Report as of FY2007 for 2006WY32B: "Predicting Drought in the Green River Basin"

Publications

- Conference Proceedings:
  - Tootle, G.A., T. Hunter and T.C. Piechota, 2006. Pacific Oceanic / Atmospheric Variability and the Wind River Range. Proceedings of the ASCE World Water & Environmental Resources Congress 2006, May 21-25, 2006, Omaha, NE.

Report Follows

Abstract

The proposed two-year research project will use proxy records derived from tree rings to examine climatic controls on Green River Basin (GRB) streamflow and assess how natural interdecadal variability might impact delivery of water from the GRB. The proposed research will review existing streamflow proxies for the GRB and assess how reconstruction methodology might affect key elements (e.g. reconstructed drought magnitude) of these records. Next, an investigation of long-term streamflow variability, focusing on extreme events such as mega-droughts, will be performed including evaluating the influence of various atmospheric – oceanic influences [e.g., El Niño-Southern Oscillation (ENSO)] on GRB streamflow. The results of the research will be used to develop probabilistic drought forecasts for the GRB. These forecasts would utilize both empirical probabilities for drought risk derived from the tree-ring record and links between streamflow and climatic drivers like ENSO and the PDO.

Statement of the Problem

From 2001 to 2003, Professor Stephen T. Jackson, Ph.D. and Stephen T. Gray, Ph.D. of the University of Wyoming's Department of Botany were funded by the Water Resources Program (WRP) on a study entitled "Combining Modern and Paleo-Climate Data to Enhance Drought Prediction and Response." Key findings of the Jackson – Gray study included: (1) Strong evidence that droughts of a greater magnitude and duration than any 20th century events have regularly occurred in western Wyoming over the past 800 year; (2) Droughts in western Wyoming show strong links to circulation patterns in the northern and tropical Pacific Ocean; (3) However, connections between western Wyoming drought and the Pacific Ocean may also be modulated by variations in other ocean basins (e.g. the North Atlantic).

The current research extends and addresses additional research needs identified in the Jackson – Gray study. In particular, the proposed research examines linkages between interannual and interdecadal ocean / atmosphere phenomena and GRB streamflow. Ultimately, the current research focuses on developing a lead-time approach where ocean / atmosphere conditions, and the resulting potential for drought, are evaluated prior to the beginning of each water year. An additional goal of the research is to develop probabilistic forecasts of drought and to perform a frequency – duration analysis of drought.

Objectives

The scientific objectives of the proposed two-year research project are to:

1. Evaluate methodologies used to reconstruct GRB streamflow.
2. Examine linkages between GRB reconstructed streamflow and large scale oceanic / atmospheric phenomena that act at interannual and interdecadal time scales.
3. Develop probabilistic forecasts of droughts, and frequency / duration analysis of droughts.
4. Supplement existing tree-ring chronologies for the Upper GRB with new collections.

Progress

The research plan is divided into four tasks, each corresponding with one of the four objectives. The following summarizes (with percent complete) the four tasks:

Task 1 – *Evaluation of Streamflow Reconstruction Methodologies* (50%). We are currently evaluating various methodologies to perform streamflow reconstructions using tree-ring chronologies. These methods include standard methods such as Step-wise Regression and new methods such as Partial Least Squares Regression, Multiple Linear Regression, Principal Component Regression and Regression applying Singular Value Decomposition. Once Task 4 (development of tree-ring chronologies) is complete we will complete Task 1.

Task 2 – *Linkages of Streamflow with Large-Scale Ocean / Atmosphere Phenomena* (50%). We have completed an evaluation of Pacific Oceanic Atmospheric Variability and Upper Green River streamflow and snowpack (01 Apr Snow Water Equivalent - SWE) for the instrumental period of record. This was published (non-peer reviewed electronic proceedings) and presented at the ASCE EWRI Conference in May 2006 (Tootle et al., 2006). This research evaluated the influence of interdecadal and interannual Pacific oceanic / atmospheric variability on the Wind River Range (WRR). Instrumental datasets were obtained for unimpaired streamflow and snow water equivalent for stations in the Green River Basin (GRB – west slope of WRR) and the Wind-Bighorn River Basin (WBRB – east slope of WRR). The phases (cold or warm) of Pacific [El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO)] oceanic / atmospheric phenomena were identified. Statistical significance testing of the datasets, based on the interdecadal and interannual oceanic / atmospheric phase (warm or cold), was performed applying the parametric t-test test. Once Task 4 is complete and we develop new reconstructions (Task 1) we will perform the same analysis for the reconstructed records.

Task 3 – *Probabilistic Forecasting of Droughts* (0%). The drought frequency/duration analysis will be performed upon the completion of Task(s) 4 and 1.

