LESSONS FROM GAUGES ON HIGH

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Existing precipitation networks in mountainous regions provide a rich source of data for exploring spatiotemporal variability in water resources in important headwater areas. The growing record of observations from networks like SNOTEL is crucial for understanding both the geographic variability in precipitation on synoptic-to-decadal timescales and resultant hydrologic and ecological impacts. Examples of lessons learned from using high elevation precipitation gauges alongside lowland gauges from the northwestern United States illustrate the value of maintaining these networks. First, spatial patterns of event-based and water-year precipitation totals exhibit striking structure whereby windward slopes of the Cascades and Northern Rockies exhibit commonalities in orographic dynamics as progressive weather systems move eastward and encounter north–south-oriented topographic barriers. Secondly, the character of synoptic patterns substantially influences the character of precipitation totals across mountain regions. For example, a distinct gradient in mountain precipitation is seen during slow moving cutoff low synoptic regimes whereby orographic enhancement on westerly slopes is greatly diminished and locations typically in the lee of mountain barriers can receive substantial precipitation amounts. Finally, spatial heterogeneity in recent precipitation trends across the northwestern United States and potential causal mechanisms are discussed.

Topography and microclimate and Pepperwood Preserve, California

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Understanding the topographic basis for microclimatic variation is very important for predicting the effects of warming temperatures. Measures like seasonal diurnal fluctuation and seasonal extremes in relation to elevation and topography give insight into regions that are buffered vs those that are coupled to free atmosphere. We studied temperature data from fifty hobo-enabled sites over an annual cycle (2014). The sites were spread across a large area of mixed evergreen-deciduous woodland in Northern California. The area is topographically diverse and houses vegetation representative of California Coastal ranges. We investigated the effect of landscape features with respect to climate variables. We found several of our sites showing considerable amount of buffering compared to regional temperatures. Furthermore, we found clusters of sites exhibiting characteristics of cold-air pools at fairly large scales. Statistical models of these patterns will be important for extrapolation across large landscapes and improved downscaling of future climate projections.

Creation of an undergraduate mountain research institute curriculum

John All, Andy Bunn, Andy Bach, Doug Clarke, Eric Dechaine, James Loucky, Ruth Sofield, and John Tuxill

Opportunities for undergraduate students to pursue mountain research, especially in international locations, are limited because of the need for travel resources, broad scientific knowledge, and specific mountain survival skills. WWU has created a consortium of mountain scientists and institutions with the goal of expanding undergraduate access to mountain research and developing holistic environmental research projects that examine both environmental and societal responses to the anthropocene. Working with faculty across disciplines, a diverse curriculum is being created to prepare students as broadly as possible for the myriad of challenges that can result from mountain research projects. Specific topics includes field data collection, grant writing, research permits, environmental science theory, community stakeholder interviews, research presentation, and outdoor survival skills including first aid, climbing, and incident response. Project locations include the North Cascades, the Rockies, the Talamancas of Costa Rica, the central Andes, and the Mount Everest region. Research data collection includes water quality, snow particulates, social adaptation to climate change, soil chemistry, vegetation change, resource management strategies, rangeland degradation, ecosystem restoration, water politics, medicinal plant management, and the creation of regional plant field guides to nurture additional research. During the initial formation of this institute, we are soliciting comments and suggestions as widely as possible, and we hope you will join us for this talk.

Plant and Microbial Functional Types at the Snowfields and Periglacial Patterned Ground of Glacier National Park

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Glacier National Park in Montana is the home of snowfields and glaciers that are in the process of disappearing due to climate change. The edges of snowfields and glaciers provide water in the form of melted snow and ice to plants that live along and near their edges. To study the distribution of species and functional types in snowfield-edge plants at GNP, we established paired lateral and leading edge transects at the Siyeh Pass, Piegan Pass, and Mt. Clements Moraine snowfields and recorded species and trait distributions. Key results of regressions were: 1) the significant decreases in the community weighted trait mean (CWTM) of specific leaf area (SLA, mm^2/mg dry weight) with distance from the snow, meaning that snowfield edge leaves were less dense than leaves from 50m away, and 2) that clonality took different forms with distance from the snow. Rhizomes were the chief form of clonality near the snow, while adventitious roots became more important with distance from the snow. The periglacial patterned ground adjacent to the Siyeh and Piegan Pass snowfields is recognizable as solifluction terraces with stripes of green risers dominated by mat-forming dwarf shrubs alternating with sparsely vegetated rocky brown treads that have a higher percentage of rare arctic-alpine plant species. In the summer of 2016, we will return to GNP to continue our comparisons of species and trait distributions of plants and to examine the distribution of microbial functional groups at the striped patterned ground. To do so, we anticipate sampling soil, extracting DNA, and classifying microbes into functional groups based on genetic characteristics. The results of this project will be useful in understanding the microbial landscape and the feedback between plant species, functional traits and microbial distribution.

CHANGING TROPHIC STATE OF AN ALPINE AND A SUBALPINE LAKE IN ROCKY MOUNTAIN NATIONAL PARK

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Mountain lakes are changing rapidly from a triad of driving forces: non-native species, cultural eutrophication, and climate change. Some combination of these influences lake ecology in alpine Sky Pond, and subalpine The Loch in Loch Vale watershed, Rocky Mountain National Park. Using a range of different methods we ask: are increasing temperature and nutrients pushing Loch Vale lakes to a new trophic state? While we have monitored these lakes for water quality since 1982, limnological studies have been more sporadic. In response to atmospheric N deposition in the mid-20th century diatom assemblages reflected a shift in lake trophic state from ultra-oligotrophic to mesotrophic. In 2010 we noticed an increase in benthic primary productivity that has continued and possibly strengthened to the present, possibly indicating yet another shift toward eutrophication. In addition to sustained high atmospheric N deposition and lake nitrate concentrations, there has been a 30-year trend of increasing summer lake temperatures and a possible increase in phosphorus availability. It now appears both benthic and pelagic productivity are increasing. In August 2015 alpine water column chlorophyll *a* in alpine Sky Pond ranged 2.5-14.2 μg L^{-1}, > 2X higher than in the subalpine Loch (range 0.9-4.2 μg L^{-1}). Benthic chlorophyll a generally increased with temperature, with peak values of about 7.0 μg L^{-1} in Sky Pond, and about 5.0 in The Loch. Past measures of chlorophyll *a* concentrations in our lakes have been sporadic since 1984, but they suggest greater productivity since 2006. We are beginning a community effort to gather limnological data from mountain lakes worldwide to synthesize what is known about their conditions and trends.

