Multi-Century Droughts in Wyoming's Headwaters: Evidence from Lake Sediments
March 2011-February 2013 Final Report
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Abstract

Wyoming has historically experienced extended periods of drought, which have had significant economic and social impacts. Tree-ring records and archeological evidence indicate that past centuries have contained multi-decadal "megadroughts" far more severe than any drought of the past 150 years. This project has studied past dry periods that likely exceeded even the severity of multi-decadal "megadroughts" in Wyoming watersheds. In doing so, we built upon funding from a previous Wyoming Water Research Program grant, and have found evidence of consistent moisture histories across the water-producing regions of the state. Evidence derives from prehistoric shoreline elevations in lakes in the Medicine Bow, Wind River, Beartooth and Bighorn Mountains, and shows that climatic shifts can rapidly generate new hydrologic regimes that persist for centuries to millennia. Aridity, at least as severe and extensive as during the AD 1930s Dust Bowl, prevailed from 9300-5500, 4500-3000, and 1400-900 years before AD 1950, although some dry periods in the north were wet in the south. The lake-shoreline elevations as well as watershed moisture budget calculations indicate that at least portions of the North Platte and Bighorn River systems were probably ephemeral for several millennia when dune activity was common across parts of Wyoming, Colorado, and Nebraska. High temperatures commonly increased evaporative losses from the region and coincided with the most severe aridity. Work included 1) surveys of lakes in the Bighorn drainage basins, using sub-surface radar, to determine the extensiveness of past periods of low lake levels, 2) sediment core collection and analysis, including radiocarbon dating and fossil analyses, of representative lakes in the Bighorn and Beartooth Ranges to date and quantify past climate conditions, 3) fossil pollen analyses used to evaluate temperature and vegetation changes associated with periods of aridity, and 4) hydroclimatic analysis, comparing paleoclimate estimates with modern climatic and stream flow data, to examine the factors that contributed to the periods of prolonged drought. Additionally, collaboration with UW archeologists has revealed that the human history of the Bighorn Basin was strongly linked to the changes in regional water supplies over the past 13,000 years. This work involved several graduate students, undergraduates, and high school interns in different activities from field work to data analysis and presentation.

Progress

Objectives

Water in the western United States, and Wyoming in particular, has long been a source of conflict within the region (e.g., long-running Supreme Court cases regarding the allocation of the North Platte, Green and Bighorn Rivers), and the past century has revealed that the availability of water can change significantly over time. Climate changes are likely to exacerbate uncertainties in water supplies, including the potential for hydroclimatic outcomes that may persist beyond reasonable resource planning horizons. Yet, water is critical for energy development, agriculture, urban use, and recreation in Wyoming, and planning requires estimates of the potential range of future availability. Long-term records of drought history, therefore, are needed to provide empirical data regarding past variability, particularly as a means to test predictive models.

Our previous work in the northern Wind River Range and in the southern portions of the Platte River basin indicates centennial to millennial periods since the last ice age when lakes across the region were lower than today – and when rivers such as the North Platte probably had ephemeral flows (Shuman et al., 2010; Shinker et al., 2010). Historic observations, therefore, do not adequately represent the full range of natural climate variability. Tree-ring data are also limited by biological and methodological constraints, which cause long-term trends to be undetected or perhaps underestimated, and **this project aimed to enhance the long-term record of drought in Wyoming** by generating new records of water-level change over the past >12,000 years from lakes across northern portions of the state (particularly in the mountain ranges that ring the Wind-Bighorn watershed).

To reach our goal, the project incorporated four activities:

1. **Confirm the extent and magnitude of past droughts**: are drought-history reconstructions from new study sites consistent with our prior results in terms of the estimated magnitude of past aridity? How geographically consistent or patterned were past droughts?
2. **Compare the lake sediment records of drought with other datasets**: at the locations of recent dendroclimatic studies, do lakes capture similar long-term variations? Do the changes relate to ecological or cultural changes?
3. **Examine the predictability of drought**: Was the timing of past drought in Wyoming consistent with sea-surface temperatures as expected from historic relationships? How do hydrologic changes relate to changes in temperature?
4. **Reconstruct in-stream flow** based on lake sediment analyses from areas of high flow contributions: did the Bighorn River have prolonged periods of extremely low flows such as we have reconstructed for the North Platte?

Methods

Previous studies have demonstrated that small lakes, such as kettle and moraine-dammed lakes in glaciated areas, can produce consistent records of climate-controlled lake-level fluctuations (e.g., Shuman et al., 2010; Shinker et al., 2010). In such lakes, the water table of the surrounding aquifer is exposed at the surface, and the lake level generally reflects the climate-controlled water budget of the aquifer. Therefore, we analyzed shore-to-basin transects of sediment cores (Fig. 1) and sub-surface profiles (Fig. 2) from multiple lakes to determine past shoreline elevations and measure regional moisture balance.

