records to infer information about large-scale climate patterns is common in the tree-ring literature. Therefore, the regional forward nest is not included in the PDSI model. Instead, we have attached the actual average JJA PDSI data (of the 44 grid cells used for modeling) from 1994-2005 to the reconstruction in order to add context to the 2000 droughts (Figure 3.5).

c. Spectral Analysis

A spectral analysis (Figure 5.7) of the most replicated period (1703-1993) was performed using the Multi-Taper Method (Mann & Lees 1996). The time-series shows significant periodicities at 2.8 (99%), 6.4-7.2 (95%), 11.6 (95%), 19.3 -25 (99%) and 40 years (90%). All three prior regional reconstructions (Pederson et al. 2001, Davi et al. 2006 & 2009) show similar significant periodicities in the 6-7 year range, and 19-25 year range. Periodicities in the 11 and 22-year range are often seen in tree-ring records (Rigozo et al. 2003, Kasatkina et al. 2006, Cook et al. 1997) and are thought to be associated with sun spot cycles, although the climate mechanisms are not fully understood (Rind 2002). The 40-year periodicity is often associated with the Pacific Decadal Oscillation (D'Arrigo & Wilson 2006), and the 2.8 periodicity is in the range of ENSO. An association with sea surface temperatures anomalies in eastern equatorial Pacific (ENSO) has been found in precipitation from North China (Lu 2005).

A spectral analysis was also preformed on the nested reconstruction 1520-1993 which shows similar periodicities as the most replicated period (described above) in the inter-annual range at 2.9-3.0 (99%) and 3.8 (99%) and also in the decadal-range 19.6-22.7 (99%). There are also significant periodicities at 56 (95%) and 204 (%) years.

5.4 Discussion

a. Spatial Complexities

The 2000 droughts show varying spatial patterns. Although many regions show extreme drought there are also regions that show mild drought and wet anomalies. At 47° N latitude (Figure 5.5A), we can see that the driest region spanned roughly from 95°-106°E and in eastern Mongolia, from 115°E into NE China. Meanwhile, western Mongolia, shows anomalously high moisture values. From 103° E longitude (Figure 5.5B) we can see that the driest region was in central Mongolia (44-50°N), with similar dryness in China (36°N), and Russia (54°N).

Spatial variability in moisture patterns raises the possibility that extreme regional droughts (or wet anomalies) may be significantly underestimated (or overestimated) by reconstructing an average PDSI for the country. Drought hazards for Mongolia may be even more severe on a regional basis than full country reconstruction suggests and one must consider this when interpreting the all-Mongolia PDSI reconstruction developed here. For the 2000 droughts, it is also possible that the regional drought was so extreme in certain areas that those extreme indices dominate the countrywide average PDSI, effectively averaging out the wetter regions. The trees site locations, on the other hand, are spread over regions affected by mild drought, extreme drought and higher moisture values during the 2000 droughts, resulting in country-wide estimates of drought (from trees) that are not as severe as the actual PDSI values.

That said, the all-Mongolia tree-ring PDSI model is robust (explaining more than 60% of the PDSI variance) and certainly captures the dominant moisture patterns of the calibration period (Figure 5.2). A homogeneous spatial reconstruction of each PDSI grid cell spanning Mongolia, will allow for detailed evaluation of the spatial patterns of drought (discussed further in Chapter 7).

b. Features of the all-Mongolia Drought Reconstruction

As described above, the 2000s drought had devastating effect on livestock and the livelihood of the herding population. The most notable benefit of the summer (JJA) all-Mongolia PDSI reconstruction (1520-1993) concerns the long-term context that it provides for the severe multi-year drought that took place from ~1999-2002. These droughts were unusually dry compared to the past 500 years and may have been the driest years reconstructed.

Another extreme multi-year drought occurred from 1640-1646 (Table 5.3, Figure 5.3) and was also found in a stalagmite record Wanxiang cave in central China (Zhang et al. 2008). Although it is not clear if the 1640s droughts were one mega-drought affecting much of central Asia, it is certainly a possibility. The summer drought of 2001 was felt in Mongolia, central and northeast China, Myanmar and Northern Thailand (Figure 5.6). Similar spatial drought patterns are seen in 1999, 2000 and 2002. Other multi-year and single dry and wet years are listed in Table 5.3.

An overall decrease in moisture variability is seen in the 1800s. This pattern was also identified in Pederson et al. (2001), a tree-ring based reconstruction for both streamflow and precipitation. Two of the driest 5-year periods occur during this century, from 1821-1825 and again from 1880-1884. The 1900s and beginning of the 20th century show more variability with extremely wet periods from 1915-1919, 1934-1938, 1955-1959, 1990-1994 and extremely dry years in 1928, 1942, 1977-1981 and again from 1999-2001 and 2004-2005 (Figure 5.3).

5.5 Conclusions

Presented here is a nearly 500-year nested drought reconstruction for Mongolia based on a large-scale network of tree-ring chronologies. This reconstruction shows that the 2000 droughts were extremely dry compared to the past 500 years of reconstructed drought. Other extremely dry periods are found from 1600-1644, 1578-1582, 1880-1884, 1600-1604, 1735-1739, 1977-1981, 1821-1825, and 1779-1783.

Spectral analysis shows significant periodicities at 2.8 (99%), 6.4-7.2 (95%), 11.6 (95%), 19.3 -25 (99%) and 40 years (90%). Periodicities in the 11 and 22-year range are often found in tree-ring records and are associated with solar cycles. Other periodicities suggest ocean/atmosphere influence on Mongolian PDSI.

Increased climate variability and extreme drought, like the one seen from 1999-2001, may occur more regularly as temperatures are predicted to continue to increase (Christensen et al. 2007). Understanding synoptic-scale climatology, especially the forcings behind precipitation in Mongolia is increasingly important for future predictions. Currently, predictions of precipitation for Mongolia are particularly uncertain during the summer, when most of the precipitation falls (Christensen et al. 2007). Synoptic scale studies have been limited in Mongolia, in part due to the lack of meteorological records and the complexity of climatic conditions in the region. There is not a clear dominant climate forcing of precipitation in Mongolia and the affects and feedbacks of many possible forcings are difficult to delineate. The tree-ring network described herein, used in conjunction with the available meteorological data, provides another significant step towards a better understanding of climate variability and forcings in the region.

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TABLES

Table 5.1 Lists of site names for all tree-ring chronologies used in this study, as well as their locations, species and time spans.

SITE	Lon.	Lat.	Species	Full period*
Ankhny Khoton	88.0	48.4	Larix sibirica	1584-2004
Bairam Ger	90.6	49.6	Larix sibirica	1526-2005
Bulgan Gol	90.6	47.1	Larix sibirica	1464-2004
Dadal	111.4	49.0	Larix sibirica	1665-2001
Dalbay Valley	100.5	51.0	Larix sibirica	1642-2002
Dayan Lake	88.5	48.2	Larix sibirica	1678-2005
Hadagtai Uul	102.3	46.4	Larix sibirica	1601-1996
Hovsgol Nuur	100.1	50.5	Larix sibirica	1627-1994
Ikh Xavbtag	92.2	45.0	Juniperus spp	1671-2005
Inferno Ridge	111.4	48.5	Larix sibirica	1703-1996
Kaizil Talvan	89.0	48.0	Larix sibirica	1640-2004
Khorgo Lava	99.5	48.1	Larix sibirica	1490-2000
Khar Uzzur	94.3	49.3	Larix sibirica	1671-1998
Khovd Gol	88.5	48.4	Larix sibirica	1643-2004
Khureegyin Oi	97.4	47.3	Larix sibirica	1594-1999
Manzshir Hiid	106.6	47.5	Larix sibirica Pinus sylvestris	1647-1994
Mandal Hill	107.5	46.5	Larix sibirica	1622-2002
ND-Bayanhangor	101.2	46.2	Larix sibirica	1609-2001
Onon gol	111.4	48.5	Larix sibirica	1665-2001
Ovoont	91.3	49.5	Larix sibirica	1475-1999
HPlar High Pass	98.6	48.2	Pinus siberica	1403-1994
South Park Ridge	94.5	49.2	Larix sibirica	1476-1998
Sulcheen Medee	100.3	47.5	Larix sibirica	1616-2002
Suuleen Bagtra	100.0	47.2	Larix sibirica	1454-1999
Telmen Beach	97.1	48.5	Larix sibirica	1649-1998
Terelj	107.3	47.5	Larix sibirica	1647-2002
Unddur Ulaan	103.1	48.6	Larix sibirica	1547-2002
Urgan Nars	110.3	48.3	Pinus sylvestris	1666-1996
Xatran Xopb	99.5	50.2	Larix sibirica	1610-2003
Xoton Nuur	88.3	48.3	Larix sibirica	1508-2004
Zuun Mod	107.3	47.5	Larix sibirica	1589-2001
Zuun Mod Gol	97.2	48.2	Larix sibirica	1550-1998
Zun Salaa Mod	100.2	48.8	Larix sibirica	1584-2001
Zurkh Togol	100.6	46.3	Larix sibirica	1547-2002

* Full period used that contains at least 6 samples

Table 5.2. Calibration and verification statistics for nested model with 20-year intervals. Top shows calibration (1972-1993) and verification (1951-1971) periods, the middle results when these periods are reversed. RE is the Reduction of Error, CE is coefficient of efficiency (Cook and Kairiukstis 1990). The bottom section shows the number of predictors that load into the model using different nested intervals and the associated variance explained (R2).

			2000*	**1703**	**1680**	**1660**	**1640**	**1600**	**1580**	**1560**	**1540**	**1520**	**1500**
calibration	**1972-1993**	**r**		0.81	0.82	0.77	0.71	0.73	0.74	0.74	0.72	0.76	0.76
verification	**1951-1971**	**r**		0.71	0.74	0.74	0.68	0.74	0.38	0.38	0.36	0.56	0.41
		RE		0.54	0.54	0.52	0.41	0.45	0.19	0.19	0.17	0.42	0.12
		CE		0.28	0.27	0.26	0.08	0.15	-0.27	-0.27	-0.3	0.09	-0.37
calibration	**1951-1971**	**r**		0.88	0.88	0.8	0.8	0.77	0.58	0.58	0.57	0.57	0.57
verification	**1972-1993**	**r**		0.74	0.74	0.72	0.63	0.68	0.58	0.58	0.58	0.58	0.58
		RE		0.28	0.28	0.33	0.23	0.31	0.27	0.27	0.33	0.33	0.33
		CE		0.01	0.01	0.08	-0.06	0.05	-0.01	-0.01	0.09	0.09	0.09
calibration	**1951-1993**	**NO. predictor**		33	32	25	19	14	6	6	4	3	
		R2		0.61	0.6	0.55	0.49	0.48	0.42	0.42	0.39	0.45	

* Forward from 1994-2000

Table 5.3. The driest one and 5-year periods.

Rank	**Dry year**	**Dry 5-yr**	**Wet year**	**Wet 5-yr**
1	2000*	2000-2004*	1993	1955-1959
2	2001*	1600-1644	1762	1612-1616
3	2004*	1578-1582	1959	1915-1919
4	1641	1521-1525	1958	1762-1766
5	2005*	1880-1884	1616	1990-1994
6	1771	1600-1604	1720	1916-1920
7	2002*	1735-1739	1915	1716-1720
8	1579	1977-1981	1595	1934-1938
9	1942	1821-1825	1956	1751-1755
10	1523	1779-1783	1917	1785-1789

*Data from 1994 to 2005 are from averaged JJA PDSI.