YELLOW-CEDAR IN ALASKA 1995-2013: POPULATION-LEVEL CHANGES IN THE CONTEXT OF CLIMATE

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Previous research has attributed yellow-cedar decline in Alaska to freezing injury in years of low snowpack. In 2014 yellow-cedar (*Callitropsis nootkatensis*) was proposed for listing under the Endangered Species Act, based on the expectation of increased mortality as the climate warms. We used a 2004-2013 FIA inventory of forests in the temperate rainforest of Alaska (5536 plots; 671 plots with yellow-cedar) to estimate current numbers and area of occupancy, examine evidence of past mortality, and assess past range contraction. A subset of 564 yellow-cedar plots which had previous measurements from 1995-1998 was used to estimate recent population change for more than 65 percent of the area where yellow-cedar occurs in Alaska. We estimate there are 1.39 billion live yellow-cedar trees in Alaska, with yellow-cedar found on an estimated 2.16 million ha of forest. An analysis of live tree to snag ratios was consistent with high levels of pre-1995 mortality of yellow-cedar, but also indicated that very little range contraction has occurred. Live tree to snag ratios increased with increasing elevation, consistent with observations that yellow-cedar decline occurs in lower elevation areas with reduced snowpack. However, we found that between the two inventories (1995-98 to 2004-2013) yellow-cedar had a relatively low mortality rate, 0.41 percent of trees per year, compared to most other conifer species in the Alaskan temperate rainforest. In the 97% of forest without previous harvesting, the yellow-cedar population increased from 1995 to 2013, with a 95% CI of a 0.3 to 3.3 percent increase per decade in live tree basal area. Increases may be related to competitive release in areas with previous mortality and/or ongoing ‘migration’ to higher elevation areas with more snowpack. Results provide strong evidence against near-term extirpation, and also illustrate that climate-related tree population dynamics can be both spatially and temporally complicated.

RESPONSE AND RESILIENCY OF WESTERN GRAY SQUIRRELS (*SCIURUS GRISEUS*) TO CLIMATE CHANGE AND LARGE-SCALE DISTURBANCE IN THE NORTH CASCADES

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Changing climatic patterns have been affecting the western US in a variety of ways: overall decreases in yearly precipitation, decreased snowpack, earlier spring snowmelt, increased sustained winds, and increased lightning strikes have created a drier and more fire-prone system, despite variability in these characteristics. Wildfires are a natural phenomenon throughout this area, but have been suppressed for much of the past century. However, the fire regime may be shifting towards a new regime with novel fire patterns due to changing climatic conditions. Effects of this evolving fire regime on native habitats and wildlife presence are not well understood. We are currently investigating how a mega-fire has affected presence of western gray squirrels (*Sciurus griseus,* WGS) in the North Cascades. The Methow Valley in north central WA experienced a record-breaking wildfire event in 2014, which disturbed nearly 50% of priority habitat for the North Cascades population of WGS. WGS populations in the Squaw Creek and Black Canyon watersheds were studied in 2010-2012. After the 2014 fires, plots were placed at identical locations to the earlier study throughout pre-burn habitat types and remaining vegetation patterns. These plots were surveyed for WGS presence using non-invasive hair sampling tubes and camera traps. In preliminary results, WGS were present at over half of the plots (58%). There was a significant difference in the number of WGS hair samples collected in different levels of remaining vegetation: the most in moderate, few in low, and none in high.One year after a large-scale, multi-severity fire we found that WGS may be more resilient to disturbance in the form of large-scale fires than previously thought. Future monitoring of this WGS population will help elucidate long-term response to large-scale fires, and aid in management decisions for the state-threatened species.

The Compounding Consequences of Climate Change and Wildfire for a High Elevation Wildflower in Western North America

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High elevation plants are disproportionally affected by climate change. As mean annual temperatures continue to rise the amount of available alpine habitat in the Rocky Mountains will decrease resulting in potential local extinctions of plant species that exist nowhere else. In addition to the direct effects of climate-driven habitat loss, alpine plants must also respond to changes in disturbance regimes, or indirect effects. One of the most tangible indirect effects is the increase in wildfire frequency in regions that fire was previously rare or absent, including the alpine. We studied the response of *Saxifraga austromontana*, a wildflower endemic to the Rocky Mountain Floristic Region, to the direct effects of climate change and the indirect effect of increased wildfire frequency. Our approach involved integrating historical herbaria records, a four-month field study, Species Distribution Models (SDMs), and future wildfire predictions. We hypothesized that direct climatic changes compounded with increased wildfire frequency will reduce the future suitable habitat of *S. austromontana* more than if climate was considered alone. The results of our field study indicate that wildfire reduces the abundance and increases the likelihood of extirpation for *S. austromontana*. Increased fire frequency compounded with direct climatic changes will reduce the range of the species by >45% by 2050 compared to 40% due to climate alone, under a conservative emission scenario. The effect of wildfire is regional, with the greatest impact in the Middle Rockies where an additional 15% reduction due to fire is predicted. Our work elucidates the importance of considering disturbance factors such as wildfire when forecasting range shifts for high elevation species.