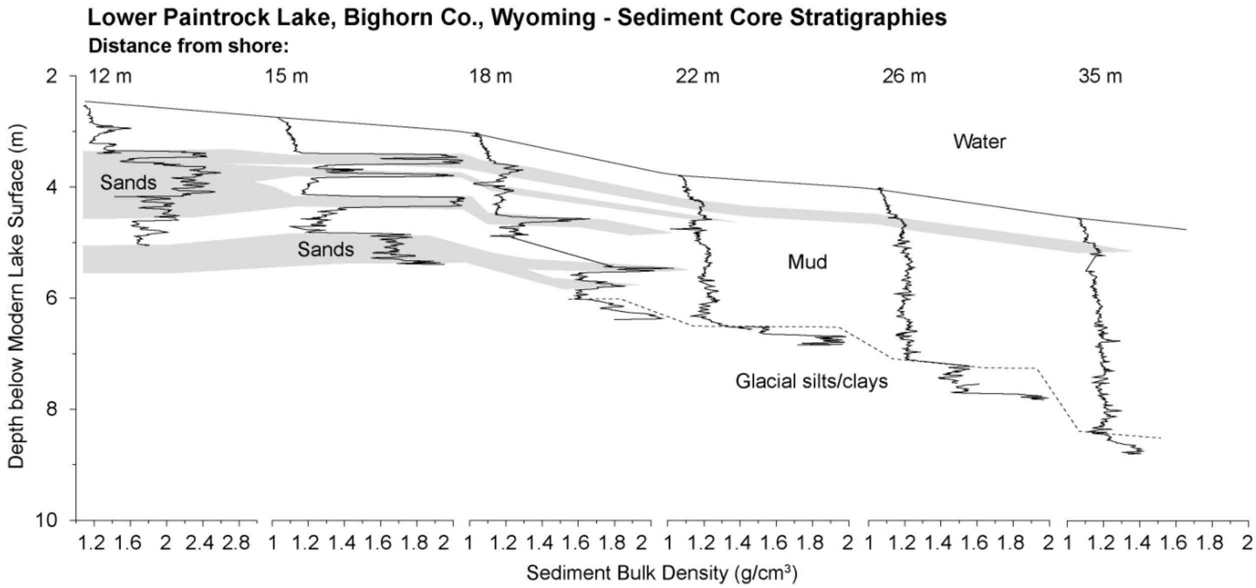

Figure 1. Sediment characteristics (such as sediment density above) in a transect of sediment cores collected perpendicular to shore can be used to track shifts in a lake's shoreline over time. Here, cores collected in July 2010 from Lower Paintrock Lake show layers of sand associated with periods of low water when the shoreline moved toward the lake center.

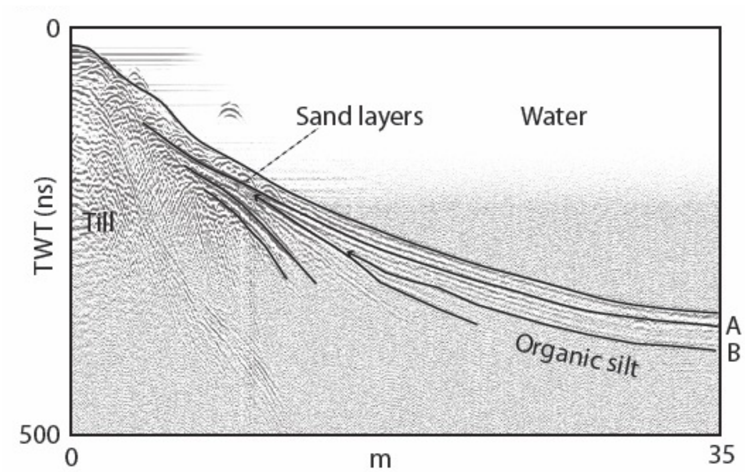

Figure 2. Ground-penetrating radar profiles show submerged paleoshorelines (sand layers marked by the convergence of stratigraphic layers and large amplitude radar reflections) in Lower Paintrock Lake. This profile spans the area of core locations (see Fig. 1), and confirms that the sand layers in the cores are associated with episodes of near-shore erosion (truncation of off-shore layers, such as layer B, at arrows). Data are presented in nanoseconds of the two-way travel time (TWT) of the radar signal, which is a function of depth.

In 2010 and 2011, we surveyed multiple lakes throughout the Bighorn River drainage with a ground-penetrating radar (GPR), as was previously done at Lake of the Woods in the northern Wind River Range and elsewhere (Shuman et al., 2010; Shinker et al., 2010), and identified changes in the geometry of the sediments that indicate past shifts in shoreline position (Fig. 2). We assume that sandy, macrophyte-rich substrates expanded toward the center of the lake and that sedimentation slowed near shore when lake levels were low (Fig. 1, 2).