FIGURES

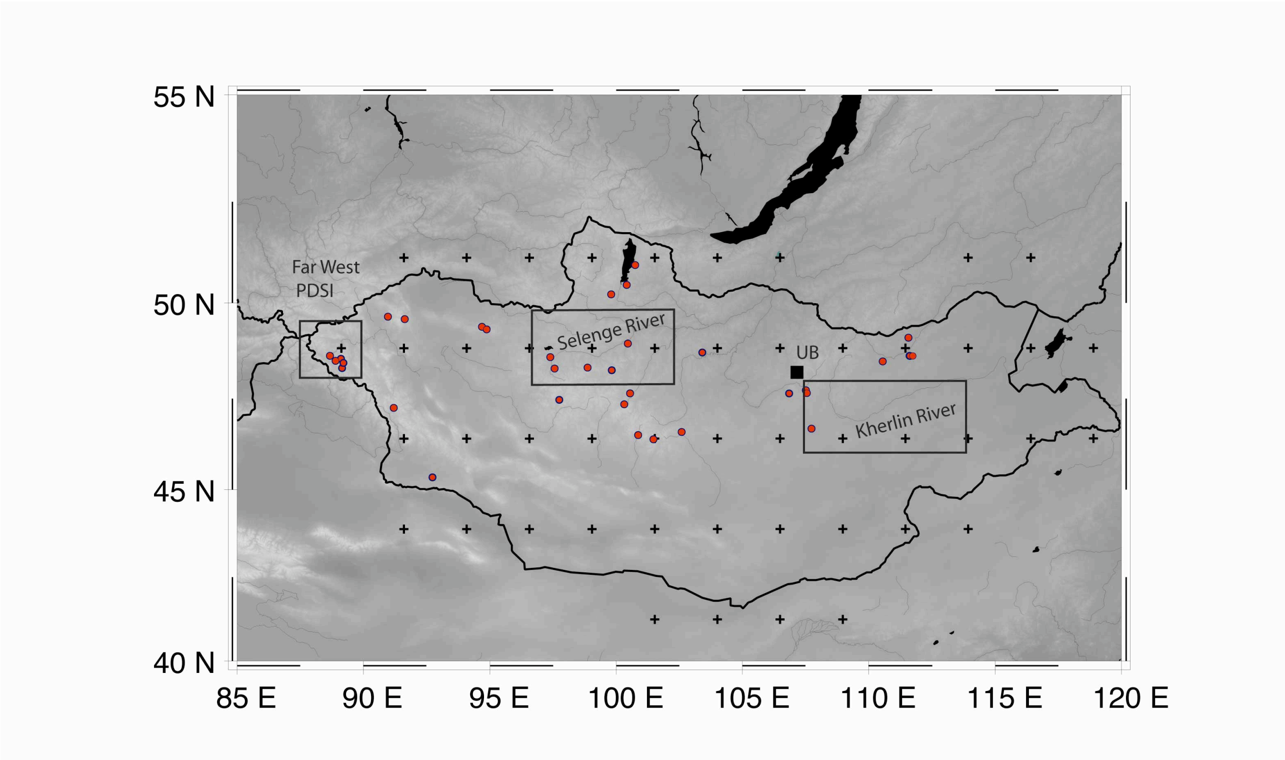

Figure 5.1. Map of 48 PDSI gridcells over Mongolia (crosses). Also shown are locations of the 34 tree-ring sites tested for modeling (red dots). Previously published regional study areas are boxed; Far west Mongolia (Davi et al. 2009), Selenge River (Davi et al. 2006), and Kherlen River (Pederson et al. 2001). The capital of Mongolia, Ulaan Baatar (UB) is shown as a square.

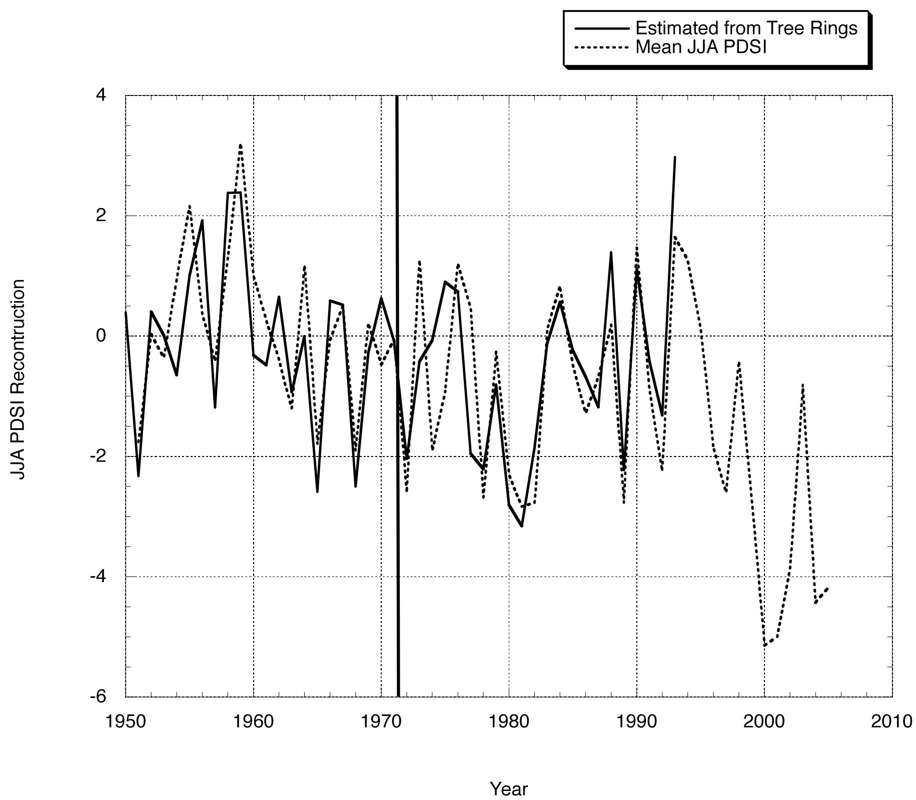

Figure 5.2. Comparison of actual (dashed) and reconstructed (solid line) June-August PDSI averaged from 48 grid-cells. Vertical line shows where the data is split for calibration and verification testing. R = 0.78 over the whole period (1951-1993). Note the extreme droughts from 1999-2003 and again from 2004-2005.

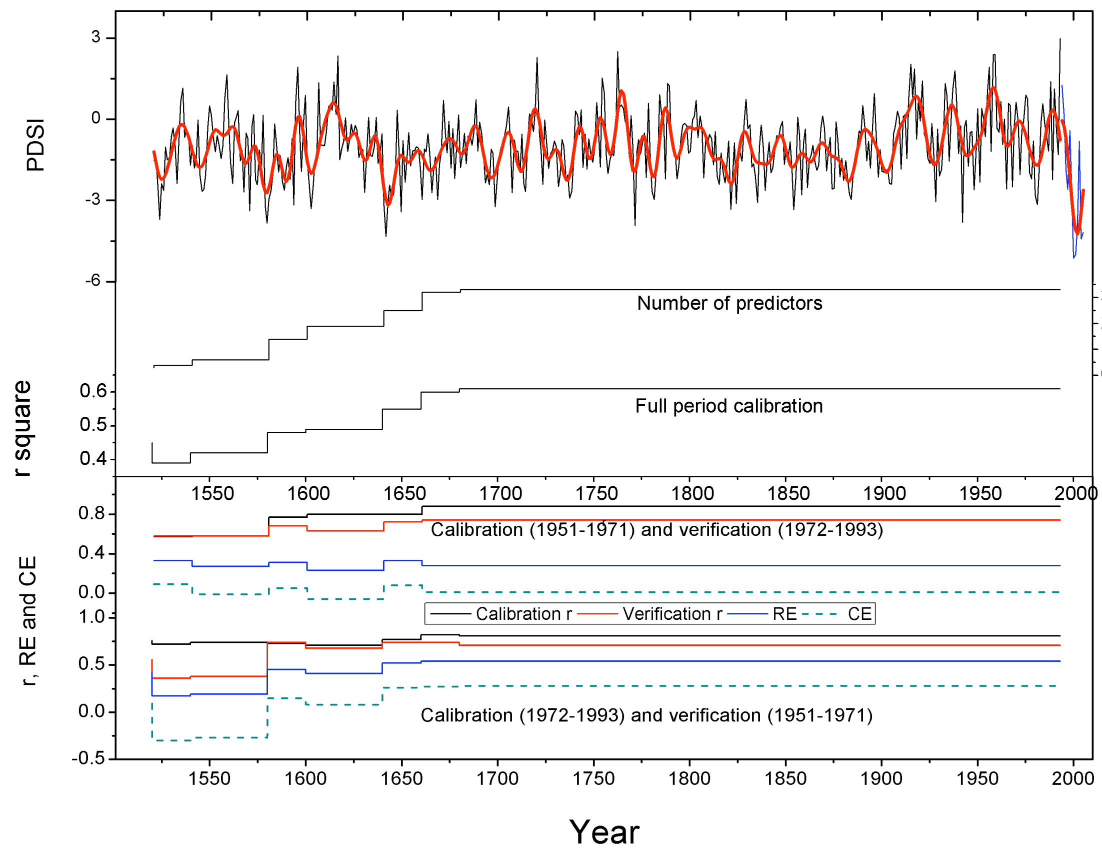

Figure 5.3. Summer (JJA) PDSI reconstruction based on tree-rings (1520-1993) with the actual JJA PDSI values from 1994-2005 attached for context, based on a nested procedure. Plot also shows the time-varying number of predictors, calibration r square for nested full period reconstruction, as well as the statistics of correlation (r), reduction of error (RE) and coefficient of efficiency (CE) for calibration and verification of the split periods (1951-1971 and 1972-1993).

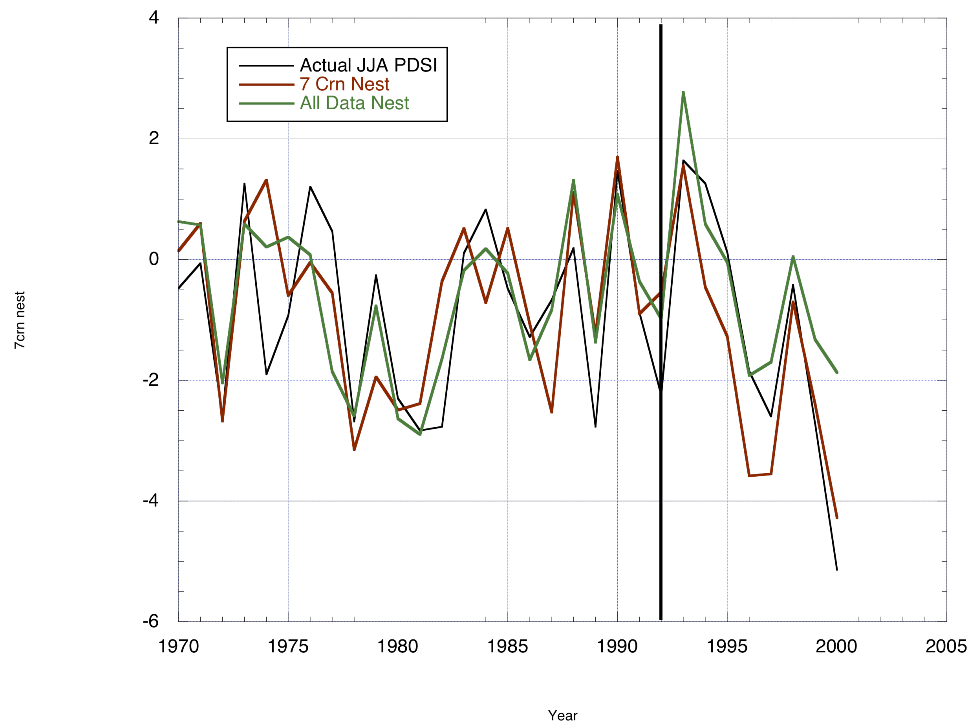

Figure 5.4. Graph showing the actual PDSI data (black line), the forward nest using all chronologies (green line), and the forward nest using only chronologies from the most affected areas (red line).