ELEVATION-DEPENDENT WARMING (EDW): EVIDENCE, MECHANISMS AND RESEARCH NEEDS

Raymond S Bradley (University of Massachusetts, Amherst, MA, U.S.A.) and the Mountain Research Institute Working Group on EDW (Bern, Switzerland)

There is increasing evidence that the rate of warming is amplified with elevation, so that high mountain environments are experiencing more rapid changes in temperature than at lower elevations. This “elevation-dependent warming” (EDW) has important implications for the mass balance of high altitude glaciers and associated runoff, as well as for rare and endangered species that reside in restricted altitudinal zones within many mountain ranges. Temperature change at the earth’s surface is primarily a response to the energy balance, and therefore factors which preferentially increase the net flux of energy to the surface, along an elevation gradient would lead to enhanced warming, as a function of elevation. This points to changes in albedo (primarily snow cover), clouds, water vapor and aerosols as likely candidates that drive EDW. However, detecting and attributing the causes of EDW is confounded by data limitations and the difficulties of modeling processes in complex terrain. We may not be monitoring some of the regions of the globe that are warming the most, and therefore we need a comprehensive global strategy for future research that will reduce current uncertainties and ensure that the changes taking place in high elevation, remote regions of the planet are properly monitored.

LOW MOUNTAIN SNOWPACK DRIVES TEMPORAL MISMATCHES BETWEEN SOCIAL AND ECOLOGICAL SYSTEMS IN MT. RAINIER NATIONAL PARK

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As the impacts of climate change continue to mount, it is important for scientists and policymakers to understand how climate influences the links between ecosystems and their social and management context. In this study, we examined how changes in climate influence the temporal match between human visitors and wildflower blooms in subalpine meadow ecosystems at Mt. Rainier National Park, where these blooms are a key visitor draw. Our analysis uses a large, field-validated dataset derived from the Flickr photo sharing service and volunteer citizen scientists to simultaneously track spatial and temporal patterns of human use and wildflowers from 2009 to 2015. We show that the temporal match between these ecological and social systems was highly sensitive to the date of seasonal snow disappearance during our study. Early snow melts, comparable to predicted mean conditions in the late 21st century, caused dramatically reduced temporal overlap between wildflower blooms and park visitors. We also show that climate-driven mismatch was greatest in regions of Mt. Rainier National Park where vehicle access is restricted seasonally, and in regions where wildflower bloom timing was most sensitive to snow melt. This indicates that variations in both the ecological response to climate, and constraints on visitor behavior have strong and direct influences on the potential for temporal mismatch between humans and wildflowers in this system. In-line with ecological and social theory, we expect these temporal mismatches to be common in systems where users of natural resources have limited information about climatic drivers of their resource, and where seasonal shifts in their behavior is constrained by non-climatic factors. Recent dramatic growth in the volume of publicly-available georeferenced photographs coupled with recent advances in computer vision and machine learning, may soon make it possible to to test this hypothesis at very large spatial scales.

PALEOCLIMATIC INDICATORS OF SURFACE WATER RESOURCES IN THE CHUSKA MOUNTAINS, NAVAJO NATION

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Long-term records of hydroclimate for the Navajo Nation are acutely limited. Short records can fail to capture the full range of hydroclimatic variability while longer records capture more climate information. Without long-term records to document the natural variability of water resources in the Chuska Mountains, anticipating water availability in a culturally important region near the Navajo Nation's most populated and economically productive areas is difficult. Snowpack in the Chuska Mountains feeds lakes, streams, and springs. Depressions at the crest of the Chuskas collect snowmelt, providing water for Navajo stock animals, wildlife, fish, and community farms. Recent decades have been characterized by declining snow water equivalent (SWE) in snowpack of northeastern Arizona. At the same time, tribal members report that surface waters supporting agricultural practices and community resources on the Navajo Nation have begun to go dry from extended drought. Here, we collaborate with the Water Management Branch of the Navajo Nation Department of Water Resources (NNDWR) to develop a preliminary 800-year tree-ring reconstruction of snowpack in the Chuska Mountains. Our pilot work is based on local, recently collected tree-ring chronologies from climatically sensitive tree species, *Pseudotsuga menziesii, Pinus edulis*, and *Pinus ponderosa*. Precipitation and snow water equivalent (SWE) data come from 9 snow survey sites in the Chuska Mountains (1985-2015). Snowpack variability and periods of cool-season drought are compared with remotely sensed observations (1984-2015) and historical accounts of lake levels in the Chuskas to examine the relationship between reduced surface waters and snowpack levels. This information may reduce uncertainty around potential variability in the Chuska climate system and is intended to inform NNDWR evaluation of water scarcity implications, assisting with drought planning and decision-making.

Niche spaces in the growth and position of high elevation Bristlecone Pine in the Great Basin, U.S.A.

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We present data on growth and position of hundreds individual bristlecone pine (*Pinus longaeva*) trees situated at and near upper treeline in the White Mountains of California and in the Snake Mountain Range of Nevada, USA. Many of the trees growing at the uppermost alpine treeline show ring-width patterns that vary with temperature at both decadal and interannual timescales. However, some of the trees growing even at the alpine treeline show growth patterns more indicative of drought, rather than classic temperature limitation. We use temperature sensors arrayed across a few square kilometers of complex terrain at treeline at two treeline sites in the Great Basin and show that the biophysical setting of individual trees can explain much of the difference between temperature or drought limitation at a scale of tens of meters. These growth disparities can be explained by understanding the role of topography in creating cold air drainages and can give physiologically-informed niches (e.g., the number of degree hours) for assessing limiting factors at relatively fine scales within a single mountain slope.