Task 4 – *Improvement of Streamflow Reconstructions for the Green River Basin with New Tree-ring Collections* (90%). Extensive field work was performed in Summer/Fall 2006 in the Upper Green River Basin in which new tree-rings were sampled. Typically, 20 to 30 trees (with a minimum of two samples per tree, all of the same species) must be collected to develop a single chronology. The goal of this task is to develop four to six new chronologies to supplement existing chronologies in the region. Once these chronologies are finalized (anticipate completion by June 2007), Task 4 will be complete. We will then proceed to Task 1 (developing new reconstructions). Once Task 1 is complete, we will then complete Task(s) 2 and 3.

Methodology

Task 1 – *Evaluation of Streamflow Reconstruction Methodologies* (50%). Various regression techniques (Step-wise Regression, Partial Least Squares Regression, Multiple Linear Regression, Principal Component Regression and Regression applying Singular Value Decomposition) are being evaluated to perform the streamflow reconstructions.

Task 2 – *Linkages of Streamflow with Large-Scale Ocean / Atmosphere Phenomena* (50%). First, spatial and temporal streamflow variability for the GRB and WBRB was evaluated by applying a 5-year filter to standardized water-year streamflow volumes for the two GRB stations and the three WBRB stations. Next, spatial and temporal snowfall (SWE) variability for the GRB and WBRB was evaluated by applying a 5-year filter to standardized 01 April SWE values for the four GRB stations and the three WBRB stations.

Finally, the impacts of the interdecadal (PDO) and interannual (ENSO) oceanic / atmospheric influences on WRR streamflow and snowfall were evaluated by testing of water-year (or 01 April) means for the individual and coupled oceanic / atmospheric influences.

The current water-year (October through September) was the period selected for streamflow and the 01 April date was selected for SWE. The previous year (or season) was selected to define the phase (e.g., warm or cold) of the PDO and ENSO. This analysis evaluated the current water-year streamflow (or 01 April SWE) response (e.g., positive or negative shifts in means) to the previous year (or season) of the oceanic / atmospheric (PDO, ENSO) phase (cold or warm). The testing performed here was for both the individual and coupled oceanic / atmospheric indices with streamflow (or SWE).

The parametric two-sample t-test (Maidment, 1993) was performed on the response of streamflow means to changes in oceanic / atmospheric phase, including coupling. The t-test compares two independent data sets and determines if one data set has significantly larger values than the other data set (Maidment, 1993). The t-test assumes that the two data sets are normal with equal variances (Maidment, 1993). A detailed discussion of this method is provided in Maidment (1993) and is also provided in most statistical textbooks. Recent applications of the t-test include Harshburger et al. (2002) evaluation of Idaho spring streamflow response to Pacific Ocean influences, Rogers and Coleman (2003) evaluation of continental U.S. streamflow response to Pacific and Atlantic Ocean influences, Tootle and Piechota (2006) evaluation of continental U.S. streamflow response to atmospheric – oceanic influences and Hunter et al. (2006) evaluation of atmospheric – oceanic influences and western U.S. snowfall. An example is hereby provided.

The PDO is an atmospheric – oceanic phenomena associated with persistent, bimodal climate patterns in the northern Pacific Ocean (poleward of 20^{o} north) that oscillate with a characteristic period on the order of 50 years (a particular warm or cold phase of the PDO will typically persist for about 25 years) (Mantua, et al., 1997, Mantua and Hare, 2002). Below is an example of applying the Two-sample t-test to determine if a significance difference in water year streamflow occurs for the Salt River when comparing PDO Cold and PDO Warm years. The streamflow response to PDO Cold years is assumed to be 1951 to 1977 while PDO Warm years is assumed to be 1978 to 2002.

Step 1 is to segregate the data (PDO Cold and PDO Warm years):

Year	**Q (AF)**	**Year**	**Q (AF)**
1951	196014	1978	1100369
1952	1178437	1979	1901620
1953	242529	1980	1361963
1954	346840	1981	315227
1955	217069	1982	601737
1956	203248	1983	1330350
1957	350370	1984	765836
1958	725958	1985	1399247

1959	239193	1986	582914
1960	850360	1987	755821
1961	170796	1988	642460
1962	726923	1989	257612
1963	383660	1990	205848
1964	275349	1991	1052467
1965	737240	1992	882214
1966	1059405	1993	2287736
1967	278607	1994	387564
1968	917749	1995	1063326
1969	522342	1996	171399
1970	300688	1997	396191
1971	202650	1998	669428
1972	425693	1999	254655
1973	1877065	2000	138097
1974	199212	2001	449523
1975	609882	2002	148872
1976	337731		
1977	193842		

Step 2 is to compute the mean (PDO Cold years $\bar{x}$ = 509957, PDO Warm years $\bar{y}$ = 764899) and standard deviation (PDO Cold years s_x = 399123, PDO Warm years s_y = 562976) of each data set. The spooled degrees of freedom (*df*) = 27 PDO Cold years + 25 PDO Warm years – 2 = 50.

Step 3 is to compute the test statistic, *t*.

$$t = \frac{\bar{x} - \bar{y}}{\sqrt{\frac{s^2_x}{n} + \frac{s^2_y}{m}}}$$

t = -1.89 which corresponds to a significance level of 90% (Fisher and Yates, 1938).