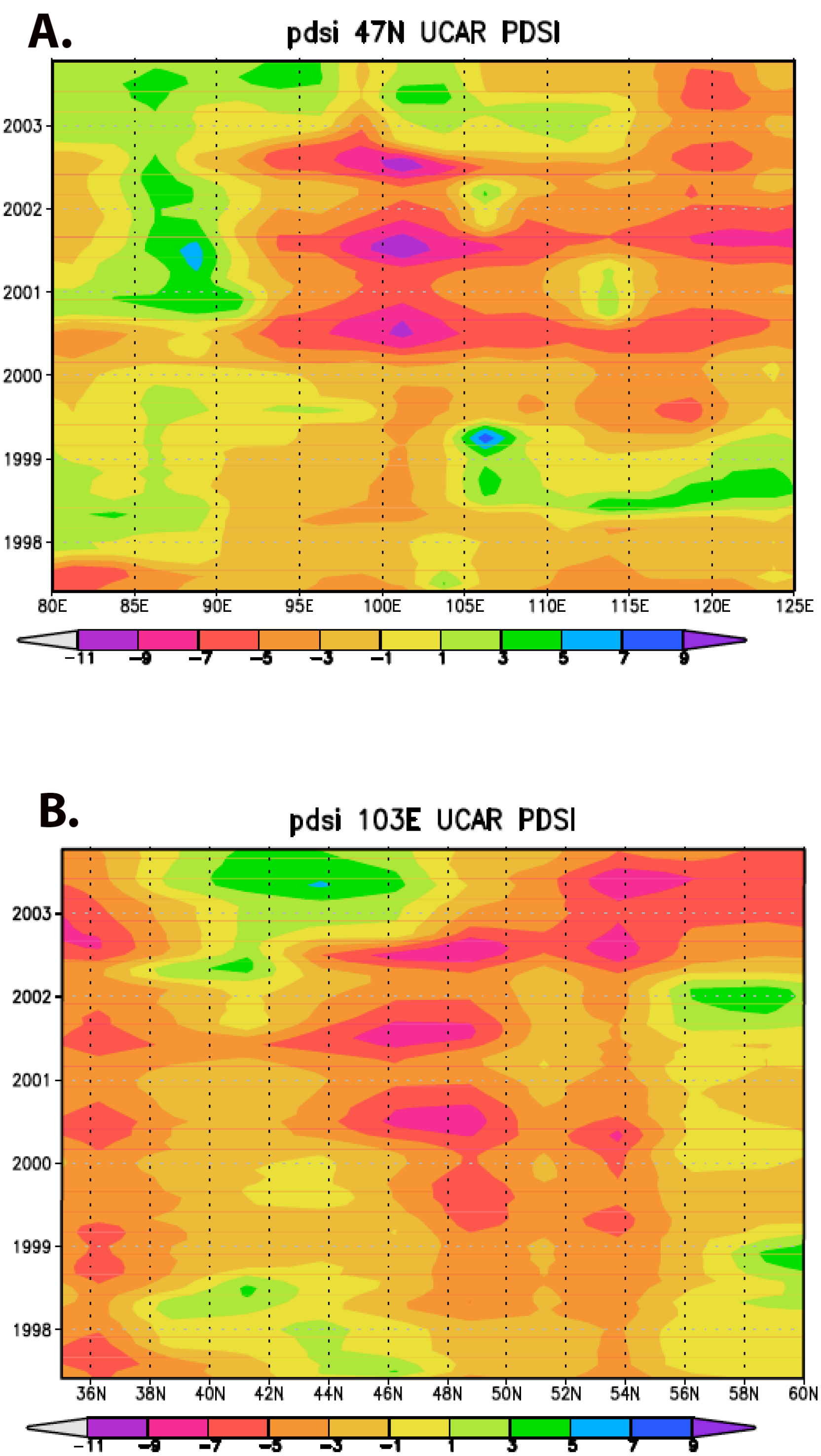

Figure 5.5. Hovmuller graphs showing the spatial and temporal extent of the three extreme JJA PDSI droughts (1999-2002), at (A) 47N latitude (80-125E) and (B) 115E longitude (35-60N). Graph created on KNMI's Climate Explorer: http://climexp.knmi.nl/

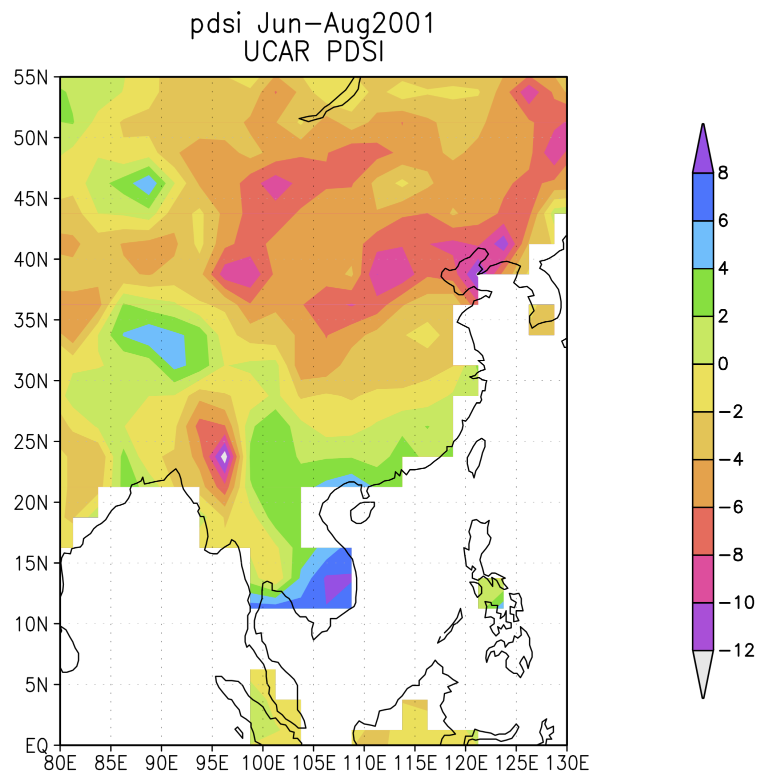

Figure 5.6. Map showing the spatial extent of the 2001 summer drought. Climate Explorer. Graph created on KNMI's Climate Explorer: http://climexp.knmi.nl/.

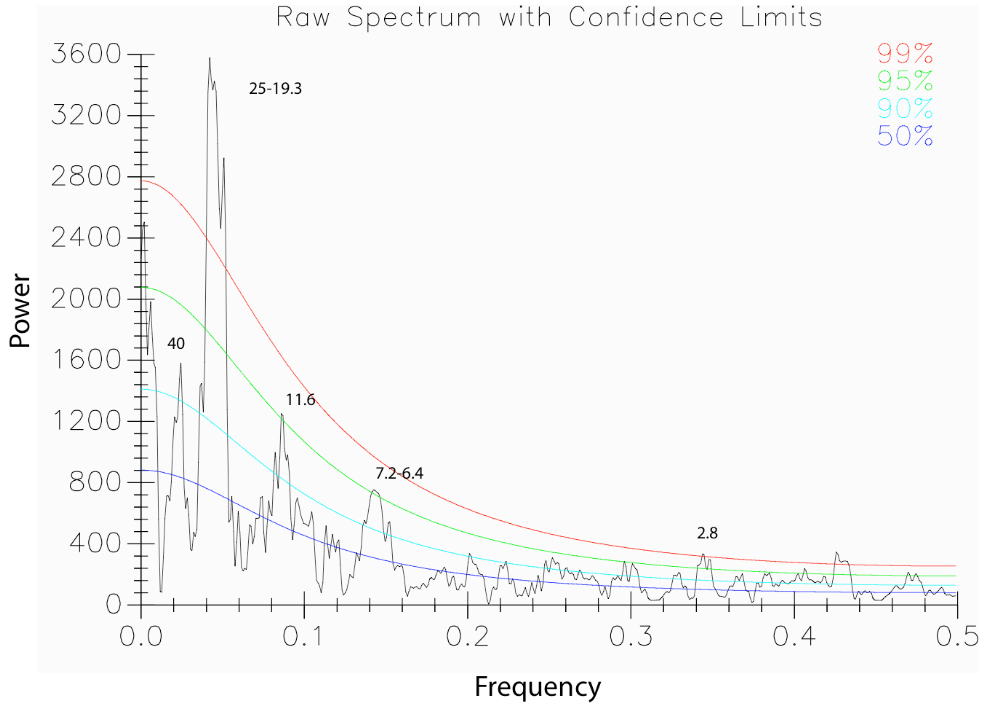

Figure 5.7. Plot of spectral properties of the most replicated JJA PDSI reconstruction (1703-1993) using multi-taper method (MTM) spectral analysis (Mann and Lees 1996). Significant periodicities are marked with associated confidence limits: 99% (red), 95% (green) and 90% (light blue) and the null (dark blue).

CHAPTER 6. DISCUSSION

In this chapter, the drought and spectral patterns of the three reconstructions described above (Chapter 3, 4 and 5) are compared and evaluated for trends. A previously published, tree-ring based reconstruction from northeastern Mongolia (Pederson et al. 2001) has been updated here for the purpose of comparing the moisture and spatial patterns from all tree-ring based drought reconstructions in Mongolia thus far. This updated reconstruction, as described below, is robust, however an in-depth analysis of this updated reconstruction will not be preformed here, as it is only used for comparative purposes. Future predictions of drought and forecast capabilities are summarized, as are current climate risk management program.

6.1 Kherlin Update

For the purpose of comparing the moisture patterns and spatial patterns from all tree-ring based drought reconstructions from this study, the original Kherlen River streamflow reconstruction [(KRS) (Pederson et al. 2001)] from northeastern Mongolia (Figure 6.1) has been updated here. The original reconstruction has been referenced in Chapter 3, 4 and 5. The original annual (prior August to current season July) KRS reconstruction was based on two tree-ring chronologies, Zuun Mod and Urgan Nars (Table 6.1), and was highly significant and valid (Pederson et al. 2001). The original tree-ring model was calibrated and validated using stream flow data from the Choibalsan hydrological station from 1947 to 1994 and resulted in a streamflow reconstruction that spans 1651–1995 and explains 48% of the variance in the instrumental streamflow data. Results from Pederson et al. (2001) showed that there was less variability in the mid to late 19th Century and more flow variability in the 18^{th} and 20^{th} centuries, and that there were more frequent and extended wet periods in the 20^{th} century.