Targeted sediment coring at representative lakes, Upper Medicine Lodge, Lower Paintrock Lake, and Duncan Lake in the west-central Bighorn Mountains (Fig. 1), and Rainbow and Lily Lakes on the Beartooth Plateau enabled us to measure the elevations and ages of past shoreline deposits (Fig. 3). Shifts in sediment composition and grain size have been assessed using loss on ignition, magnetic susceptibility, grain-size analysis, and other core logging techniques that can be conducted in the UW Geology and Geophysics Department, using equipment in Shuman's lab. To determine the ages of sedimentary and thus hydrologic changes, one-cm thick slices were removed from sediment cores and sieved to find plant macrofossil material for AMS radiocarbon dating. Thirty-nine radiocarbon ages were obtained from four cores at Lower Paintrock Lake; twenty-nine from six cores at Duncan Lake; and twenty-seven from four cores at Rainbow Lake. Additionally, we used standard pollen analysis techniques, carried out in Minckley's lab, to reconstruct vegetation composition during periods of long-term drought. The fossil pollen data also provided a basis for inferring regional temperature trends for comparison with the lake-level histories (Fig. 4, 5).

We focused our effort on lakes with well-defined watersheds and groundwater inputs, because such lakes can be used to estimate long-term moisture-balance changes. By reconstructing the change in lake volumes, we were able to reconstruct past changes in precipitation minus evaporation (ΔP-E). To calculate long-term ΔP-E (e.g., Fig. 4B), we have developed a new method for systematically estimating elevational shifts in each lake's shoreline from the maximum depths of the paleoshoreline sediments compared to the water depths of similar sediment today (Pribyl and Shuman, in review). We then calculated changes in lake volume by accounting for lake size and bathymetry, and divide by the watershed area and lake-equilibration times to obtain a ΔP-E value for the watershed in mm/day (Shuman et al., 2010; Shinker et al., 2010). Analyses of climatologically patterns and processes consistent with the observations were completed in Shinker's lab in UW Geography (e.g., Frederickson, 2012).

Activities

- Fieldwork: GPR profiles were collected from nine lakes in Bighorn Range and six lakes on the Beartooth Plateau, as well as Brooks Lake near Togwottee Pass; sediment cores were collected from three lakes and four small ponds in the Bighorn Mountains, and two lakes on the Beartooth Plateau. Additional profiles and cores were collected from Long Lake, Medicine Bow Mountains, as a training exercise for undergraduates and SRAP (Summer Research Apprenticeship Program) high-school interns.
- Lab work: Core analyses have focused on Lower Paintrock Lake (Bighorn Co.), Duncan Lake (Sheridan Co.), Rainbow and Lily Lakes (Park Co.), and Long Lake (Carbon Co.), including loss-on-ignition, grain-size, sediment density, sedimentary charcoal, macrofossils and radiocarbon analyses.
- Analyses: We developed a new methodology to quantify lake-level reconstructions and calculate associated changes in watershed moisture balance. We also incorporated results from Wyoming lakes into a continental-scale database of similar data, and conducted analyses of historic droughts in Wyoming to examine climatic processes that might have contributed to past aridity.
- Paper writing: See list of publications and manuscripts below.
- Outreach: The 2010 meeting of the American Quaternary Association (AMQUA) was held in Laramie in August 2010, and the PIs organized related field trips for >60 people to several of our study sites in the Platte River watershed. Shuman was also the program organizer for the 2012 AMQUA meeting (Duluth, MN), which had droughts, floods, and

hydrologic variability as its theme; the meeting provided an opportunity to present our results to a focused scientific audience as we have also done at meetings of the American Geophysical Union and Association of American Geographers. Presentations were also given to Wyoming Farm Bureau, State Engineer's Office Water Forum, the Wyoming Water Association, the Geologists of Jackson Hole, and at the Teton County Library. Shuman also discussed findings on *Morning Edition* on National Public Radio, as well as on newscasts and *Open Spaces* on Wyoming Public Radio.

Principal Findings

1. **The extent and magnitude of past droughts**: Our new methodology (Pribyl and Shuman, in review) enabled us to systemically produce comparable time series of water-level changes from our sediment core data, and then calculate watershed hydrologic balance based on these data. We have produced reconstructions of the balance of precipitation and evaporation for the Beartooth Plateau, Wind River Range, Bighorn Mountains, and Medicine Bow Mountains, and compared these datasets with those from other areas, such as central Colorado (Fig. 3, blue lines). The reconstructions show similarities, such as a rapid increase in lake levels across the region at ca. 5500 years ago (gray bar, Fig. 3), but also meaningful differences such as periods when northern lakes were low and southern lakes high (dashed lines, Fig. 3). The patterns can help reveal processes involved, such as the potential for factors like El Nino to shift storm tracks north or south and cause opposite patterns of change in different areas (Shuman et al., in review-a).