Task 3 – *Probabilistic Forecasting of Droughts* (0%). The Weibull method and the Compound Renewal Method (Loaiciga, 2005) will be utilized to determine drought frequency / duration of streams in the Upper Green River basin.

Task 4 - *Improvement of Streamflow Reconstructions for the Green River Basin with New Tree-ring Collections* (90%).

Training and Equipment.

Tree-ring research was initiated in March, 2006. Prior to field work, students were trained on the methods of dendrohydrology. In May, a group from the University of Wyoming attended a dendrochronology workshop in Boulder, CO put on by Connie Woodhouse (NOAA Paleoclimatology Pogram) and Jeff Lukas (Institute of Arctic and Alpine Research). The workshop was designed to teach procedures of field collection and to give a brief overview of site selection, lab setup, lab analysis, and basic reconstruction techniques.

Following the workshop, Jeff Lukas provided instruction on the setup of a new tree-ring lab at the University of Wyoming and the equipment that is required to conduct field sampling. The new lab is necessary since other tree-ring analysis equipment on campus is older and the equipment needs to be located in an area that is accessible to students. The new lab (see figure and table below) was completed in the fall of 2006 and will provide the necessary tools for streamflow reconstructions.

Civil Engineering tree-ring lab.

Major equipment used in field and laboratory work.

Equipment	Purpose
Velmex TA System	
1) Acu-Rite SENC 150	Precision ring width measurement
2) METRONICS Quadra-Chek 10	Digital readout and computer interface
Leica stereozoom microscope	Accurate measurements
Dolan-Jenner gooseneck illuminator	Lighting under microscope
Desktop computer	Logging ring width measurements
Measure J2X	Data logging software
6 - 5.15mm increment borers	Tree core collection
Bench mounted belt sander	Core sample preparation

Site Selection and Sampling

Dr. Steve Gray assisted students with the identification of appropriate sites around the Green River Basin and Wind River Mountains. A prospective site has one of two moisture sensitive species of tree. The two most prevalent species of moisture sensitive trees in northwestern Wyoming are Douglas Fir and Limber Pine. It is preferred for the trees in a site to be growing on a south facing slope in rocky soil that will not hold moisture for a long period after a precipitation event. When a promising site was located, spot samples were taken from trees and the cores were used to determine the approximate age of the trees by roughly counting visible rings (see figure below).

Spot sampling a site to determine approximate age of trees before sampling the full site.

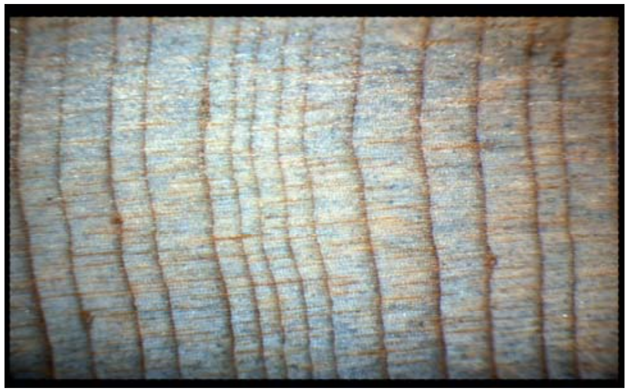
In August 2006, ten sites around the Wind River Mountains were sampled. Douglas Fir were much easier to sample, work with in the lab, and often show a stronger moisture signal. However, it is necessary to sample Limber Pine since they may be the only moisture sensitive species in the area and can provide more detail on regional climate. Three of the sites sampled were Douglas Fir and seven were Limber Pine. Thirty to Fifty trees were sampled per site with a minimum of two 5.15mm core samples (see figure below) per tree. All core samples taken were placed in paper straws and labeled for transportation back to the lab.


Sampling a nearly 1000 year old Limber Pine.

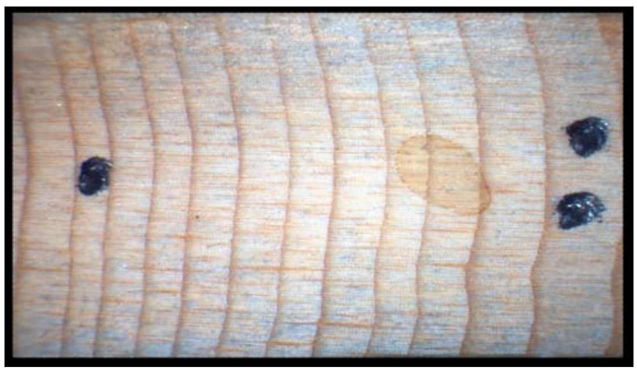
Lab Analysis

The first step (when returning to the lab) involves removing the core samples from straws and gluing the cores to a mounting block (wood trim with a quarter inch groove cut into the top). Once the core is mounted each core is given a flat surface using a bench mounted belt sander with 180 grit sand paper. The first round of sanding is completed by re-sanding the surface with 320 grit sandpaper to remove the grooves caused by the rough sandpaper used to create the flat surface. The second round of sanding is completed just before analysis under the microscope and consists of hand sanding using 400, 600, and if a sample has fine enough rings, 1200 grit sand paper.