Climate influences on mountain pine beetle outbreaks in lodgepole and whitebark pine forests in the western US

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We evaluated the relative influences of climate conditions on recent mountain pine beetle outbreaks in lodgepole and whitebark pine forest types. We developed separate logistic regression models of the probability of lodgepole and whitebark pine mortality across the western US. Our models accounted for stand age, previous year beetle population size, temperature effects on beetle survival and development, and precipitation effects on tree condition. We applied the models to historical climate data from 1978-2009 to investigate the relative influence of each climate metric on the initiation and continuation of the recent outbreaks. In both forest types, tree mortality increased as fall, winter, and spring-summer temperatures increased from the minimum temperatures observed. However, as seasonal temperatures approached the maximums observed, the effects on tree mortality varied by forest type and temperature metric. Lodgepole pine mortality increased with decreasing precipitation at high beetle populations. Whitebark pine mortality increased with decreasing precipitation at all beetle populations. The relative influences of each temperature metric preceding and during the recent outbreaks varied by forest type and geographic region of the western US. Outbreak initiation coincided with years of low precipitation and warmer winter temperatures in whitebark pine more often than in lodgepole pine. After the outbreaks began, climate influences were less important than beetle population influences in both forest types, consistent with previous studies on the self-driving nature of high-density beetle populations. Climate influences were relatively more important in whitebark pine than lodgepole pine stands. We also applied the models to a future climate scenario, using 1978-2009 observations plus two degrees Celsius. Averaged across the west, future climate suitability for lodgepole pine mortality remained nearly equal to historical suitability and future suitability for whitebark pine mortality increased. There were, however, differences in future suitability trends among geographic regions.

DISTURBANCE AT TREELINE: A MECHANISM FOR CHANGE OR STABILITY IN AN ERA OF GLOBAL CHANGE?

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Treelines are globally predicted to respond to climate change, however the role that disturbance may play in accelerating or slowing these dynamics remains poorly understood. To that end, we conducted a review and synthesis of the literature; specifically, we assessed whether disturbance caused measurable differences in the direction, magnitude, or rate of treeline ecotone response to climate change. To identify relevant studies we searched the literature (Scopus database) and developed an initial database of 1323 unique results. We then eliminated papers that did not meet the following criteria: original research conducted in arctic and alpine ecotones, the intervention must be some type of natural pulse disturbance, and an outcome of the disturbance on the treeline ecotone was reported. We did an in-depth assessment of the papers for which the above criteria were met, recording on the following outcomes: changes in treeline position, tree species composition, abundance, and the pattern and structure of the ecotone. We also noted any information about climate effects on the treeline, linkages between disturbance and subsequent disturbances, and indirect effects (*e.g.* competition, changes in environmental stress. Disturbance could immediately affect treelines by directly killing trees; in most cases where the elevation of treeline shifted in response to disturbance, it shifted downwards. In contrast, disturbance sometimes accelerated treeline movement upslope or to higher latitudes, particularly in arctic regions, by changing competitive interactions in formerly treeless areas. Indirect impacts of disturbance were often long-lasting, and occurred in response to post-disturbances changes in biotic interactions and abiotic stresses. Interactions between multiple disturbances were common, particularly between fire and grazing in European and tropical alpine treelines. While climate may limit the maximum elevation at which trees can grow, the rate and direction of treeline responses to climate change will vary due to the direct and indirect effects of disturbance.

FIRE INFLUENCES FOREST STRUCTURE IN ALPINE TREELINE ECOTONES

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Alpine treelines are expected to move upward in a warming climate, whereas anticipated increases in wildfire are expected to depress them. We studied the effects of fire on vegetation structure and composition within four alpine treeline ecotones in the Pacific Northwest and Northern Rocky Mountains extending from *Abies lasiocarpa/Picea engelmannii* forests at lower elevations, through *Pinus albicaulis*/*Larix lyallii* parkland, to alpine tundra. We estimated the likelihood that different pre-fire canopy-cover structural classes would burn or change to a different structural class after fire. We also evaluated changes in the size structure and composition of trees. Fire severity and fire effects were mixed: non-forested areas were less likely to burn than the landscape as a whole; forests were more likely to remain forests than to become non-forested; and dense closed-forests never became non-forested, even when they burned with high severity. Higher severity fire also killed larger overstory trees more than expected. Our results suggest that vegetation at the alpine treeline will not respond simply to a warming climate and increased fire. Instead, ecotones will become wider and more heterogeneous with larger patches.

Fine-scale environmental influences on red fir seedlings in the Sierra Nevada

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Given observed increases in the mortality of conifer species in mountainous regions of the Western US and projections of future climate change, seedling recruitment is critical to forest persistence. Fine-scale environmental conditions (approximately 1 m^3) are thought to play an important role in successful tree recruitment, but little is known about which specific environmental factors are most influential. Furthermore, coarser-scale environmental controls on recruitment may differ from fine-scale controls. We report results from a five-year study of 3,500 red fir seedlings in a 1-hectare site located in the western Sierra Nevada (2,500m). Additionally, we measured a suite of fine-scale environmental factors at 225 locations to project environmental conditions at a 1-m spatial scale with spatial statistics. Using machine learning techniques, we found that several fine-scale biotic and abiotic conditions, including stand structure characteristics, snowmelt date, potential evaporation, and access to mineral soil, influence the persistence of seedlings in the complex forested landscape. We also found that influences differ as seedlings mature, and preliminary evidence suggests that influences differ across spatial scales. Based on our results that fine-scale environmental conditions are important for seedling recruitment, we posit that a better understanding of fine-scale environmental heterogeneity is needed to project future geographical ranges and to identify refugia for conifer tree species.