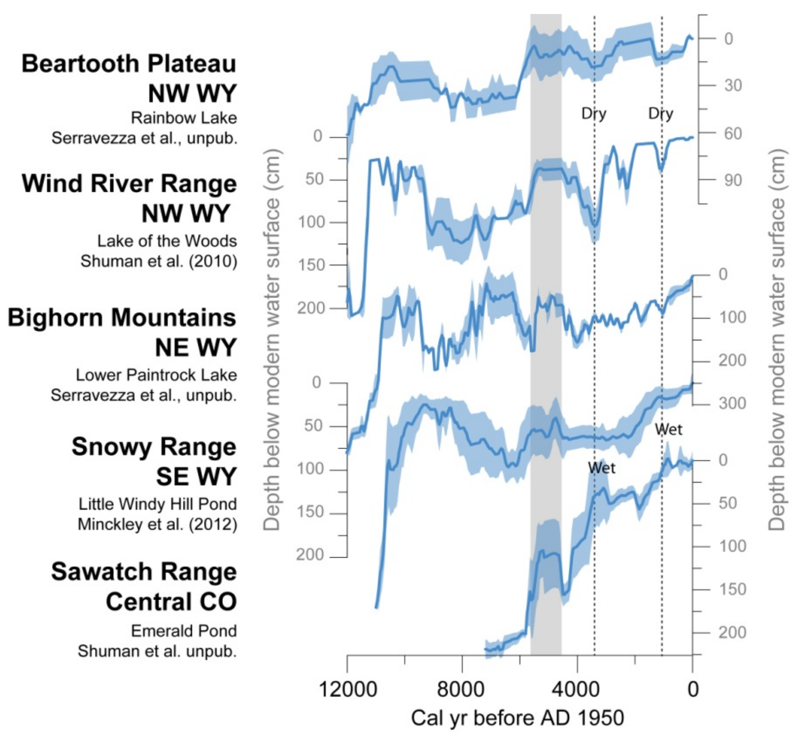

Figure 3. Lake elevations reconstructed at several sites across Wyoming as part of the WWRP-funded work compared with an NSF-funded study of a lake from central Colorado. The comparisons reveal that most Wyoming lakes rose substantially at ca. 11000 years before AD 1950 (BP) and remained high until extended drought after ca. 9300 years BP. The duration and timing of the aridity varies, possibly due to interactions between lake-specific levels of evaporation (see below) and north-south shifts in storm tracks (e.g., opposite timing of wet-dry phases in the Bighorns and Snowy Ranges before ca. 5500 yrs BP). All lakes record a rapid rise at 5500 yrs BP (gray bar), and then show broad-scale evidence of north-south contrasts in wet/dry phases in the past 4000 years (dashed lines).

2. **Comparisons with other types of data**: The most recent periods of low water recorded by the lakes coincide in time with periods of frequent or prolonged drought captured by tree-ring studies (Shuman et al., 2010; Shuman et al., in review-a; Calder et al., in review). In addition, long-term changes in forest composition also coincide with the hydrologic shifts that we documented, although some forests may be less sensitive to such changes than others because of the ecological influence of frequent forest fires (Minckley et al., 2012).

   Additionally, the observed hydrologic changes appear to have had cultural significance, and likely controlled the size of the human population in northern Wyoming (Kelly et al., 2013). During wet periods the numbers of archeological sites (and thus the estimated human population) grew exponentially, but during dry periods the numbers fell (Fig. 4). In fact, during the warmest and driest period from ca. 9300-5500 years BP (Fig. 3, 4), the Bighorn Basin was essentially de-populated (Fig. 4C).

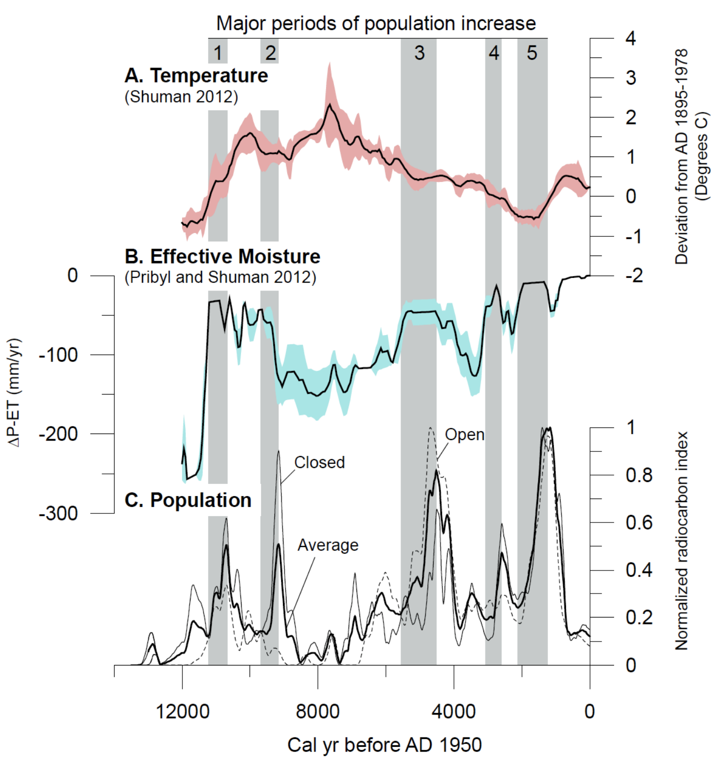

*Figure 4. Trends in temperature (A, annual mean shown) and moisture availability (B) in Wyoming correlate (r=0.71) with high temperatures coinciding with long-term low water periods. Additional millennial-scale moisture variations (gray bars) explain significant changes in the regional human population with the population growing during millennial wet/cool phases (Kelly et al., 2013). A linear regression of temperature and moisture reconstructions correlates well with the population reconstruction (r=0.656, p=7.7 * 10^{-30}); a meaningful lag of ~300 years in the population trends is well explained by slow exponential population growth following shifts in environmental carrying capacity (Kelly et al., 2013).*