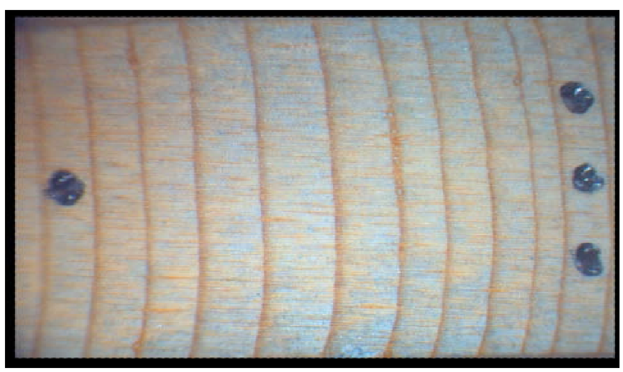
After sanding each sample, the rings are counted under the microscope and marks are place every decade, half century, and century (see figures below). This gives a reference to check when measuring the sample. The reference system also allows for accurate data collection of the rings and may identify false rings or areas where a missing ring may exist. Ring measurement is measured down to thousandths of a millimeter and logged by a computer connected to measurement slide. Once the samples are measured, they are dated using the last ring, the total number of rings, and patterns of ring growth within the sample. The logged and dated data is compiled and verified using two software programs COFECHA (Grissino-Mayer, 2001) and DPL (Dendro Program Library). Both programs are widely used in the creation of tree-ring chronologies.



Ring width variability.



Decade and half century markings.

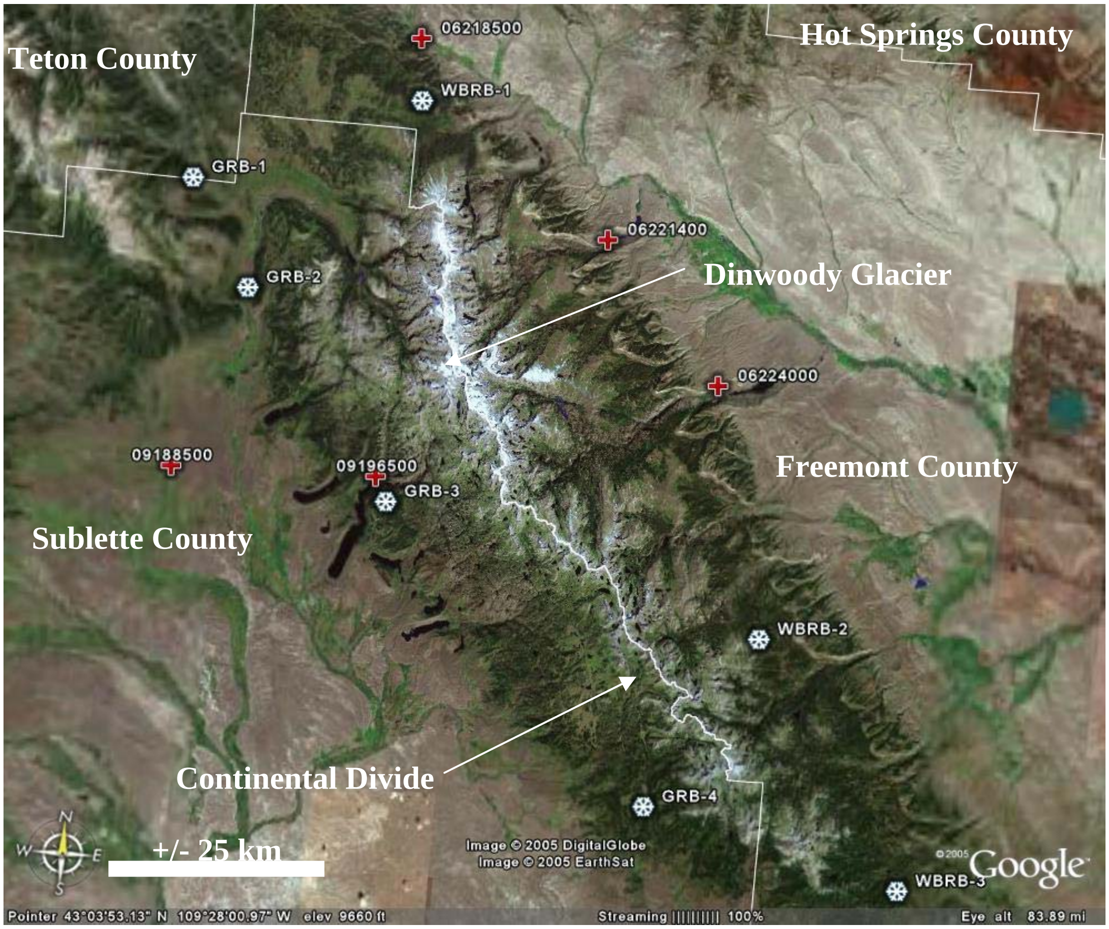


Decade and century markings.