SNOWY MOUNTAINS WITHOUT SNOW? INSIGHTS FROM A NEW SEDIMENT CORE FROM BLUE LAKE, KOSCIUZSKO NATIONAL PARK, AUSTRALIA

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The Snowy Mountains are an iconic symbol of the conditions in the highest, coldest mountains in mainland Australia. However, have they always been "snowy," and will they continue to be in the face of anthropogenically-forced warming? Blue Lake, a 320 ha tarn in the highest part of the Snowy Mountains in Kosciuszko National Park, provides an excellent site to evaluate the timing and magnitude of climate change since the last glaciation. The lake occupies the cirque of a small Pleistocene valley glacier that was deglaciated by 17-18 ka, as indicated by exposure ages on downvalley moraines. As such, it should contain a detailed, continuous sedimentologic record of climatic and ecological change in the area since that time. In particular, the sediments should record responses in the range to regional events, such as the Antarctic Cold Reversal (ACR), as well as to more recent shifts during the Holocene. In mid-July, we recovered two short gravity cores and a ~8-m long Livingston core from the lake. Preliminary analysis of the cores indicate that they preserve a highly detailed record of environmental change in the region, including possible varved sediments immediately following deglaciation. Further analyses, to be presented at the meeting, will include an age model based on AMS ^{14}C dating of macrofossils, detailed sedimentology, and chironomid-based lake temperature records. These results promise to provide the most detailed record of post-LGM climate fluctuations yet established in southeastern Australia. As such, they should help test regional climatic synchrony between Australia and similar records from New Zealand and Patagonia, as well as test potential teleconnections between the southwest Pacific and the northeast Pacific. The chironomid temperature reconstructions should also let us assess whether the Snowy Mountains have truly been "snowy" through the Holocene, and, by inference, predict how the range may respond to warmer conditions in the future.

INVESTIGATING HYDROCLIMATE VATIABILITY IN EASTERN WASHINGTON USING A TREE-RING ISOTOPES ($\delta^{18}O$ AND $\delta^{13}C$).

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Here we present isotopic records of $\delta^{18}O$ and $\delta^{13}C$ from ponderosa pine (*Pinus ponderosa*) from six sites located in the lee of the Cascades in eastern Washington, USA. We have data from two sites for the period 1700-2015 and from 1900-2015 from the remainder.The trajectory of incoming storms from the Pacific Ocean has a strong impact on hydroclimate in the Pacific Northwest. Shifts between zonal and meridional flow are a key influence on drought and pluvial regimes in both the PNW and the western United States as a whole. Circulation-dependent variability in the isotopic composition of precipitation can be recorded and potentially reconstructed using $\delta^{18}O$ records derived from tree-rings. Because of the orientation of the Cascades zonal flow will result in an intensified rain shadow, and a drier E. Washington, whereas meridional flow allows moisture to penetrate at a lower elevation leading to a lower rainout effect. We hypothesized that more depleted precipitation $\delta^{18}O$ values will occur with periods of more zonal flow and will be recorded by trees at our sites. We also hypothesized that $\delta^{13}C$ should provide us with information about summer drought stress at our sites. Results show a strong relationship between our $\delta^{18}O$ chronologies and winter precipitation ($R = -0.50$; $p<0.001$). We regressed the tree-ring $\delta^{18}O$ anomaly against the instrumental record of total precipitation and compared the residual series to records of storm track for the period 1978-2008, and focused on years with clear zonal and meridional flow regimes and found a detectable signal where the most depleted $\delta^{18}O$ was generally associated with zonal flow and the most enriched $\delta^{18}O$ with meridional flow, however there are still some years where the relationship is unclear. We also compared our records against atmospheric variables and found a strong correlation between tree-ring $\delta^{18}O$ and 500mb geopotential heights over Washington, suggesting that storm track shifts are likely responsible for the variability in $\delta^{18}O$.

REDUCING OUR IMPACT ON RIVERS AND STREAMS THAT ARE AFFECTED BY HYDROELECTRIC DAMS, BY IMPROVING THE TECHNOLOGIES THAT ARE USED TO HARNESS HYDROELECTRIC POWER.

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It’s apparent that the more commonly practiced methods of harnessing hydroelectric power are not so efficient and far too obtrusive to wildlife. What I have chosen to focus on for the duration of this conference is a less intrusive and more efficient personal hydroelectric power generator. The term is Micro Hydro power, I believe. The goal of this project is to minimize altercations with fish and wildlife that are otherwise losing access to accustom living areas. Recently there have been some great developments in the Elwha river restoration project. The Glines Canyon Dam was recently removed and stream restored to its usual flow and has already seen a return of the indigenous wildlife. The use of Micro Hydro Power systems will in turn yield a much larger stream flow in rivers once deprived of proper flow due to the large structures. The current state of rivers and streams affected by dams should be compelling enough evidence to sway your opinion. It has been stated by residents along the Elwha River that the streams have not seen salmon runs in nearly one hundred years and that prior to the dams salmon runs were so thick that you could not help but bump into salmon when swimming. The less intrusive and obstructive our structures can be the lesser our impact will be on the delicate ecosystem which has already been tampered with. With the completion of this project streams nationwide would be restored to their full flow and smaller hydroelectric systems set in place far enough out of the way that they would not disrupt salmon runs and other wildlife residing in rivers.