3. **<u>The predictability of drought</u>**: Both the common patterns of change in the lake-level histories, and the site-to-regional scale differences (Fig. 3), can provide insight into important processes that influence Wyoming's water supply. For example, the water-level history of Lower Paintrock Lake (Bighorn Co.) differs from that of other lakes around the Bighorn Basin, such as Rainbow Lake (Park Co.) and Lake of the Woods (Fremont Co.) shown in Fig. 3. Paintrock Lake also differs hydrologically from the other two because none of the other lakes have surface streams flowing through them, and water flows into and out of Paintrock Lake from Paintrock Creek sufficiently fast that water (hydrogen and oxygen) isotope measurements show no evaporative loss from the lake. All of our other study sites have water isotopic values consistent with long water-residence times and important losses of water by evaporation from the lake surface.

   The hydrologic differences have allowed us to separate out the long-term influence of temperature-driven evaporation from precipitation changes on the regional hydrologic history (Fig. 5)(Serravezza and Shuman, in prep). A comparison of Lower Paintrock Lake and other lakes around the Bighorn Basin shows that evaporative loss of water can cause aridity (negative P-E) even if precipitation rates were as high or higher than today during periods of high temperatures such as ca. 8000 years BP (Fig. 5). Precipitation changes recorded at Paintrock Lake explain 43% of the explained variation at Lake of the Woods, but the remaining 57% can be attributed to long-term evaporation trends predicted by our reconstructed temperature history (derived from fossil pollen data; Shuman 2012); 17% of the variation in the Lake of the Woods hydrologic history is not explained by these two factors and reflects our level of uncertainty.

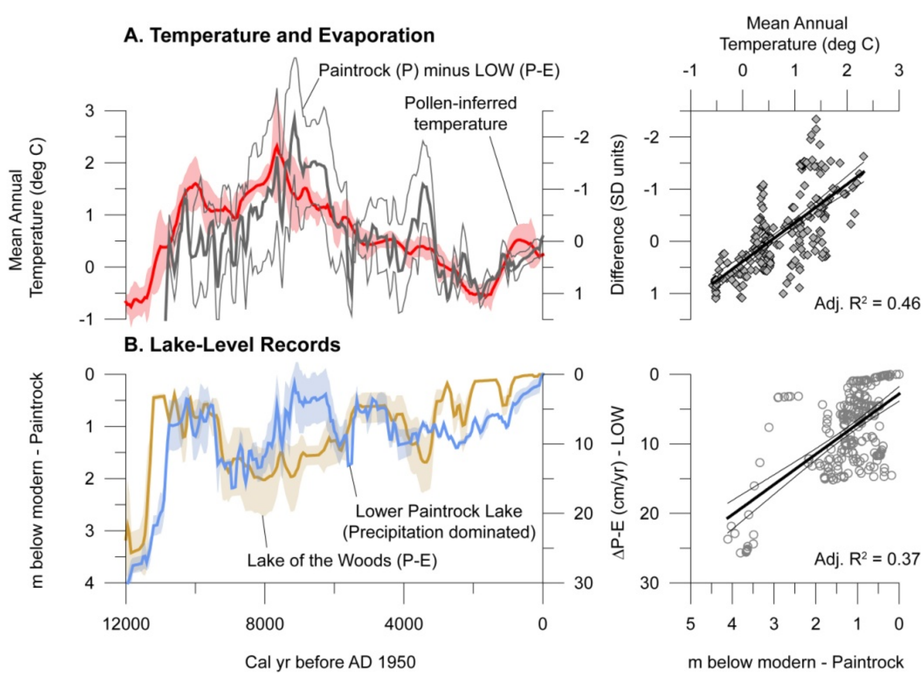

Figure 5. Most lakes in the Bighorn Basin (such as Lake of the Woods, orange in B) reflect the difference between precipitation and evaporation (P-E) and were low from 9300-5500 yrs BP, but Lower Paintrock Lake (blue, B) has almost no evaporative losses today and was high from ca. 7800-6300 yr BP. The episode of high water likely indicates a period of high precipitation (B), and difference in lake-level histories (e.g., Paintrock minus Lake of the Woods) correlates well with temperature trends (A) consistent with the difference resulting from evaporation of any added precipitation (Serravezza and Shuman, in prep).

The timing of past drought in Wyoming also appears to be linked to the histories of Pacific and Atlantic sea-surface temperatures (Fig. 6). Such a relationship is consistent with modern influences on storm tracks that deliver most of Wyoming's snow. For example, periods of frequent El Nino events (Fig. 6E) coincide in time with wet episodes in Wyoming (Fig. 6D) and drought to the south in Colorado (dashed lines, Fig. 3).