Principal Findings and Significance

Task 1 – No report.

Task 2 – The 5-year filter analysis resulted in stations (both GRB and WBRB) having similar spatial and temporal relationships (see figure and table below).

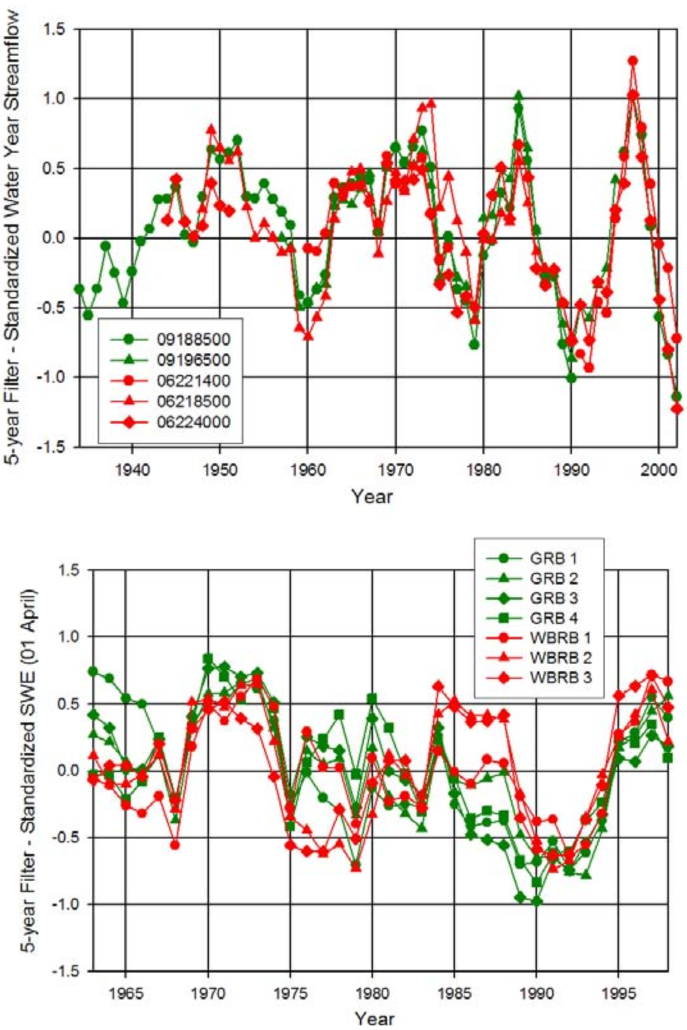


Locations of unimpaired USGS streamflow stations and NRCS SNOTEL stations in the Wind River Range.

List of unimpaired USGS streamflow stations and NRCS SNOTEL stations in the Wind River Range.

River Basin	Site Name	USGS or NRCS Site #	Latitude / Longitude
Green	Green River, Near Daniel, WY	09188500	43.02/-110.12
Green	Pine Creek Above Fremont Lake, WY	09196500	43.03/-109.77
Wind-Bighorn	Wind River Near Dubois, WY	06218500	43.58/-109.76
Wind-Bighorn	Dinwoody Creek, Near Burris, WY	06221400	43.35/-109.41
Wind-Bighorn	Bull Lake Creek Above Bull Lake, WY	06224000	43.18/-109.20
Green	Gros Ventre Summit, WY	506 (GRB-1)	43.39/-110.13
Green	Kendall R.S., WY	555 (GRB-2)	43.25/-110.02
Green	Elkhart Park G.S., WY	468 (GRB-3)	43.01/-109.76
Green	Big Sandy Opening, WY	342 (GRB-4)	42.65/-109.26
Wind-Bighorn	Little Warm, WY	585 (WBRB-1)	43.50/-109.75
Wind-Bighorn	Hobbs Park, WY	525 (WBRB-2)	42.87/-109.09
Wind-Bighorn	South Pass, WY	775 (WBRB-3)	42.57/-108.84