CONSEQUENCES OF MIDLATITUDE PACIFIC STORM TRACK VARIABILITY FOR ECOSYSTEMS OF WESTERN NORTH AMERICA

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Much of the precipitation delivered to western North America arrives during the cool season via the midlatitude Pacific storm track. The strength, position, and angle of the storm track varies from year to year, and this variation is a major driver of western hydroclimate. Here, we find that the standardized precipitation-evapotranspiration index (SPEI) in western North America exhibits a dipole-type response to changes in the position of the storm track. For land areas south of 50°N latitude, particularly the northwestern United States, more northerly storm track positions are associated with drier winters while wet winters tend to occur during years when the storm track is displaced farther south. Higher latitude ecosystems, particularly along the Pacific coast in northwestern Canada, tend to exhibit the opposite response. When the storm track is displaced north, the reduced water delivery to the Pacific Northwest results in a reduced snow pack throughout the Cascades, Sierras, and parts of the Rockies. Using the AVHRR normalized difference vegetation index and historical fire extents derived from Landsat satellite imagery, we show that variation in the position of the midlatitude Pacific storm track and associated precipitation and snow pack anomalies have significant consequences for the ecosystems of western North America. The start of the growing season exhibits a relatively small but spatially coherent response to storm track variability, while the peak greenness of terrestrial vegetation exhibits a dipole response similar to the SPEI. In the northwestern United States, the area burned by moderate and severe fire is positively correlated with storm track latitude. A long-term northerly shift in the position of the midlatitude Pacific storm track, as expected under a warming climate, could therefore alter both the prevailing hydroclimatic regimes and ecosystem processes of western North America.

THE EFFECT OF SEVERE DROUGHT ON TREE MORTALITY IN OLD-GROWTH MIXED CONIFER FORESTS OF THE SIERRA NEVADA CALIFORNIA

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California is experiencing a drought of a severity unprecedented in the instrumental record. Not surprisingly, the drought has had substantial effects on California forests, including large increases in tree mortality, particularly at lower elevations. Some evidence suggests that such droughts may become more common in a changing climate. In that light, the consequences of the current drought may be highly relevant to our understanding the future of forests in the Sierra Nevada. We took advantage of long-term forest demography plots, some of which are experiencing highly elevated drought-related mortality, to study the similarities and differences between typical background mortality and mortality during a severe drought. We found that that the size structure of mortality was not substantially different than that of background mortality but that there were marked differences in the species composition of that mortality. Increases in overall mortality were associated with strong increases in biotic attack, and there was evidence of substantial increases in the activity of insects normally considered minor contributors to tree mortality. These results suggest that drought mortality likely differs in some respects from those of other disturbances, such as fire, and that previously unexamined biotic factors made lead to unexpected outcomes. In addition, our results may have implications for understanding drought vulnerability, particularly with regard to tree size. We argue that understanding biotic interactions will be critical for improving our ability to forecast future mortality.

TALLYING UP THE CALIFORNIA DROUGHT

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California's recent drought has been singular in the amount of public and scientific attention it has garnered, in its intensity and duration, and in the number of attempts to ascribe it in part or all to climate change. Precipitation lagged well behind normals during 2012-2015, and temperatures were record-breaking warm in several years. Kelly Redmond describes drought as "insufficient water to meet needs," a necessarily inclusive definition that leaves the question of "which needs" to the reader. From this perspective, the current drought has trickled down into all sectors of the water cycle and to water users in all parts of the State. California's reservoirs, snowpacks, rivers, vegetation, and groundwater have all suffered considerably. This presentation tracks the drought through key parts of the California water cycle in shared units so that the drought in various sectors can be directly compared. Specifically, how much of the drought has been precipitation deficit and how much "extra" evaporative demand? How much less (than normal) snowpack and streamflow formed? How much extra groundwater has been pumped? How have the State's reservoirs fared, and how much hydropower generation has been lost? How has the salinity of the San Francisco Bay-Delta evolved? Comparisons of these different drought metrics indicates, e.g., that precipitation deficits drove most of the drought--especially in the Sierra Nevada--but not all of it. Indeed, in the immediate rain shadow of the Sierra Nevada, extra evaporative demands amounted to more water than the precipitation deficits. In absolute terms, snowpack deficits have dwarfed reductions in reservoir storage, and surface water deficits have been much larger than extra groundwater pumpage. These and other niceties of the drought will be explored, along with some first looks at extents to which various aspects of the drought recovered during this year's "great" El Nino.

Uncertainties in drought risk assessment under climate change because of differences in methodological choices for the estimation of evaporative demand

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We examine sources of uncertainties arising from the methodological choices and selection of global climate model (GCM) output for the assessment of future drought risk in the continental US (CONUS). One such uncertainty is in the climate models' expression of evaporative demand (E_0), which is not a direct climate model output but has been traditionally estimated using several different methods. We analyze daily output from CMIP5 GCMs to evaluate how different methodological, driving data and GCM choices made for the estimation of E_0 give different assessments of spatio-temporal variability in E_0 and different trends in 21st-century drought risk. First, we estimate E_0 using three widely used E_0 formulations: Penman Monteith, Hargreaves, and Priestley-Taylor. Our results show that seasonal patterns of E_0 differ substantially between these three formulations. Overall, we find higher magnitudes of E_0 and its interannual variability using Penman Monteith, in particular for regions like the Intermountain West and Great Plains where E_0 is strongly influenced by variations in wind and relative humidity. When examining projected changes in E_0 during the 21st century, there are also large differences among the three formulations, including some regions showing changes in opposite directions, particularly the Penman Monteith relative to the other two formulations. The 21st-century E_0 trends, particularly in percent change and standardized anomalies of E_0, are found to be sensitive to the long-term mean value and the amplitude of interannual variability, i.e. if their magnitudes are low, the trend is amplified. These methodological choices, as well as specific climate model selection, also have a large influence on the estimation of trends in standardized drought indices used for drought assessment operationally. We find that standardization tends to amplify divergences between the E_0 trends calculated using different E_0 formulations, because standardization is sensitive to both the climatology and amplitude of interannual variability of E_0.