Here KRS has been updated (using the same methods as described in Pederson et al. 2001) to include six new chronologies (Table 6.1) that were sampled following publication of Pederson et al. (2001). Although the variance explained by the updated model is the same (48%) and the time-span is not extended (1651-1994), the reconstruction is improved by having more replication and spatial coverage and shows valid calibration and verification statistics (Table 6.2, Figure 6.2). Table 6.1 shows the chronologies used to update Kherlin River streamflow. A comparison of the original and updated Kherlin River streamflow reconstructions is shown in Figure 6.3. The original reconstruction had a decimal point error and was off by one decimal point, which has been corrected here. For example, the variation in the original reconstruction ranged from 0-500 M^3/sec, but should have ranged from 0-50 M^3/sec. The original and updated Kherlen reconstructions are quite similar (R= 0.9), and show very similar interannual and decadal patterns. The fact that the model has not changed very much, even with the addition of six new tree-ring chronologies demonstrates that the original model (based on only 2 chronologies) represented the Kherlen river basin quite well. The biggest difference between the models is the mean streamflow. The updated reconstruction has a lower mean (18.4 m^3/sec) streamflow than the original (23 m^3/sec). The original Kherlen River streamflow reconstruction may have been overpredicting streamflow.

6.2 Moisture patterns across Mongolia

Figure 6.4 is a graph of all four reconstructions created for this dissertation. 6.4 (a) is the All-Mongolia PDSI reconstruction (Chapter 5), 6.4(b) the far western Mongolia PDSI reconstruction (Chapter 4), Figure 6.4 (c) the Selenge streamflow reconstruction (Chapter 3) and 6.4 (d) the updated Kherlen streamflow reconstruction (described above). Evaluation of the three regional reconstructions (Chapter 3, 4 and Kherlen update) and one large-scale reconstruction (Chapter 5) may reveal spatial patterns of drought across Mongolia.

Only two reconstructions extend past the 1600s, All-Mongolia and Far-West PDSI. Both of these reconstructions show a very dry period during 1578-1582 and again at 1600-1604. An analysis from lake sediments from the Altai Mountains in Mongolia also shows drought from 1580-1600 (Kalugin et al. 2005). From 1640 to about 1646 there was an extremely dry interval for all reconstructions that extend back that far, including All-Mongolia, Far-west and Selenge (Figure 6.4). This drought has also been identified in central China (Zhang et al. 2008) and coincides with the collapse of the Chinese Ming Dynasty (Fang et al. in press).

The three regional reconstructions show a high degree of variability in the 1700s, particularly Selenge and Kherlin. The wettest period for Kherlin Streamflow is around 1720 and is followed by very dry conditions in the1730s. Selenge streamflow shows a very wet interval in the 1750 and 60s, followed by extremely dry conditions in the 1770s and early 1780s, and shows extreme wet conditions again in the 1790s to early 1800s.

The wettest period of the entire reconstruction (1794-1798) is followed by severely reduced flow in the early 1800s (Table 6.3 & 6.4, Figure 6.4).

Reduced variability is evident in the 1800s in the Kherlin streamflow reconstruction (Pederson et al. 2001) and in the All-Mongolia reconstruction. Decadal length low flow periods are reconstructed for the Selenge during much of that century. The top ten 5-year dry and 5-year wet intervals for all reconstructions are listed in Table 6.3 & 6.4.

6.3 20th Century Warming

What are the affects of increasing temperature in Mongolia on tree-growth? Figure 6.5 shows recorded temperature from 1900 and, Figure 6.7 (Chapter 2) shows inferred Mongolian temperatures for the past 1700 years (D'Arrigo et al. 2001). Both show that the temperatures in the later half of the 20th Century, particularly after the 1980s, are unprecedented. The only trend seen in the reconstructions, during the 20th Century, is the increasing moisture trend in far western Mongolia (Chapter 4). As explained in Chapter 4, this may be a result of changes in the Siberian High pressure system allowing for increases in westerly airflow which could bring more moisture to the mountain and plain regions of middle Asia (Aizen et al. 2001).

Many of the reconstructions stop in the mid 1990s, prior to when the highest temperatures (Figure 6.5) and most severe droughts (Figure 6.6) occurred (1999-2002 and 2004-2005). Although there may be tree-ring sites that extend to 2000, for example, the reconstructions are limited by the common period of all chronologies (which can often be the 1990s). All reconstructions show drought in the early 1980s, however, no significant trends are seen in the Kherlen (east) and Selenge (central) reconstructions in the 20th Century (Figure 6.4).

Evaluation of the chronologies that extend to 2000, and are growing in regions that were the most drought effected, (Figure 6.7 and described in more detail in Chapter 5) have severely limited tree-growth during the driest years (~1999-2002). In Chapter 5, a forward nest (1994-2000) using these trees produces an acceptable model that captures the 2000 droughts, however the actual average PDSI for the country is attached to the reconstruction rather than the forward nest (explained in detail in Chapter 5). The all-Mongolia PDSI reconstruction (Chapter 5), gives the 2000 droughts a long-term perspective and shows that they may have been the driest of the past ~500 years and occur during an extremely warm period. Evidence of these droughts (severely small annual rings) is present in newly sampled trees (summer 2009) near the capital of Mongolia, Ulaan Baatar (N. Pederson personal communication).

6.4 Spectral/multi decadal climate variability discussion:

Decadal-scale periodicities in the 11 and 22-year range are often found in paleoclimatic records from regions that are continental (Cook et al. 1997, Zhang et al. 2008). These periodicities are attributed to solar cycle variations (Cook et al. 1997, Zhang et al. 2008). In fact, all four tree-ring reconstructions created for this study (Selenge, Far-West, Kherlen Update and All-Mongolia) show significant spectral periodicities in or near the solar range (Hale 1924) at 11 and 22-years.

Paleoclimate records also appear to be recording periods of low solar activity (Esper et al. 2001, Zhang et al. 2008), referred to as the Little Ice Ages (LIA) which occurred in the Northern Hemisphere at ~1570, ~1730, and for much of the 19th Century (Bradley & Jones 1993). The problem is however, that although these patterns are found in the paleo-records (and appear to be forced by solar variation) there is no physical link between the sun and the response of the various proxies (Rind 2002). In other words, many tree-ring records show quasi-solar periodicities (Cook et al. 1997), even when the meteorological data does not. Rind (2002) suggests UV irradiance variation and it affects on ozone in the stratosphere as one possible explanation for this discrepancy. How solar variation influences tree growth is an interesting and unanswered question. But it is clear that 11 and 22-year periodicities are persistent and found in trees in continental regions of the Northern Hemisphere and that solar influence cannot be ruled out.

The causes for multi-decadal variation in climate records for Mongolia (and many other regions of the world for that matter) are not fully understood. There is evidence of solar influence (as discussed above) and there are also significant periodicities in the ENSO range (2-7yrs) (Pederson et al. 2001, Davi et al. 2006, Davi et al. 2009). Eastern Mongolia and regions in NE China show significant correlations with SSTs and the Asian Monsoon (Li et al. 2007). Decadal-scale variability and possible forcing of that variability is gaining interest in the climate modeling community and is considered a 'frontier in climate science' mainly because our understanding of the physical mechanisms and teleconnections that drive climate are still developing (Goddard et. al

2009). Managing potential impacts from changes that will occur in the next 10 to 20 years is not only more immediate and urgent from the public's point of view, but also more actionable from the perspective of policy and decision makers.

6.5 Future Changes

One of the most pressing climate issues in Mongolia is large-scale and significant changes in temperature. These changes could affect regional and seasonal climate, the environment, agriculture and society. Temperature sensitive tree-ring chronologies from Mongolia show that the 1990s were extremely hot compared to the prior 1700 years (D'Arrigo et al. 2001, Jacoby et al, in press). Not surprisingly, some impacts of climate change can already be seen in Mongolia: increasing intensity of Zuud (described in Chapter 1) related climate events (although that has not yet been quantified and would be very difficult to do so as "Zuud" is a fairly loose term), significant impact on natural zones, water resources, snow cover, and permafrost (Batima et al. 2006). Other possible impacts of climate change are increased desertification and dust events, changes in growing season length, and heat-wave duration.

The IPCC 4th Assessment Report (Christensen et al. 2007, Chapter 11) shows that temperatures are predicted to continue to warm throughout Asia through this century, the rate at which depends upon which emissions scenario is followed. Also, precipitation is predicted to increase throughout Mongolia as higher temperatures will result in a higher capacity of the atmosphere to hold water vapor and a general intensification of the global hydrological cycle. If true, an increase in climate variability (possibly more storms) could result, with more intense droughts and precipitation. For June-August, the time when there is the most precipitation in Mongolia, models show the largest variability and uncertainty. The ensemble models do not agree on Mongolian JJA precipitation trends (Figure 6.8).

A study that focuses specifically on Mongolia (Batima et al. 2006) uses scenario runs from IPCC's 3rd Assessment Report "AR3" model (Nakicenovic et al. 2000). This model is based on three coupled GCMs (HadCM3, ECHAM3, and CSIRO Mk2) that analyzed the response to the middle forcing scenarios A2 and B2 for 30-year time periods (2020s, 2050s, and 2080s) relative to the climatological baseline period 1961-90. By comparing observed temperature and rainfall data from 1961-90, with modeled results, they validated the GCM models and found that the HadCM3 GCM gave the closest result to observed data. This model shows that: 1. Future warming will vary from 0.9 C to 8.7 C, while summer temperature increases vary from 1.3 C to 8.6 C. 2. Winter precipitation will increase by between 13 per cent and 119 percent when the summer rainfall varies from 3 percent decrease to 11 percent increase. 3. Evapotranspiration is expected to increase, due to warmer temperatures, by 13-91 percent, depending on ecosystem regions. The IPCC's 4th Assessment Report (AR4) released in 2007 has not yet been evaluated.

Sato & Kimura (2006) apply dynamical downscaling using a regional climate model technique to evaluate future regional-scale climate change in Mongolia (2071-2080). Similar to the two studies described above, their model results indicate that temperature continues to rise over all of Mongolia in every season. They also find that precipitation decreases during the warm season, particularly where the sources of major rivers are located in central Mongolia.

6.6 Climate Forecasting

a. Institute for Hydrology and Meteorology (IHM)

Roughly half of Mongolia's population is nomadic herders. Seasonal forecasting, if successful, could help the herders prepare for the upcoming herding season. Climate predictions are often difficult in regions such as Mongolia that are far away from ocean influence (Goddard et al. 2001). The scarcity of meteorological data also adds to the difficulties of prediction. The main source for current climate information and forecasts for Mongolia comes from the Institute for Hydrology and Meteorology (IHM) in the Ministry of Nature and Environment (http://www.env.pmis.gov.mn/Meteoins). IHM provides hourly, five day, weekly, monthly, seasonal and decadal forecasts. A lead-time of one to five days is usually possible for IHM to issue warming messages about upcoming anomalous climate events (Swift& Bass 2007). It is not possible to evaluate the forecast models because information about the forecast are written in Mongolian. A study that evaluates the forecasting system states that the Mongolian forecasts provide good warning of sudden events (Swift & Baas 2007).

b. International Research Institute for Climate and Society (IRI)

The International Research Institute for Climate and Society (IRI) also produces seasonal forecasts for Asia, and the rest of the world, starting in 1997 and extending to the present. Predictions give percent likelihood that an event will either be above normal, near normal or below normal. These predictions are based on A) coupled ocean-atmosphere model predictions of tropical Pacific SST, B) forecasts of the tropical Indian and Atlantic oceans, and C) global atmospheric circulation model (GCM) predictions of the atmospheric response to the present and predicted sea-surface temperature patterns.