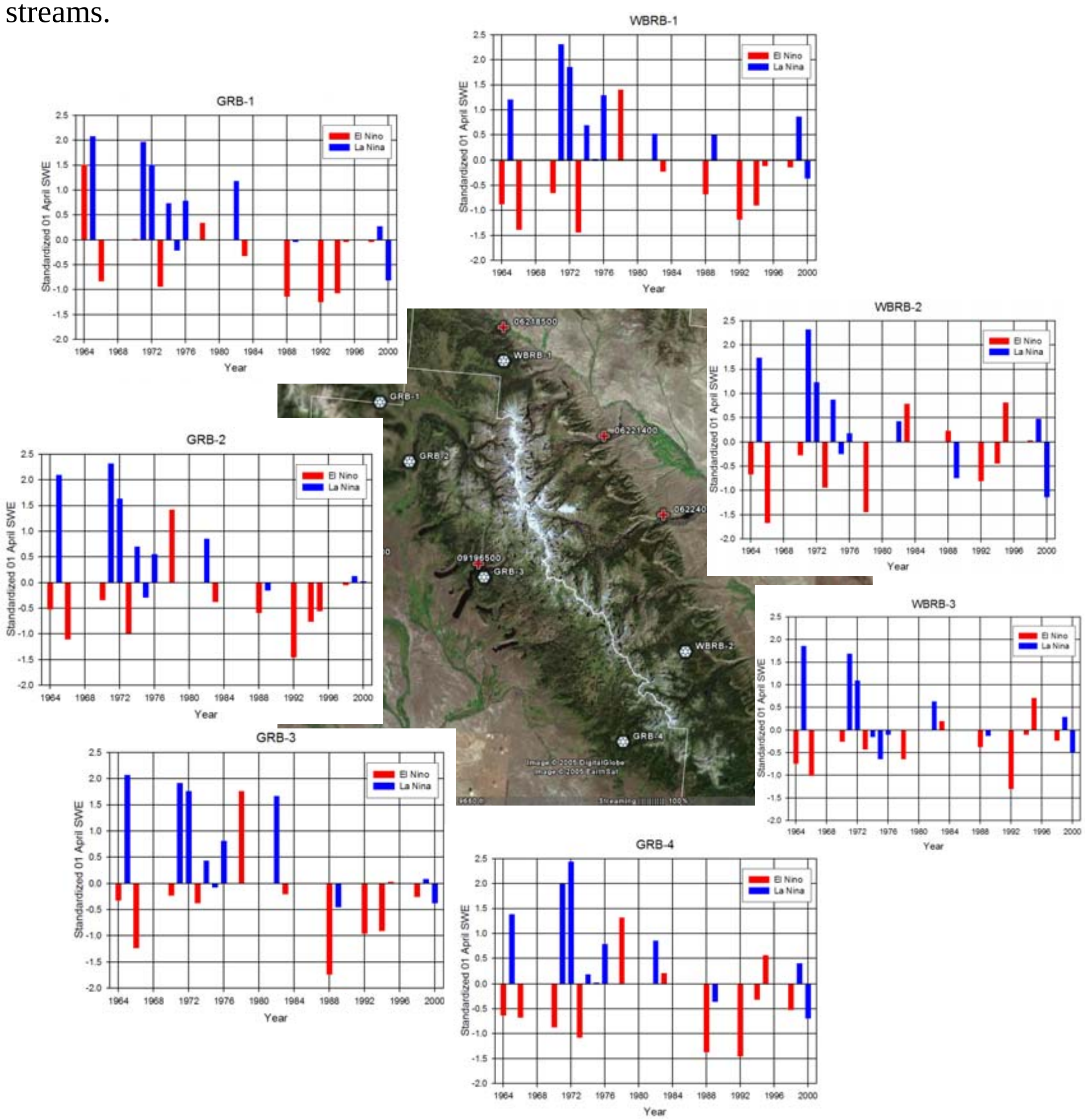
The period of record varied for the streamflow stations while a common period of record (1961 – 2000) was identified for the SNOTEL stations. Interestingly, for the 40 year period of record (1961-2000), the average 01 April SWE for the four GRB SNOTEL stations was 14.4 inches with a standard deviation of 4.7 inches. The average 01 April SWE for the three WBRB SNOTEL stations was 14.4 inches with a standard deviation of 4.2 inches. Therefore, snowfall amounts were virtually identical on each side of the continental divide.



5-year filter applied to Standardized Water-year Streamflow and 01 April SWE.

Initially, the phases (cold and warm) were evaluated for the PDO and ENSO (individually) such that significant (greater than 95%) differences in streamflow (and SWE) means were reported. Next, the coupled impacts of the interdecadal PDO phases on La Niña (and El Niño) on streamflow (and SWE) means were evaluated.