AN INVENTORY OF GLACIERS ACROSS THE AMERICAN WEST AND THEIR CHANGES OVER THE PAST CENTURY

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Glaciers are important features of the alpine landscape. They are significant agents of erosion and deposition that modify the landscape and in some situations they trigger dangerous debris flows and flooding. Glaciers and perennial snowfields (G&PS) are also important hydrological features posing as frozen reservoirs of water, releasing most melt water during the hottest and driest months of summer. This runoff mitigates droughts and provides a dependable source of cool water to high alpine ecosystems. Defining the population, distribution, and change of G&PS contributes to our current understanding of alpine hydrology and ecology, and to predicting future changes in the face of climate warming. An inventory of G&PS suggest as many as 5029 exist in the American West of which about 1275 are considered glaciers. The elevation distribution of the G&PS is bi-model with low elevation (<2800m) G&PS in the Pacific Northwest and high elevation (>3200m) elsewhere. All glaciers are in retreat with the smallest recession in the Pacific Northwest. The glaciers on the Cascade volcanoes from northern California to Washington, the highest and largest glaciers in the Pacific Northwest, show significant mass losses over the past 20-30 years. Their mass loss with elevation does not show a uniform decrease but display a more complex pattern with the maximum losses in the middle elevations, probably due to rock debris that typically mantle and insulates the lowest elevations. The temporal pattern of loss over the past century is largely uniform across the region with rapid retreat early in the 20th century, stabilization/advance mid-century, followed by accelerated retreat in the late 20th to early 21st century. These changes are governed by variations in air temperatures and modified by variations in precipitation. Modeling of future climate and glacier response suggests that G&PS loss will continue to accelerate in the coming decades.

Spatiotemporally variable thermal landscapes and implications for Pacific salmon in a changing climate

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Understanding spatial and temporal patterns in water temperature will be essential for evaluating vulnerability of salmon to future climate and for identifying and protecting diverse thermal habitats. We used high-resolution remotely sensed water temperature data for over 16,000 km of 2nd to 7th-order rivers throughout the Pacific Northwest and California to evaluate spatial patterns of summertime water temperature at multiple spatial scales and to consider how these patterns may change. We found a diverse and geographically distributed suite of whole-river spatial patterns. About half of rivers warmed asymptotically in a downstream direction, whereas the rest exhibited complex and unique spatial patterns. Patterns were associated with both broad-scale hydroclimatic variables as well as characteristics unique to each basin. Within-river thermal heterogeneity patterns were highly river-specific, but cool patches were generally large enough for juvenile rearing and for resting during migration, and the distance between patches was within the movement capabilities of both juvenile and adult salmon. We found considerable thermal heterogeneity at fine spatial scales that may be important to fish that would be missed if data were analyzed at coarser scales. Climate change will cause warmer temperatures overall, but thermal heterogeneity patterns may be less responsive in the future for many rivers. We used empirical data in one watershed to generate spatiotemporally explicit predictions of water temperature and considered how our understanding of thermal regimes is shaped by the way we summarize data (e.g., minimum, mean, maximum, variance). Spatial patterns of mean water temperature across the watershed were very different than spatial patterns for, say, variance in water temperature during months when fish eggs incubate. Using data for 2015, a warm, dry year suggestive of conditions that will occur more often given climate change, we found differences in spatiotemporal patterns from more typical years that may be important to fish.

SNOW PROMOTES FOREST GROWTH IN WATER-LIMITED PINE FORESTS—A RELATIONSHIP AMPLIFIED BY FOREST DENSITY

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Climate warming and subsequently declining snowpacks are driving widespread changes across the western US. Forest growth is related to water and energy limitations, as well as biophysical interactions of competitive intensity. In four pine forests which span an aridity gradient across the western US, we examine correlations of forest growth from a range of forest densities with multiple snow and seasonal climate metrics. Forest growth demonstrated differential responses to the seasonality of water availability depending on the water- vs. energy-limitations of the site and the competitive intensity of the forest. Winter precipitation promoted forest growth in the water-limited sites, whereas growing season precipitation promoted forest growth in the energy-limited sites. Snow water storage provides an important moisture subsidy to high elevation/low latitude water-limited forests; whereas snow may restrict forest growth in high latitude energy-limited forests by reducing the duration of the growing season. Water-limited forests, particularly at high densities, may be exceptionally vulnerable to future declining snowpacks and increasing frequency and severity of drought.

NO SNOW NO FLOW?: NEW INSIGHTS FROM A YEAR WITHOUT SNOW IN THE CASCADE MOUNTAINS OF OREGON, USA

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The winter of 2015 brought almost no snow to the Cascade Mountains of the U.S. Pacific Northwest, eerily presaging what climate models predict for the region by 2080 as a result of climate warming. We explored the consequences of this anomalous year on streamflow, focusing on how mountain landscapes in the Cascades underlain by both old and new volcanic rocks would respond. Previous predictions from hydrologic models suggested that streamflow in the newer portions of the volcanic arc would have record low streamflows. While summer streamflows tied records, they did not go as low as predicted. In some cases, streamflow recessions closely mirrored other low flows previous years despite substantial differences in precipitation and recharge, suggesting that some degree of streamflow response to extreme snow drought might be hard-wired into the landscape's plumbing. We draw on these and other data to argue that in regions with large volume aquifers, year-to-year variation in recharge might be substantially buffered. But for how long? Extreme years such as 2015 provide both a window into the future and an opportunity to test predictions on regional response to a warming climate.