The precipitation forecast from IRI for the summers of 2000, 2001 and 2002 (the most extreme drought years on record (Figure 6.6)), did not predict drought, although the validation for those same years did show dry anomalies. The summer of 1999 was anomalously warm (Figure 6.5), a feature that was partially captured by the IRI seasonal forecasts, which predicted a higher percent likelihood that southern Mongolia would have higher temperatures. 2000 was also an anomalously hot year, and the forecast did not favor any particular climatological category. These models predicted that there would be an enhanced probability for above normal temperature (25%-30%-45%) in northern China and southern Mongolia in summer 2001 and although the meteorological data confirms this as true, the validation maps for IRI show no data.

c. Climate Communication

Even if Mongolia had excellent forecasting abilities, communicating those forecasts to people in the countryside is a major problem. These forecast can be vital for climate 'readiness' of herders. People that live near cities can communicate, as much of the rest of the world does, via cell phone or text message. But out in the countryside, it is not possible to get reception. The main form of communication there is the short-wave radio, although many of the nomads do not have radios and rely on face-to-face communication with local officials, which is often too late to prepare for climate disaster (Swift & Baas 2007).

The UNs International Strategy For Disaster Reduction proposed the E-Soum project (E-Soum proposal draft 2005) as a solution to the communication problem. The main objective is to ‘bring advances of modern digital information technology to rural Mongolia’, mainly by building digital service centers that provide regular information about ‘weather, climate, physical parameters of pasture and crop fields, yields, vegetation and biomass. At present, there is no follow-up information about this project.

6.7 Climate Adaptation and Mitigation

When snow covered pasturelands during the winters of 1999-2000 and 2000-2001 it blanketed the already drought depleted grasslands, making it difficult for animals to forage. This resulted in widespread livestock loss for Mongolia - as much as 40% of the nation's livestock (Helminen 2002). This widespread devastation led to international interest and support in Mongolia for climate related risks (described below).

a. Netherlands-Mongolia Trust Fund for Environmental Reform (NEMO)

In 2005, the World Bank’s Netherlands-Mongolia Trust Fund for Environmental Reform (NEMO) program was established with a mission to strengthen and advance natural and environmental resources, and to reduce poverty and expand economic development. In 1998, 114 ecological macro-plots were established in four representative ecological zones. Although this study is ongoing and unpublished, a recent press-release (NEMO

2009) summarized preliminary results. It finds that pasture quality is declining at an alarming rate, which may leave herders even more vulnerable to climate change. Plots from the Gobi Desert region and a forest-steppe region show that the total number of plant species that comprise forage have declined by more than 33% over an 11 year span (1998-2009), while bare soil and rock have increased. Rangeland productivity also declined on winter and transition rangelands. Productivity increased in the summer, however this was a result of the increased presence of plant species that animals do not eat. Declining pasture quality is thought to be a result of two forces, increased pressure on rangelands due to increased livestock numbers (particularly cashmere goats), and climate change. The final report is due out at the end of 2009.

b. Pilot Index-Based Insurance

Index-Based Insurance (PIBI) is a pilot program (2006-2009) in Mongolia that may help herders alleviate some of the financial risk from climate related livestock deaths (Mahul & Skees 2006 & 2007). Traditional agriculture insurance is not possible in Mongolia mainly because it is too hard to do any type of monitoring, where the insured are mainly nomads with high risks of extreme livestock loss due to harsh conditions. Weather based insurance is also not feasible because the weather monitoring system in Mongolia is under-funded, stations are very far apart, and the climate dynamics of Zuud are complicated.

In 2006 a risk management model designed by the Work Bank was used to start the PIBI program. It is a collective system, where indemnity payments reflect the loss of herders in a given area (like an indicator herd or a canary in a coal mine). A payment is made whenever the adult mortality rate (on this particular indicator herd) exceeds a certain threshold (6% a year) determined by the National Statistical Office of the Government of Mongolia. Therefore there is a strong incentive for herders to manage the herds because if a period is deemed an 'event', they all receive the same payment whether or not the animals survived. There are 33 years of mortality data by county for five different species, which is critical for actuarial information and understanding costs and losses.

PIBI is a layered public-private system, where the herders retain high-frequency, low-severity losses (once every 5 years) that do not affect the viability of their businesses (self-insurance). The larger losses are covered by private insurance (between 6-30% loss/yr) that are expected to occur once every 5 to 25 years. Catastrophic loss, occurring once every 25 years or more, which would be too costly for the domestic insurance industry, would be transferred to the government (social insurance) (30% +), which has access to international assistance.

Herders have the option to buy the private insurance (covering between 6-30% loss) and/or pay a small fee for the catastrophic insurance (losses over 30%). A recent email communication between myself and the founder of the PIBI program (Dr. J. Skees) resulted in the following unpublished information (the following 6 bullets):

- Herders are paying USD $45 on average (per capita income (2001)= USD 1770$).
- These are relatively small herders having about 135 animals on average (it takes 200 to sustain a family).

- They are purchasing only about 30% of the value of the animals that they insure and many herders select only a couple of species.
- Nearly 20% of the herders in the first 3 provinces are now buying insurance.
- The program will expand from 4 to 9 provinces next year.
- By 2011, it will be a national program.

As of summer 2009, the program has been considered a success with four insurance companies participating. As much as 14% of herders were covered by the insurance in the pilot provinces in 2008 (Hellmuth et al. 2009).

Although the program has been successful there are major challenges, including:

- An imperfect match between losses and payout.
- Reaching and educating herders about the products.
- Transparency of information.
- Confidence in calculations of Indemnities.
- Fraud.
- Significant financial exposure for a nascent industry.

One complicating factor for index based insurance is that some of the calculations are based on the 33 years of historical livestock mortality rates and in a changing climate, particularly Mongolia, it is very possible that future catastrophic events will have a different frequency and magnitude (as already demonstrated in the meteorological record (Batima 2006)). Mongolia temperatures are rapidly increasing and the highest degree of climate variability and subsequent livestock losses occurred in the current decade and the 1990s.

6.8 Conclusions

It is very likely that the climate of Mongolia has already undergone significant climate and environmental changes that have had huge impacts on the people of Mongolia and the economy. Model results suggest that these changes are predicted to continue. Temperatures are likely to continue to rise, but there is less certainty with regard to summer precipitation. Models (Christensen et al. 2007) suggest that climate variability will increase with rising temperatures. The much higher than average temperatures of the late 1990's (Figure 6.5) were followed by extreme droughts (Figure 6.6), that were some of the driest years of the past nearly half millennium (Chapter 5). With continued temperature increases, increased climate variability is expected, and it is possible that droughts of this magnitude could happen more frequently.

At present, it is not possible to evaluate the IHM early warming and climate forecasting systems. The IRI prediction maps did not capture the severity of the 1999-2002 drought event. Complicating the already difficult job of producing climate forecast in central Asia (away from most oceanic influence) is the poor quality of the meteorological data. Significant steps have been taken to evaluate climate risks in Mongolia (NEMO described above) and to develop an index-based insurance program. Such programs have had success insulating nomadic herders financially from climate related livestock losses (as described above, the payouts to herders are based on death rates, not on climate forecasts or events).

Tree-ring records provide not only information about inter-annual scale variability, but also decadal and centennial scale variability, a scale that is not possible from the limited instrumental records in Mongolia. Perhaps decadal to centennial scale information from tree-ring records could be incorporated into climate models to improve future forecast and predictions. Using tree–ring reconstructions to fill in the gaps and extend the meteorological data, and develop a better understanding of prolonged drought and extreme winter weather (e.g. Zuud) and climate cycles, could greatly aid in developing future climate predictions for the people of Mongolia.

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TABLES

Table 6.1. Original and new tree-ring chronologies used for the Kherlen River streamflow reconstruction.

Sites	Lat. (N)	Long. (E)	Elevation (m)	*Species*	Time Span	# Trees
Dadal	49° 00.607'	111° 35.433'	1020	*Pinus sibirica*	1704-2001	15
Urgan Nars*	48° 34.62'	110° 32.75°	1070	*Pinus sylvestris*	1651-1996	17
Manzshir Hiid	47° 45.96'	106°59.72'	1755	*Pinus sibirica*	1505-1994	15
Onon Gol	48° 49.633'	111° 41.174	1012	*L. sibirica*	1576-2001	16
Terelj old	47°54.39'N	107°26.58'	1565	*Larix sibirica*	1798-1994	16
Terelj Nuur	47° 48.686	107° 21.195	1510	*Larix sibirica*	1603-2000	9
Terelj pass	47° 57.709	107° 27.528	1590	*Larix sibirica*	1652-2001	7
Zuun Mod*	47° 47.002'	107° 30.12	1448	*Larix sibirica*	1582-2000	18

* Used in original Kherlen Streamflow reconstruction.

Table 6.2. Calibration/Verification model for an updated Kherlin River streamflow, dendroclimatic year (previous August through current July) based on additional tree-ring chronologies (see text). The adjusted *r*2 = variance explained adjusted for loss of degrees of freedom.

	1948-1970 Calibration	1971-1994 Verification	1971-1994 Calibration	1948-1970 Verification	1948-1994
Variance Explained	67	---	48	--	49.62
Adjusted r2	.64	---	45.1	--	0.473
Pearson correlation coefficient	0.820	0.661	0.689	0.777	
Reduction of error	0.673	0.367	0.475	0.409	
Coefficient of efficiency	0.673	0.362	0.475	0.399	
Sign test	20+ 3-	18 +6-	20+ 4-	20+ 3-	

Table 6.3. Top 10 dry 5-year non-overlapping periods.

All-Mongolia PDSI	Selenge River	Far West PDSI	Kherlin River
2000-2004*	1779-1783	1755-1759	1732-1736
1600-1644	1854-1858	1882-1886	1943-1947
1578-1582	1862-1866	1600-1604	1928-1932
1521-1525	1736-1740	1642-1646	1771-1775
1880-1884	1901-1905	1793-1798	1696-1700
1600-1604	1696-1700	1838-1842	1903-1907
1735-1739	1640-1644	1821-1825	1791-1795
1977-1981	1927-1931	1688-1692	1851-1855
1821-1825	1809-1813	1588-1592	1722-1727
1779-1783	1821-1825	1578-1582	1876-1880

*Data from 1994 to 2005 are from averaged JJA PDSI.

Table 6.4. Top 10 wettest 5-year non-overlapping periods.