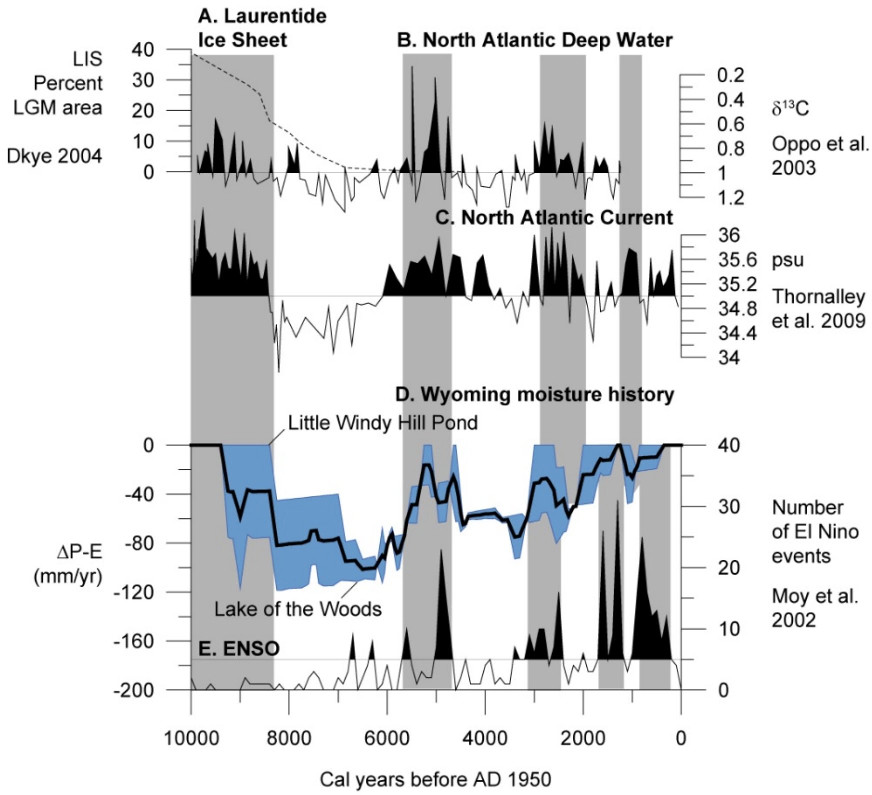

Figure 6. Wyoming moisture reconstructions (plotted in blue as change in precipitaion minus evaporation, ΔP-E, versus time) have variations consistent with documented oceanic variability. Before ca. 8000 years before AD 1950, the presence of the Laurentide Ice Sheet in central Canada (A, dashed line) likely contributed to wet conditions in Wyoming. Since then, wet phases have coincided with periods of frequent El Nino events (E), and may have also been influenced by variability in the North Atlantic (B, C).

Additional work by Shinker and students (Frederickson 2012) has examined the atmospheric dynamics and circulation associated with dry episodes in Wyoming to help explore the mechanistic linkages that may have been the underpinning to the events of the past 11,000 years.

4. **Significant reductions in in-stream flow:** Based on lake sediment analyses from Lower Paintrock Lake, which today overflows into Paintrock Creek and ultimately the Bighorn River, past arid periods may have substantially reduced regional river flow (which is consistent with decreases in the human population of the Bighorn Basin, Fig. 4). Sand layers, which mark the periods of low water, date to the same intervals as changes in the North Platte River watershed (e.g., Little Windy Hill Pond, Carbon Co., in Fig. 3) when the North Platte was likely ephemeral (Shinker et al., 2010). The layers also lie at elevations (Fig. 2) below the modern outlet of Lower Paintrock Lake (<50 cm below the modern lake surface), and indicate periods of reduced overflow. Analyses of Upper Big Creek Lake (Jackson Co., Colorado) reveal similar low water episodes, which also produced shoreline deposits below the modern lake spill over point and thus contributed to the lack of water in Platte River tributaries (Pribyl and Shuman, in prep.).

Significance

Our results are confirming that climatic processes, including intrinsic and forced variability in regional temperatures and the state of the global oceans, can drive large and persistent changes in the availability of water in Wyoming. Severe dry episodes have lasted for centuries to millennia across much of the state's water producing regions, including 1) the North Platte River headwaters in the Snowy Range of southeastern Wyoming and the Park Range of northern Colorado, 2) the convergence of the Snake (Columbia), Green (Colorado), and Bighorn (Missouri-Mississippi) River watersheds on the Continental Divide in the Wind River Range, and 3) the eastern Bighorn River watershed in the Bighorn Mountains. Evidence that lakes that today overflow into these major river systems have not overflowed for prolonged intervals in the past indicates that climate changes can dramatically reduce flow rates in rivers that are already fully allocated to various uses. Surface flow rates and the availability of shallow groundwater, which feeds most of our study sites, may fall if temperature increases, even if precipitation rates rise.

Severe changes in Wyoming water supplies were part of larger continental shifts in moisture availability (Shuman et al., in review-b), and also had impacts on regional vegetation (Minckley et al., 2012), wildfire regimes (Calder et al., in review; Minckley et al., 2012; Minckley and Shriver, 2012), and pre-historic human populations (Kelly et al., 2013). Our inferences appear robust given the consistency of results across watersheds, and evidence that they were part of larger climatic changes with meaningful landscape and cultural impacts. If so, water supplies in Wyoming may be susceptible to dramatic and persistent shifts, which should be considered in water management plans.