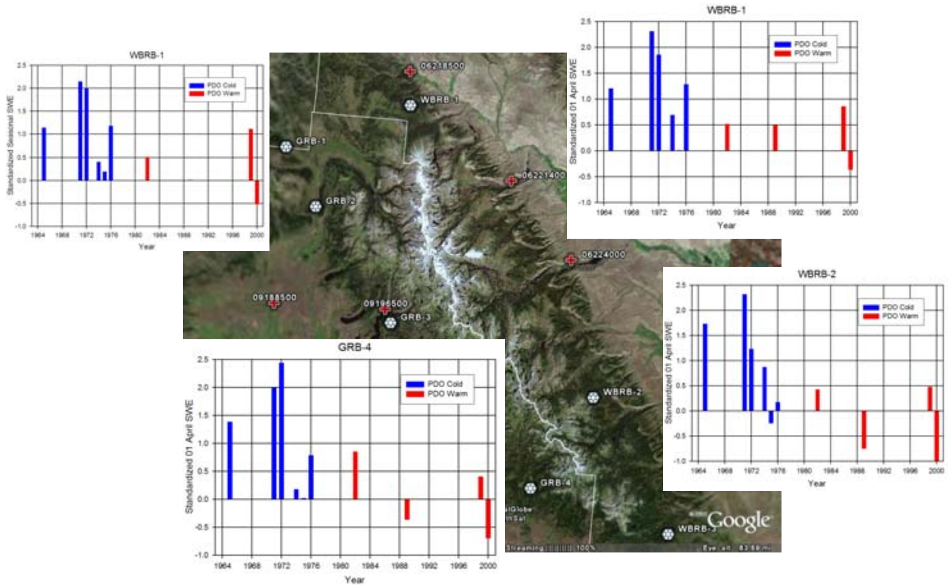
The PDO signal (at 95% significance) was not detected in either streamflow or SWE. However, a significant ENSO signal was detected in three of five streamflow stations and all seven SWE stations. Figure 4 presents standardized 01 April SWE for La Niña and El Niño years. For all the SWE stations, the average standardized 01 April SWE after a previous summer season La Niña (El Niño) was +0.69 (-0.43). Neutral previous year summers resulted in average standardized 01 April SWE of -0.12. Therefore, a previous year summer La Niña (El Niño) results in increased (decreased) snowfall. Interestingly, the two streamflow stations (Dinwoody Creek – 06221400 and Bull Lake Creek – 06224000) that failed to show an ENSO signal appear to have high contributions of glacial meltwater. This may explain why the ENSO signal was not identified in these streams.



Standardized 01 April SWE for La Niña (blue) and El Niño (red) years.

Finally, an evaluation of the PDO’s influence on ENSO was performed. For example, given the occurrence of a La Niña (or El Niño), how does the phase (cold or warm) of the PDO enhance (or dampen) the influence of La Niña (or El Niño) on streamflow (or SWE). The testing of PDO Cold – El Niño and PDO Warm – El Niño and, the testing of PDO Cold – La Niña and PDO Warm – La Niña for the streamflow stations resulted in no stations having a statistically significant difference in water-year streamflow.

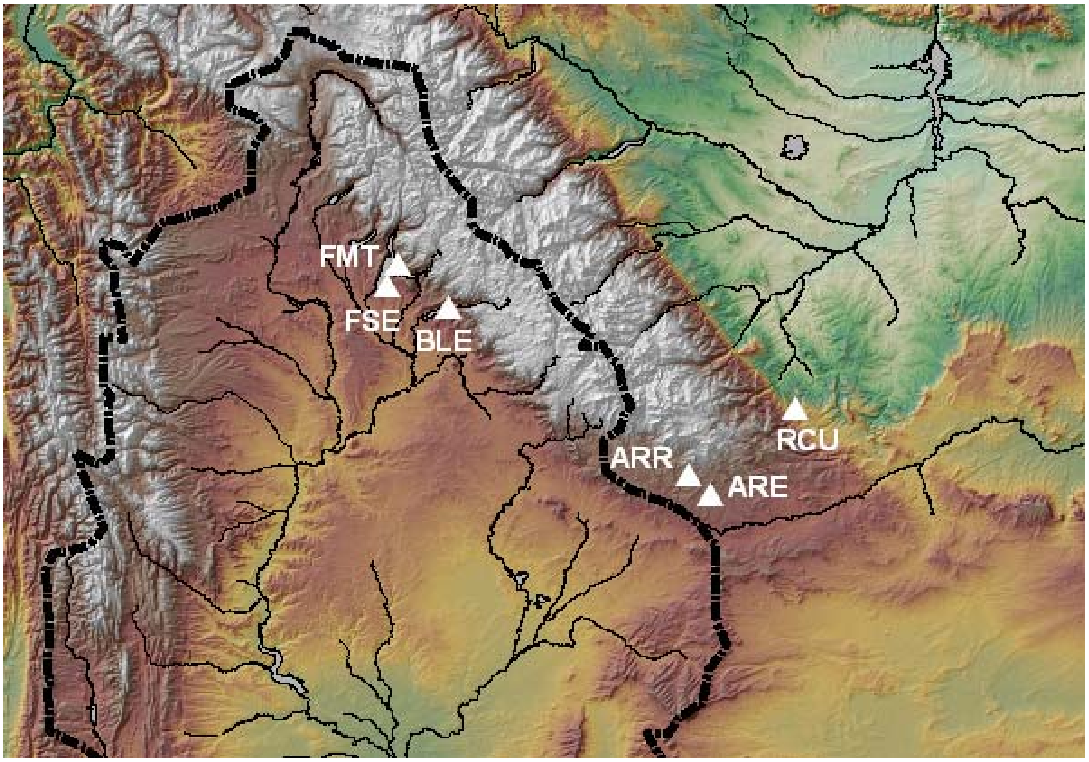
The testing of PDO Cold – El Niño and PDO Warm – El Niño for the SWE stations resulted in no stations having a statistically significant (greater than 90%) difference in 01 April SWE. However, when testing PDO Cold – La Niña and PDO Warm – La Niña, three of the seven SWE stations were identified as having statistically significant (greater than 90%) differences in means (Figure 5). For all seven stations, the average standardized 01 April SWE, given a previous summer season La Niña during a PDO Cold phase, was +1.07 while the average standardized 01 April SWE, given a previous summer season La Niña during a PDO Warm phase, was +0.12. Given that La Niña (i.e., ENSO cold phase) results in increased SWE, the PDO Cold phase enhances La Niña in this region. This is consistent with the findings of Harshburger et al. (2002) that ENSO (El Niño or La Niña) is strongest during the similar PDO (warm or cold) phase.