All-Mongolia PDSI	Selenge River	Far West PDSI	Kherlin River
1955-1959	1794-1798	1741-1745	1718-1722
1612-1616	1764-1768	1993-1997	1761-1765
1915-1919	1917-1921	1943-1947	1917-1921
1762-1766	1990-1994	1739-1743	1908-1912
1990-1994	1798-1802	1740-1744	1700-1744
1916-1920	1751-1755	1742-1746	1959-1963
1716-1720	1671-1675	1992-1996	1934-1938
1934-1938	1955-1959	1999-2003	1810-1814
1751-1755	1799-1803	1683-1687	1738-1743
1785-1789	1962-1966	1957-1961	1687-1691

FIGURES

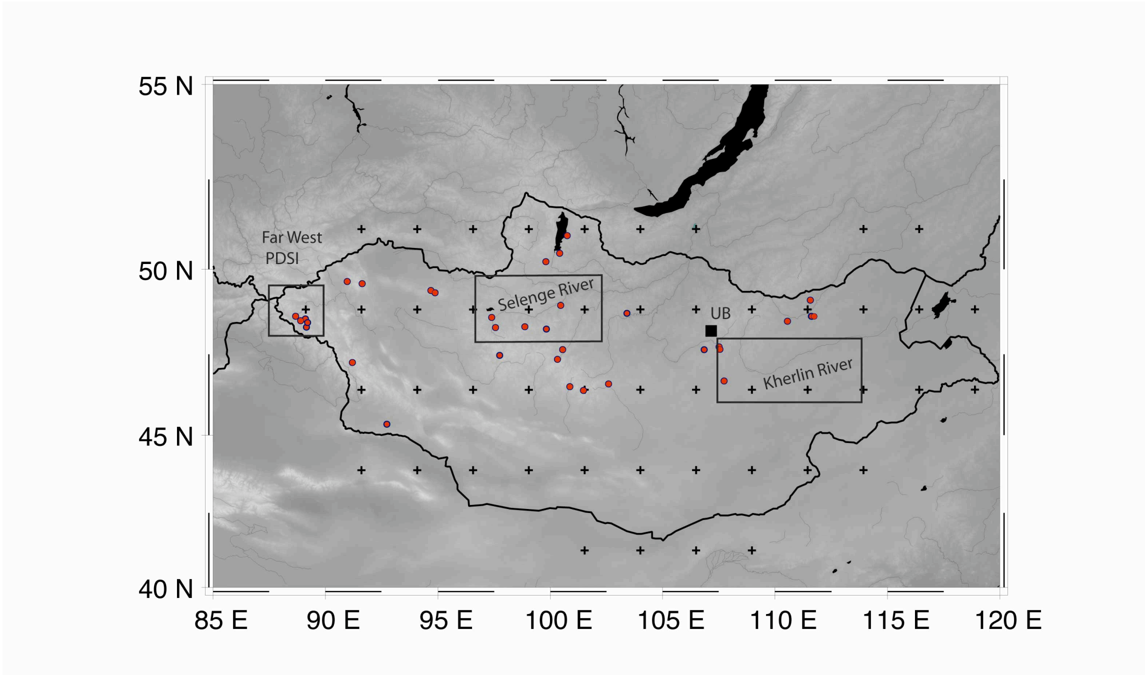

Figure 6.1. Map of 48 PDSI gridcells over Mongolia (crosses). Also shown are locations of the 34 tree-ring sites tested for modeling (red dots). Previously published regional study areas are boxed; Far west Mongolia (Davi et al. 2009), Selenge River (Davi et al. 2006), and Kherlen River (Pederson et al. 2001). The capital of Mongolia, Ulaan Baatar (UB) is shown as a square.

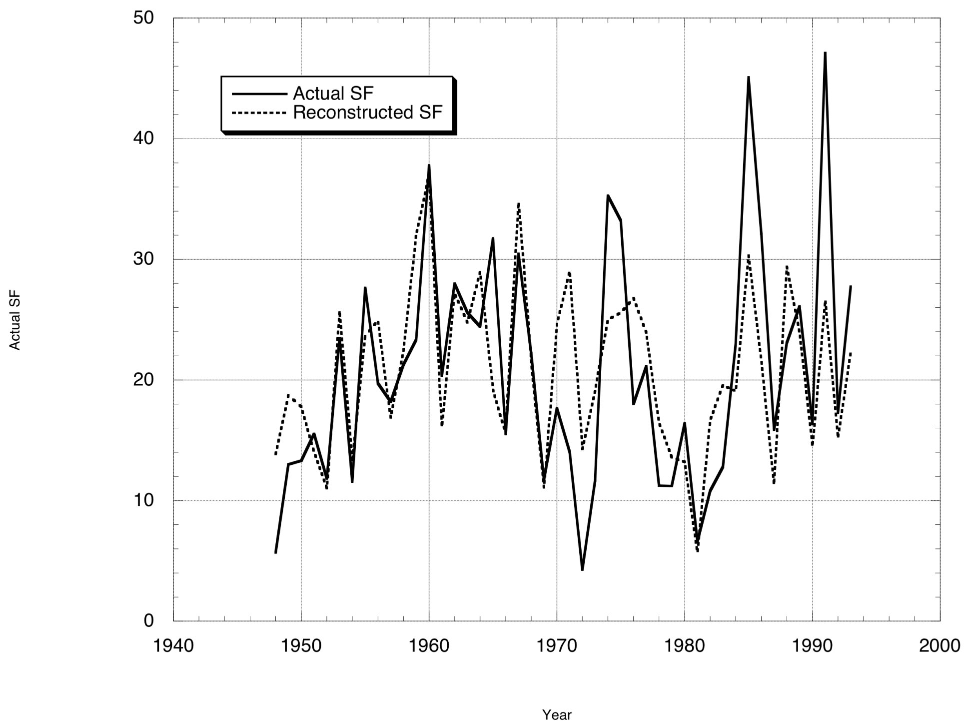

Figure 6.2. Actual Kherlen River streamflow (solid line) graphed with reconstructed (dashed line) streamflow based on tree-rings.

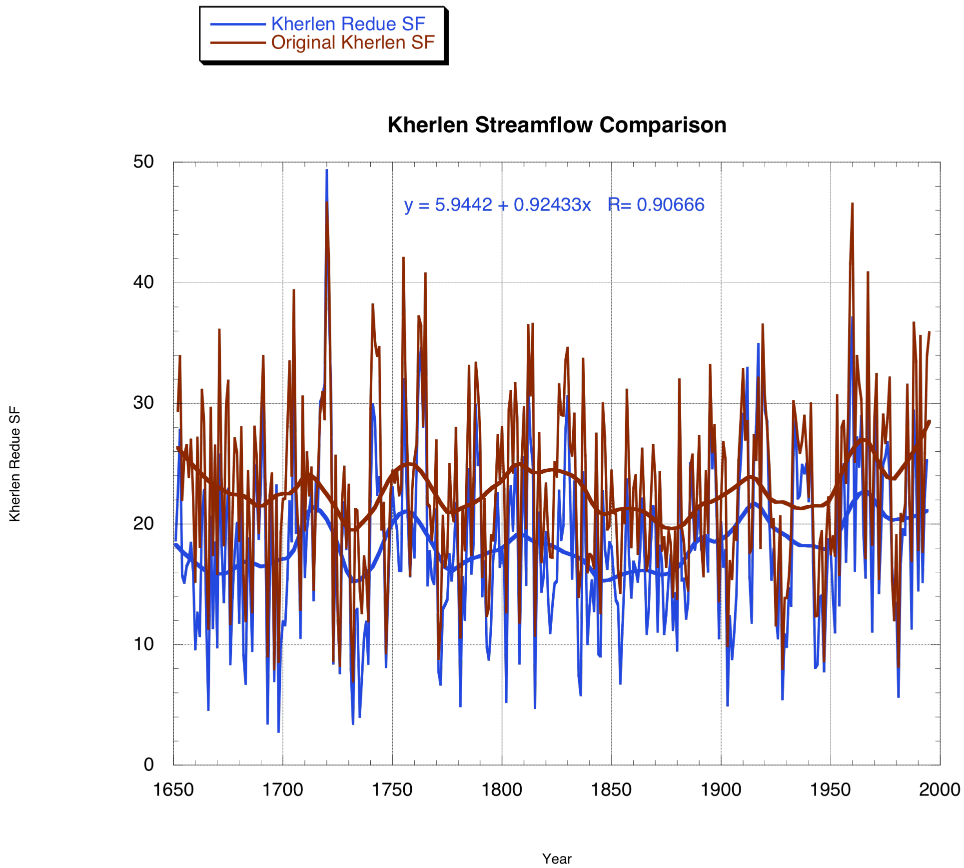

Figure 6.3. Original Kherlen River streamflow reconstruction (red) from Pederson et al. (2001) compared to an updated version (blue). The updated version includes the original 2 tree-ring chronologies and additional 6 chronologies.

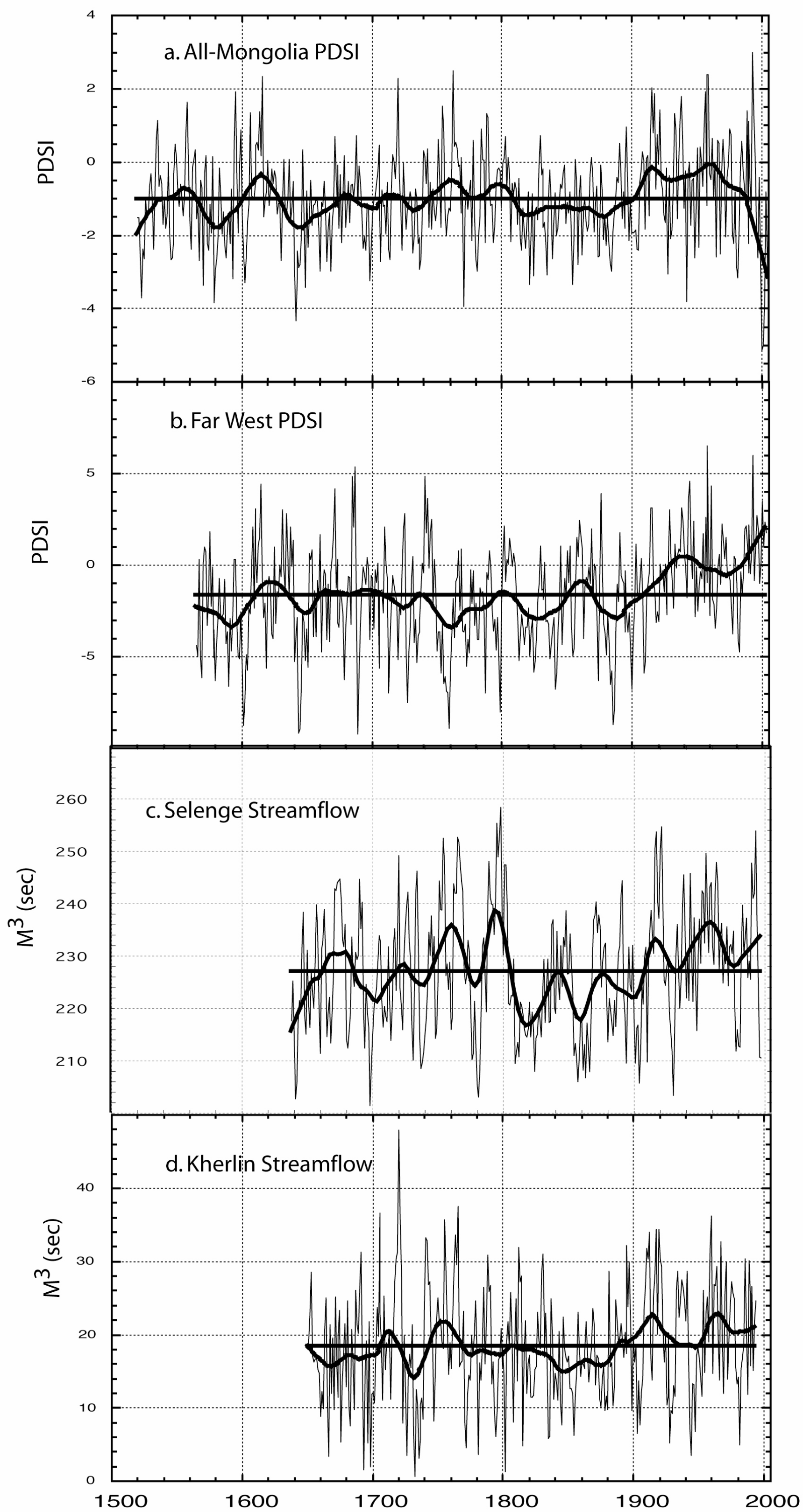
a. All-Mongolia PDSI
PDSI
4
2
0
-2
-4
-6
b. Far West PDSI
PDSI
5
0
-5
c. Selenge Streamflow
M3 (sec)
260
250
240
230
220
210
d. Kherlin Streamflow
M3 (sec)
40
30
20
10
0
1500
1600
1700
1800
1900
2000

Figure 6.4. Mongolian drought reconstructions created for this study. 4a. All Mongolia PDSI (Chapter 5), 4b. Far west Mongolia PDSI (Chapter 4), 4c. Selenge River streamflow (Chapter 3) and 4d. Kherlin River streamflow (Pederson et al.2001: updated for this dissertation).