Publications and Presentations (* Undergraduate author, † Graduate student author)**:**

Published

Fredrickson, J. (2012) Hydroclimatic variability in Wyoming headwaters. University of Wyoming, Masters of Arts thesis, 68 p.

Kelly, R., T. Surovell, B. Shuman, G. Smith. (2013) A Continuous Climatic Impact on Holocene Human Population in the Rocky Mountains. *Proceedings of the National Academy of Sciences* 110 (2): 443-447.

Minckley, T. A., R. Shriver*, B. Shuman. (2012) Resilience and regime change in a southern Rocky Mountain ecosystem during the past 17000 years. *Ecological Monographs* 82(1): 49-68.

Minckley, T.A., and R.K. Shriver*. (2012) Vegetation response to different fire-types in a Rocky Mountain forest. *Journal of Fire Ecology*.

Shinker, J. J., Shuman, B. N., Minckley, T. A., and Henderson, A. K.† (2010). Climatic Shifts in the Availability of Contested Waters: A Long-term Perspective from the Headwaters of the North Platte River, *Annals of the Association of American Geographers (Special Issue on Climate Change)*, 100 (4), 866-879.

Shuman, B. (2012) Recent Wyoming temperature trends, their drivers, and impacts in a 14,000-year context. *Climatic Change* 112 (2): 429-447.

Shuman, B., Pribyl, P.*, Minckley, T. A., and Shinker, J. J**.** (2010). Rapid hydrologic shifts and prolonged droughts in Rocky Mountain headwaters during the Holocene, *Geophysical Research Letters*, DOI:10.1029/2009GL042196.

Submitted publications

Calder, J.†, Stopka, C.*, and B. Shuman. Evaluating the influence of drought and temperature change on fire regimes of high-elevation sub-alpine forests in the southern Rocky Mountains. *Rocky Mountain Geology*. Peer Reviewed.

Minckley, T.A. Postglacial vegetation and climate history of southeastern Wyoming. *Rocky Mountain Geology.* Peer Reviewed.

Pribyl, P.*, and B. Shuman. Quantifying sediment-based lake-level reconstructions: A Holocene case study from the headwaters of the Green, Snake, and Bighorn Rivers, Wyoming, USA. *Quaternary Research*. Peer Reviewed.

Shuman, B. Carter, G.†, Hougardy, D.,* Powers, K.*, Shinker, J.J. (A) A north-south moisture dipole at millennial scales in the central and southern Rocky Mountains during the late-Holocene. *Rocky Mountain Geology*. Peer Reviewed.

Shuman, B., A. K. Henderson*, and C. Plank*. (B) Moisture Patterns in the United States and Canada over the Past 15,000 Years: A New Synthesis of Lake Shoreline-Elevation Data. *Quaternary Science Reviews*. Peer Reviewed.

Publications in preparation

Pribyl, P.*, and B. Shuman. Severe regional river-flow reductions during the Younger Dryas and mid-Holocene, northern Colorado. Plan to submit to *Geology*. Peer Reviewed.

Serravezza, M†, Shuman, B. The role of temperature-driven evaporation in Holocene hydrologic changes in the Bighorn Basin, Wyoming USA. Plan to submit to *Quaternary Research*. Peer Reviewed.

Shuman, B., J. Marsicek† The structure of Holocene climate change in mid-latitude North America. Plan to submit to *Earth and Planetary Science Letters*. Peer Reviewed.

Presentations

2010

Shinker, J. J**.**, B. N. Shuman, T. A. Minckley, and A. K. Henderson†. 2010. "Climatic shifts in the availability of contested waters: A long-term perspective from the headwaters of the North Platte River," Poster presenter, American Quaternary Association, Laramie, WY.

Shinker, J. J., B. N. Shuman, T. A. Minckley, and A. K. Henderson†. 2010. "Climatic shifts in the availability of contested waters: A long-term perspective from the headwaters of the North Platte River," Association of American Geographers, Washington, DC.

Shinker, JJ. 2010, Women in Science Conference, Career Panelist, University of Wyoming.

Shuman, B. N., J.J. Shinker and T. A. Minckley. 2010. "Millennial-scale hydroclimatic variation and prolonged episodes of ephemeral river flow in the Rocky Mountains during the Later-Quaternary," Geological Society of America, Denver, CO.

Shuman, B., 2010. Late-Quaternary Hydroclimatic Changes in North America and their Ecological Impacts. VU (Vrie) University – Amsterdam, Geology.

2011

Shinker, J. J., 2011, Spatial Heterogeneity of Western U.S. Climate Variability. Association of American Geographers, Seattle, Washington.

Heyer, J.* and Shinker, J.J., 2011. "An Investigation of Climatic Controls in the Upper Laramie River Watershed During Low Stream Flow Years", at UW Undergraduate Research Day, April, 2011.