Standardized 01 April SWE for PDO Cold (blue) and PDO Warm (red) for La Niña years.

Task 3 – No report.

Task 4 – The ten sample sites collected in August were narrowed down to useable samples after the first round of sanding. Two of the sites were immediately eliminated due to their spatial location with respect to sites that had longer record and cleaner samples. One site had samples with rot pockets (in the same time period) that limited the number of usable cores such that it would require re-sampling. Two Limber Pine sites with good sample size were combined into one large site due to their close spatial proximity. After reducing the number of sites, this resulted in three Douglas Fir sites and three Limber Pine sites (see figure and table below).



6 sites sampled that are being analyzed in lab.

Site name and species.

Site Name	Tree Species
ARE	Limber Pine
ARR	Douglas Fir
BLE	Douglas Fir
FME	Limber Pine
FMT	Douglas Fir
RCU	Limber Pine

Presentations

Tootle, G.A., T. Hunter and T.C. Piechota, 2006. Pacific Oceanic / Atmospheric Variability and the Wind River Range. Presentation at ASCE World Water & Environmental Resources Congress 2006, May 21-25, 2006, Omaha, NE.

Hunter, T. and G.A. Tootle, 2006. Oceanic-Atmospheric Variability and Western Snowfall. American Geophysical Union (AGU) Hydrology Days, March 20-22, 2006, Fort Collins, Colorado.

Cheesbrough, K., Watson, T. and G.A. Tootle, 2006. Pacific Oceanic / Atmospheric Variability and the Wind River Range. American Geophysical Union (AGU) Hydrology Days, March 20-22, 2006, Fort Collins, Colorado.

Barnett, F.A. Climate History of the Upper Green River Basin. University of Wyoming Stook Forum, November 2006, Laramie, Wyoming.

Barnett, F.A. Upper Green River Basin Drought Analysis. November 2006, USGS/WRP Annual Meeting, Cheyenne, Wyoming.

Student Support Information

The USGS / WRP research grant is currently supporting three graduate students: Anthony Barnett, Kyle Cheesbrough and Tom Watson. Tom is scheduled to graduate (Master's in Civil Engineering) in Summer 2007 while Anthony and Kyle are scheduled to graduate (Master's in Civil Engineering) in Fall 2007.

References

Fisher, R.A. and F. Yates, 1938. *Statistical Tables for Biological, Agricultural and Medical Research*. Oliver & Boyd, Edinburgh.

Grissino-Mayer, H.D., 2001. *Evaluating Crossdating Accuracy: A Manual and Tutorial for the Computer Program COFECHA*, Tree-Ring Research, Vo 57(2), 205-221.

Harshburger, B., H. Ye, and J. Dzialoski, 2002. Obervational evidence of the influence of Pacific sea surface temperatures on winter precipitation and spring stream discharge in Idaho. Journal of Hydrology 264(1-4):157-169.

Hunter, T., Tootle, G.A., and T.C. Piechota, 2006. *Oceanic-atmospheric variability and western U.S. snowfall*. Geophysical Research Letters, 33, L13706.

Loaiciga, H.A., 2005. *On the Probability of Droughts: The Compound Renewal Model*, Water Resources Research, 41,W01009,doi:10.1029/2004WR003075

Maidment, D.R. (1993). *Handbook of Hydrology*. McGraw-Hill, New York, NY.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997. *A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production*. Bulletin of the American Meteorological Society, 78, 1069-1079.

Mantua, N.J. and S.R. Hare, 2002. *The Pacific Decadal Oscillation. Journal of Oceanography*, 59(1), 35-44.

Rogers, J.C. and J.S.M. Coleman, 2003. Interactions between the Atlantic Multidecadal Oscillation, El Niño/La Niña, and the PNA in winter Mississippi Valley stream flow. *Geophysical Research Letters*, 30(10), 25-1-4.

Tootle, G. A., and T. C. Piechota, 2006. *Relationships between Pacific and Atlantic ocean sea surface temperatures and U.S. streamflow variability*, Water Resources Research, 42, W07411.