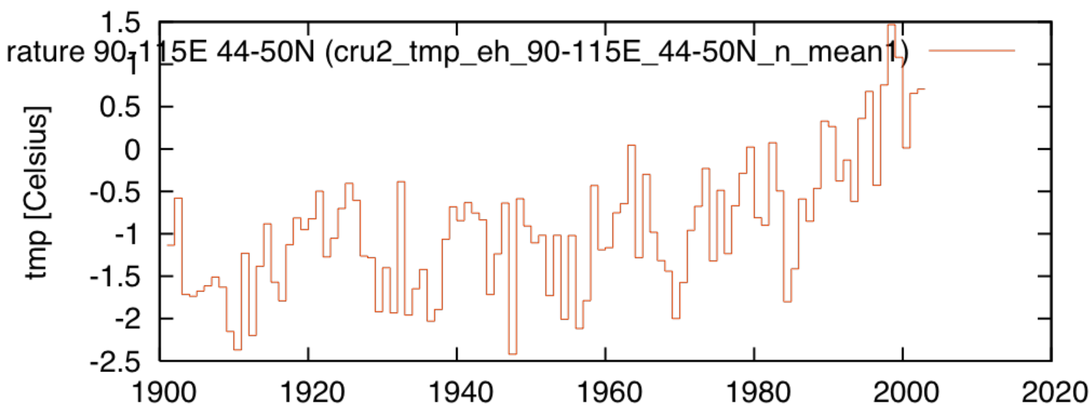

Figure 6.5. Annual average temperature anomalies from 90-115E and 44-50N. Interpret pre-1950s data with caution as there is extremely limited meteorological data at that time. Generated from The Royal Netherlands Meteorological Institute's (KNMI) Climate Explorer (Oldenborgh et al. 2009).

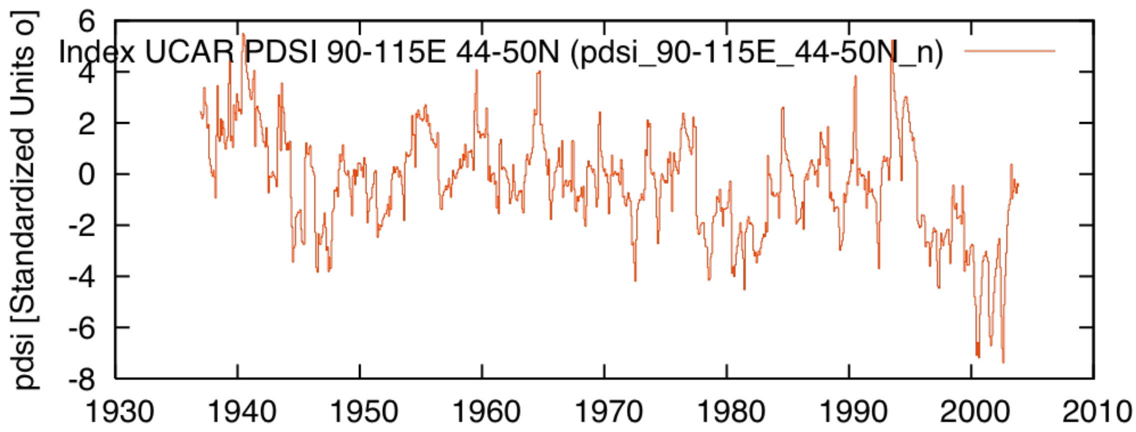

Figure 6.6. Average annual PDSI anomalies from 90-115E and 44-50N. Interpret pre-1950s data with caution as there is extremely limited meteorological data at that time. Generated from The Royal Netherlands Meteorological Institute's (KNMI) Climate Explorer (Oldenborgh et al. 2009).

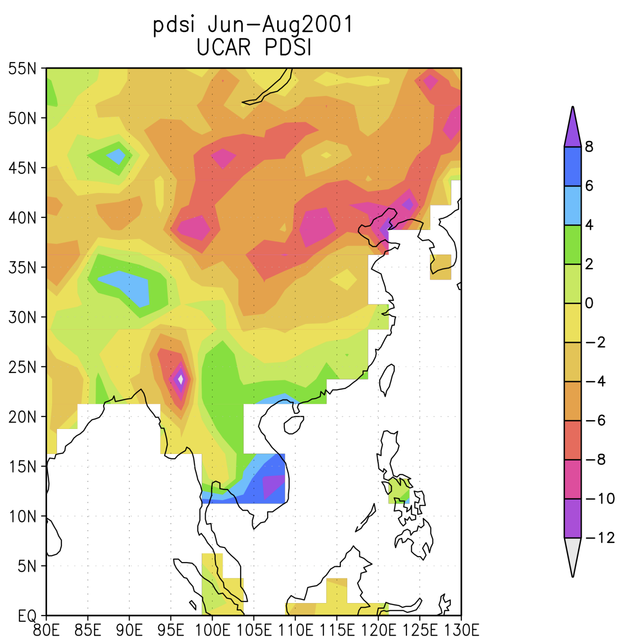

Figure 6.7. PDSI values for summer 2001. Anything below a -3 is considered a drought. Generated from The Royal Netherlands Meteorological Institute's (KNMI) Climate Explorer (Oldenborgh et al. 2009).

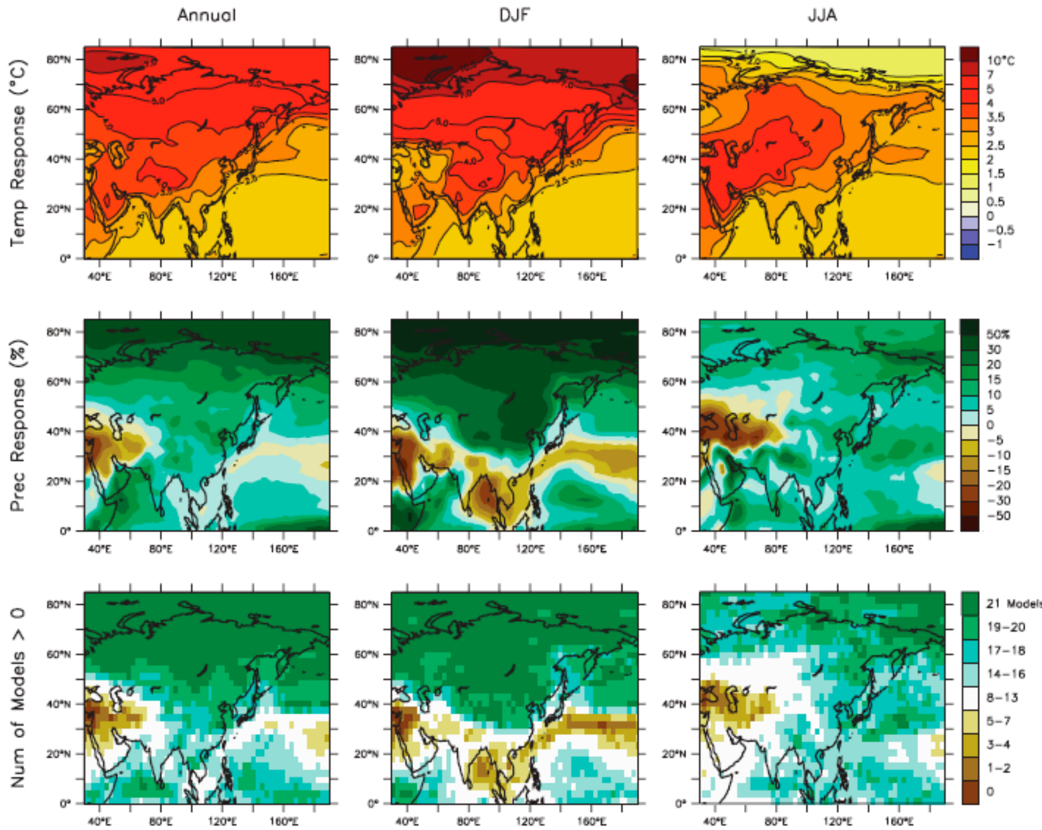

Figure 11.9. *Temperature and precipitation changes over Asia from the MMD-A1B simulations. Top row: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation.*

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Figure 6.8. (Figure 11.9 from IPCC 4th Assessment Report (Christensen et al. 2007), Chapter 11). 'Temperature and precipitation changes over Asia from the MMD-A1B simulations. Top row: Annual mean DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation.' Bottom right panel shows JJA precipitation. Roughly half the models project more precipitation and half don't.

CHAPTER 7. CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

Reconstructed hydrological variations, the focus of this dissertation, have supplemented and extended the limited meteorological records for central (1637-1997) (Chapter 3), and western Mongolia (1565 -2004) (Chapter 4). An all-Mongolia drought reconstruction that utilizes the large-scale network of tree-ring chronologies, collected over more than a decade, was created and spans 1520-1993 (Chapter 5). These reconstructions are used to reveal the full range of past drought variability (patterns, periodicities, duration and severity), a range that is much larger than what is captured in limited instrumental records.

In Chapter 3, streamflow (1637-1997) for the Selenge River Basin in central Mongolia is reconstructed based on five tree-ring chronologies (Figure 7.1). The Selenge River is the largest river in Mongolia, a major source of freshwater, and a major input into Lake Baikal in Siberia. The tree-ring based model explains 49% of the recorded streamflow variation (In the grand scheme of dendroclimatology, tree-ring models generally explain anywhere from 30-60% of the variance). Spectral analysis shows peaks in the Pacific Decadal Oscillation and El Nino Southern Oscillation range (4 yr (99% significance) and 5–6 yr (90% significance). There is also spectral power in a quasi-solar range (Hale 1924) of about 22–24 yr (95%), and for Khorgo Lava, one of the five sites used for reconstruction, there is some power in the lunar-nodal range of about 16–19 yr (90%–95%). Evidence of power in the range of PDO variations of 35–50 yr is also present (99%). In the 20th century there is no increasing or decreasing trend seen in streamflow.