Serravezza, M. †, 2011. "Ground-penetrating radar as a tools for reconstructing past droughts in Wyoming," UW Roy J. Shlemon Center for Quaternary Studies, Quaternary Research Symposium, Fall 2011.

Shuman, B., 2011. From Causes to Impacts of Holocene Hydroclimatic Change in the Mid-Latitudes. U. Colorado – Boulder, INSTAAR (Institute for Arctic and Alpine Research).

2012

Fredrickson, J. † , 2012. Hydroclimatic variability in Wyoming headwaters. Master's defense, UW Geography, May 15, 2012.

Fredrickson, J. † and Shinker, J.J., 2012. Hydroclimatic variability and drought in Wyoming headwater regions. Annual meeting of the Association of American Geographers, New York City.

Heyer, J.*, Fredrickson, J. † and Shinker, J.J., 2012. Climate, drought and low stream flow in the headwaters of the North Platte River. Annual meeting of the Association of American Geographers, New York City.

Serravezza, M. † and Shuman, B., 2012. Millennial-scale hydrologic fluctuations during the Holocene in the Bighorn Basin, northern Wyoming. Poster presentation, American Quaternary Association, Duluth, MN.

Shuman, B. 2012. A Mid-Holocene Regime Shift in Mid-Latitude North Hemisphere: Pollen and

Lake-Level Datasets. NSF/NCAR SynTrace Climate Model Workshop, Providence RI.

Shuman, B. 2012. Patterns and Impacts of millennial-scale hydroclimatic change in North American during the Holocene. American Geophysical Union Fall meeting, San Francisco.

Student Involvement

Marc Serravezza, a Ph.D. student in Geology & Geophysics, was supported by this grant and took the lead on reconstructing the water-level histories of Lower Paintrock, Duncan, and Rainbow Lakes. Serravezza is a continuing UW student, but his experience in this project helped him to secure an ExxonMobil Research Corporation internship for summer 2013.

Joshua Fredrickson, a Geography/Water Resource master's student was also supported through this grant and a one-year fellowship from the Geography Department. Fredrickson analyzed climate data associated with recent low stream flow events in the Platte and Colorado River drainages. He is also partially funded through the McNair Scholars program to mentor undergraduate Joshua Heyer. Fredrickson was offered a position through the Wyoming State Engineer's Office as a Hydrographer-Commissioner in Worland beginning March 2013.

Serravezza was supported in his work by UW undergraduates, Devin Hougardy (Geology), Jacob Buettner (Geology, McNair Scholar), and Tyler Dooley (Geography), and by graduate students John Calder (Geology/PiE) and Fredrickson (Geography/Water Resources). The students contributed to field work in the Bighorn Mountains and Beartooth Plateaus, and helped to complete our lab analyses (in particular preparing samples for radiocarbon analyses). Likewise, Grace Carter and Jeremiah Marsicek, Ph.D. students in Geology & Geophysics contributed to field work in summer 2010 and 2011, and have generated complementary datasets from other regions (via support from the National Science Foundation and NASA Space Grant), which is providing a broader-scale perspective on the events documented in Wyoming (such as the shift in moisture availability at ca. 5500 years before AD 1950). Two other undergraduate students, T.J. Gajda (Geography) and Reid Olson (Botany), contributed to the project by completing the chemical processing of sediment samples for fossil pollen analyses.

Joshua Heyer (Geography) and Jacob Buettner (Geology & Geophysics) were partially supported through the McNair Scholars program, which supports first-generation undergraduate student research in preparation for a graduate school. Heyer's contribution to our research project included training in climate analysis related to understanding drought and low stream flow years. Heyer presented his preliminary research, "An Investigation of Climatic Controls in the Upper Laramie River Watershed During Low Stream Flow Years", at UW Undergraduate Research Day, April, 2011. Buettner helped to evaluate the potential of north-south contrasts in regional moisture trends by working on sediment cores from a lake in southern Colorado. He presented his results at the 2012 annual meeting of the Geological Society of America (GSA) and at UW Undergraduate Research Day, April 2013, and will be attending graduate school in geochemistry in Fall 2013 at New Mexico State University.

Noah Berg-Mattson, an undergraduate in Botany, worked with Devin Hougardy (Geology & Geophysics) on the cores collected at Long Lake, Carbon Co. David Webster at visiting undergraduate from the Cardiff University (UK) counted sedimentary charcoal from the lake sediment cores for comparison with the moisture history. Likewise, three visiting high-school students were involved in field work and some lab analyses through the Summer Research Apprenticeship (SRAP) program at UW.

Leveraging of funds

Results from this study help to motivate UW's successful NSF EPSCoR proposal, "Water in a Changing West: The Wyoming Center for Environmental Hydrology and Geophysics (WYCEHG)," which is providing $20 million over five years to enhance hydrologic research in Wyoming. One of the core WYCEHG science teams is focusing on paleohydrology using the methods applied and refined in this WWRP grant. In particular, the WYCEHG project will examine how hydrologic connectivity (e.g., via deep groundwater transfer) within watersheds influences sensitivity of water resources to changes in temperature.