In western Mongolia (Chapter 4), a particularly sparse region for meteorological data, three tree-ring chronologies are used to reconstruct and extend a grid-cell of Palmer Drought Severity Indices (Dai et al. 2004) (Figure 7.1). The regression model resulted in a reconstruction of PDSI that extends from 1565 to 2001 and explains 41% of the drought variation. This region of western Mongolia shows a trend of increasing moisture starting in the beginning of the 20th century, which is consistent with observations and other proxy data and may be related to a weakening Siberian high and strengthening of westerly airflow (Aizen et al. 2001).

The driest year of the tree-ring based PDSI reconstruction is 1690 (-4.0 standard deviation (SD)), followed by 1646 (-3.9 SD) and 1760 (-3.8 SD) (Table 3). The 1690 drought was quite widespread, as also seen in paleoclimatic records for northwest China (Li et al. 2006), eastern China (Zhang 2005), and the Altai Mountains of southern Siberia (Kalugin et al. 2005). The mid-1700s show extreme variation: 1741-1745 is the wettest 5-year period, 1739-1746 being extremely wet, followed by the driest period 1755-1759, staying extremely dry until 1761. Extreme drought years and extended drought periods occur fairly regularly prior to the 20th century. Spectral analysis shows significant peaks in the quasi-solar range --22 (99%) and 11 (90% years) which has been shown in other hydrometeorological reconstructions in Mongolia (Pederson et al. 2001, Davi et al. 2006). Periodicities in the 7 and 5.5 year range (99%) are within the range of variability of the North Atlantic Oscillation (NAO) and ENSO, respectively.

In chapter 5, a network of tree-ring chronologies (34) that span the country are used to create an All-Mongolia summer drought reconstruction (Figure 7.1a). Nested model methods are used in order to create the longest reconstruction possible (1520-1993). The most replicated period (1703-1993) explains 61% of the PDSI variance and demonstrates valid calibration/verification statistics (Chapter 5: Table 5.2, Figure 5.3). This reconstruction shows that the 2000 droughts in central and eastern Mongolia were extremely dry compared to the past nearly 500 years. An extremely dry period was also reconstructed for the 1640s and reached as far as central China. Other extremely dry periods are found from 1578-1582, 1600-1604, 1735-1739, 1779-1783, 1821-1825, 1880-1884, and 1977-1981. Significant periodicities are found at 2.8 (99%), 6.4-7.2 (95%), 11.6 (95%), 19.3 -25 (99%) and 40 years (90%).

7.2 Future direction

The development of a large-scale network of drought sensitive tree-ring chronologies spanning Mongolia, allows for more detail about spatial patterns of drought through time. This network will be used for exactly that purpose, in the following current and/or future studies:

a. Monsoon Studies

The all-Mongolia drought data set, 34 chronologies, has been incorporated into two large-scale climate studies in China and Mongolia (Li et al. submitted & Fang et al. submitted). Each paper explores the spatial patterns of drought for all of China and Mongolia. I am the 4th author on the Li et al. paper and the 2nd author on the Fang et al. paper, and have contributed to and edited each manuscript.

The data has also been contributed to Dr. Ed Cook, the director of the Tree-Ring Laboratory (TRL) at Lamont-Doherty Earth Observatory, for a large-scale, tree-ring based Asian Monsoon Drought Atlas study. This monsoon study will incorporate tree-ring data from across Asia, contributed by several scientist at the TRL, in order to produce a gridded PDSI reconstruction (2.5 x 2.5 °) for all of Asia (similar to the North American drought reconstruction by Cook et al. (1999)).

b. Mongolian PDSI reconstruction

I plan to use the gridded Mongolia PDSI data from the above monsoon study to evaluate the spatial components of drought though time and the possible internal forcings such as ENSO, NAO, the Asian Monsoon, and pressure anomalies. Previous studies are regional and reconstruct different variables (streamflow, precipitation or PDSI). Having a uniform drought parameter across the county (PDSI) would aid greatly in understanding and visualizing the spatial and temporal complexities of drought and the possible forcings.

c. Zuud

The Zuud, as described in Chapter 2, typically refers to drought in the summer followed by a cold or snowy winter that limits herd access to grasslands. These Zuuds often result in widespread livestock losses. It may be possible to create an index of Zuud using the tree-ring network developed for this dissertation in combination with livestock mortality data (Jerry Skees, personal communication) and snow data (from satellites). There is recorded snow data in Mongolia, but access to it is extremely difficult (Batarbileg

Nachin, Director, Department of Forestry, National University of Mongolia, personal communication). Gridded snow data from NOAA (1967-present) may be used as a substitute. A comparison of livestock mortality data, snow data, and recorded or reconstructed climate reconstructions might make it possible to develop a deeper understanding of Zuud and the atmospheric conditions that generate it.

7.3 Strengths and limitations of tree-ring studies

The strength of tree ring records--and all paleoclimatic records--is that they give us a long-term perspective of climate and climate change. Trees can live a long time. At some tree-ring sites in Mongolia, we found trees that were considerably more than 600 years old. A long-term perspective of climate and climate change is particularly important in countries such as Mongolia because reliable meteorological data goes back only 60 years (i.e., the 1940s). The 2000 droughts (chapter 5) were quite extreme and unusual in the context of the past nearly 500 years.

Tree-rings differ from most other paleoclimate records because they are exactly-dated and have annual to seasonal data resolution. The whole science of dendrochronology depends on the correct dating of each ring, from every core of every tree. Because trees cores have high resolution and extend to the present, it is possible to determine the strength of the climate signal in the trees by comparing them with monthly meteorological data. For example, the All-Mongola PDSI reconstruction (Chapter 5) explains 61% of the PDSI variation over the common period of the trees and recorded data (1951-1993). This is a very robust model and explains a fairly high amount of variation, given that a tree is a living organism with numerous possible influences that could affect its growth. Careful site selection, as described in Chapter 2, is the main reason why it is possible to isolate the climate signal so well.

Dendrochronology has its limitations as well. Paleoclimate records can only be created where old-aged, relatively undisturbed trees, can be found. If trees are found in regions where there is evidence of other influences (human, animal, fire, insects) the climate signal may not be very strong. Finding old-aged, relatively undisturbed trees can require considerable time and effort, and it is often necessary to travel to remote areas. In densely populated regions, most trees are used for building or burned.

Paleoclimate records can only extend for as long as the trees are old, unless there are 'relict' trees to be found, but relict trees, if found at all, are usually at higher elevations and are temperature sensitive (and therefore were not used for this dissertation). Although every effort goes into isolating the climate signal, and all cores from every tree are visually checked for evidence of disturbance, it is not always possible to rule out non-climatic disturbances during periods/years outside of the calibration period. That said, historical evidence of known droughts, SST anomalies, volcanic events or other possible climate variables are always checked and compared to the tree-ring records.

One other limitation of tree-ring reconstructions is that it is difficult to get the information compiled from tree-ring studies into the hands of people that could use it, such as decision makers or environmental resource managers. So often, these studies are published in peer-reviewed journals and read mainly by other dendrochronologists. After the completion of this dissertation, my goal will be to make the data I use more accessible to non-scientists. For example, I plan to write a more popular style article about tree-ring based drought reconstructions in Mongolia. I also plan to write an executive summary of my research, get it translated into Mongolian and have it distributed to appropriate government and non-profit organizations.

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FIGURES

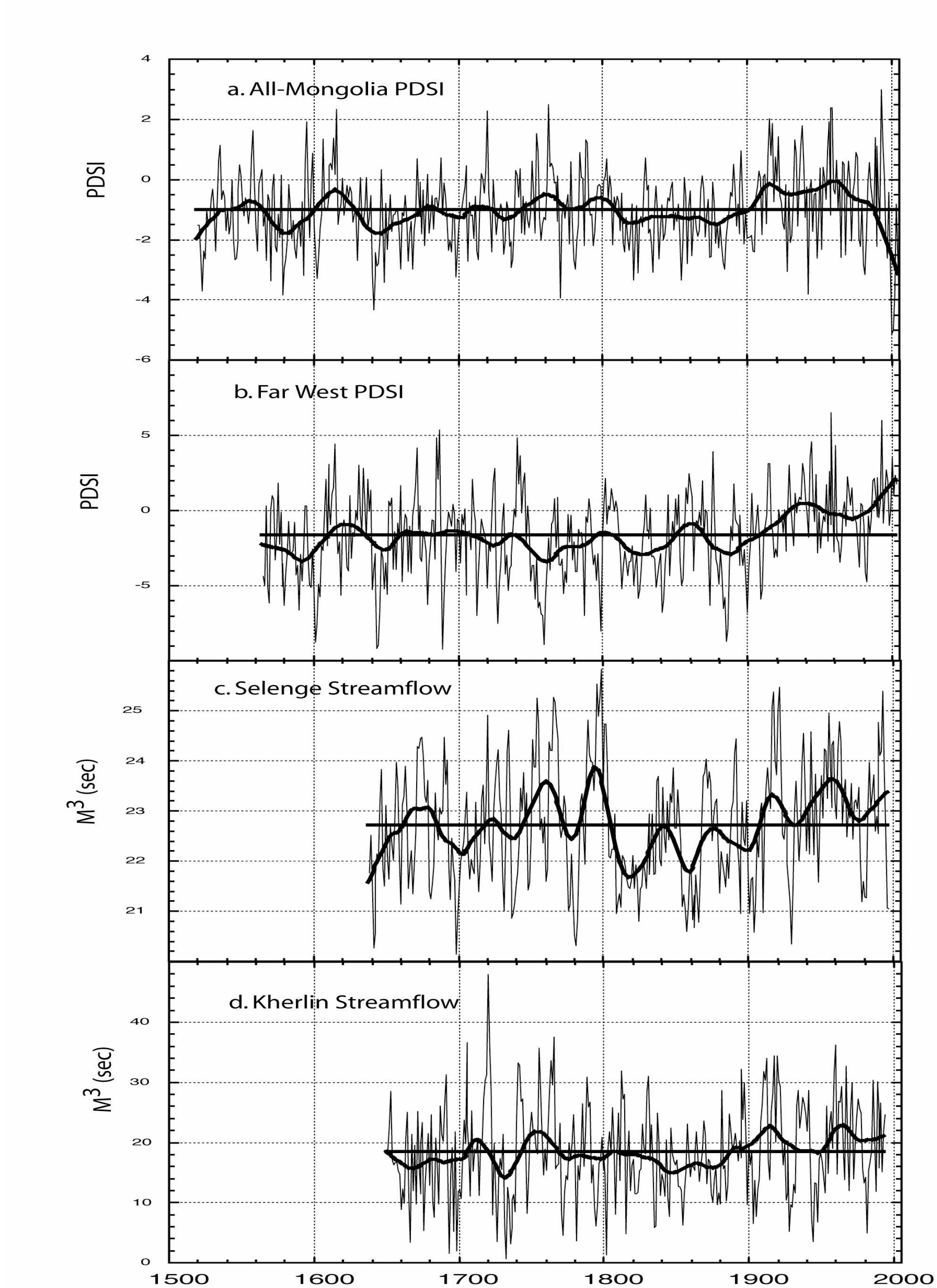

Figure 7.1. Mongolian drought reconstructions created for this study. 4a. All-Mongolia PDSI (Chapter 5), 4b. Far west Mongolia PDSI (Chapter 4), 4c. Selenge River streamflow (Chapter 3) and 4d. Kherlin River streamflow (Pederson et al.2001: updated for this dissertation).

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