ADAPTING NATURAL RESOURCE MANAGEMENT TO CLIMATE CHANGE IN THE PACIFIC NORTHWEST: THE BLUE MOUNTAINS, SOUTH CENTRAL OREGON, AND SOUTHWEST WASHINGTON ADAPTATION PARTNERSHIPS

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Concrete ways to adapt to climate change are needed to help natural resource managers take the first steps to incorporate climate change into management and minimize the negative effects of climate change. We recently initiated three science-management climate change adaptation partnerships in the Pacific Northwest, encompassing seven national forests and one national park. Goals of the partnerships were to: (1) synthesize published information and data to assess the exposure, sensitivity, and adaptive capacity of key resource areas, including water use, infrastructure, fisheries, and vegetation and disturbance; (2) develop science-based adaptation strategies and tactics that will help to mitigate the negative effects of climate change and assist the transition of biological systems and management to a warmer climate; (3) ensure adaptation strategies and tactics are incorporated into relevant planning documents; and (4) foster an enduring partnership to facilitate ongoing dialogue and activities related to climate change in the partnerships regions. After an initial vulnerability assessment by agency and university scientists and local resource specialists, adaptation strategies and tactics were developed in a series of scientist-manager workshops. The final vulnerability assessments and adaptation actions are incorporated in technical reports. The partnerships produced concrete adaptation options for national forest and other natural resource managers and illustrated the utility of place-based vulnerability assessments and scientist-manager workshops in adapting to climate change.

BIG UNRESOLVED QUESTIONS IN ECOHYDROLOGY REQUIRE TRANSDISCIPLINARY MOUNTAIN SCIENCE

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Water resources are being stressed by changing climate and increasing demand from ecosystems and people. Most water resources are derived from snowmelt in the Western U.S. Despite this reliance on snowmelt, basic questions in mountain ecohydrology related to changing snowpacks remain unanswered: Will we get more water in streams and aquifers as snow changes to rain? How will vegetation adapt their water use to new snowmelt regimes? How will future hydrological regimes impact carbon uptake and sequestration in mountain forests? How do we measure and predict these changes over landscapes with widely variable hydroclimate and surface and subsurface structure? Answering these questions requires transdisciplinary research that transcends a single discipline, captures greater complexity, and creates new intellectual advances that are synergistic across the disciplines of hydrology, ecology, meteorology, soil science, geomorphology, and the social sciences. While this sounds good in theory, actualizing transdisciplinary science is not easy. I will present examples of where transdisciplinary successes have occurred in my own career, where there are existing opportunities to further transdisciplinary mountain science, and what roadblocks early career scientists should consider when navigating transdisciplinary collaborations.

SLOWER SNOWMELT IN A WARMER WORLD WILL ALTER SUBSURFACE HYDROLOGY AND BASIN-SCALE WATER BUDGETS

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Mountain snowmelt is a critical water source for ecosystem health and downstream human populations. Here we explore the relatively unknown hydrologic effects of two recent trends in Western U.S. snowpack dynamics: 1) increasing magnitude of winter season ablation and 2) earlier and slower snowmelt. We used 463 Snow Telemetry (SNOTEL) stations with >7500 site-years to demonstrate that winter ablation (i.e. melt or sublimation prior to peak snow water equivalent) has increased by an average of 1.1 cm/decade from 1985-2015. A total 139 of 463 sites had significant increases in winter ablation, with the largest increases in the Pacific Northwest. The average spring snowmelt rate decreased by an average of 7.3 mm/day/decade on average, with significant decreases at 55 stations. Additionally, the 10% highest ablation days slowed by 21.3 mm/day/decade on average, with significant trends at 149 stations. We applied two modeling tools with different strengths to understand the hydrologic effects of recent snowmelt trends: 1) the Variable Infiltration Capacity (VIC) at 6 km-scale with more simplistic representation of subsurface properties and processes and 2) the one-dimensional (point-scale) HYDRUS model that used measured soil properties at SNOTEL stations to solve the Richard's equation. The VIC model runs across mountain regions of the Western U.S. showed streamflow was lower during slower snowmelt, with snowmelt rate explaining 42% of the variance in climate-corrected streamflow. The HYDRUS model runs confirm that earlier and slower snowmelt limits exceeding soil field capacity and reduced drainage below the root zone. Together these observations and modeling results suggest that expected slowing of snowmelt rates will lead to reduced runoff efficiency and greater partitioning of precipitation to evapotranspiration. We will discuss how co-variation between snowmelt patterns and streamflow generation determines the most at-risk areas for altered snow water resources across the Western U.S.

The influence of snow water equivalent, summer drought, and habitat quality on spatiotemporal patterns of spruce beetle infestation in the Southern Rocky Mountains

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Throughout coniferous forests of western North America native bark beetles (*Dendroctonus* spp.) have caused widespread tree mortality, altering timber resources, carbon sequestration, habitat quality, hydrology, ecosystem structure and function. Despite an increased recognition of the importance of drought in promoting broad-scale bark beetle outbreak, it is unclear how snow, which may account for more than 60% of the annual precipitation in bark beetle-prone forests, affects outbreak dynamics. Here we present results from a spatiotemporal analysis of spruce beetle (*Dendroctonus rufipennis*) outbreak across the Southern Rocky Mountains that demonstrates the sensitivity of spruce beetle populations to snowmelt water availability, summer drought, and habitat heterogeneity. We first used Landsat imagery to create annual maps of spruce-beetle induced tree mortality for the 1999-2014 period. These maps were then aggregated to a stand scale (990 x 990 m) and used as input in an aspatial cluster analysis to determine the distinct temporal patterns of infestation. Plots of the geographic locations of each temporal pattern revealed both concentric growth patterns, indicative of spruce beetle dispersal, and multiple disconnected locations of incipient spruce beetle activity, suggestive of a regional driver (e.g. drought). After accounting for spruce beetle dispersal, a random forest model driven by GIS-based biophysical covariates revealed high tree cover, summer drought, and low peak snow water equivalent favored beetle infestation. These results confirm the importance of drought and habitat quality in driving spruce beetle outbreak and suggest that predictions of future outbreak should consider climate change-driven changes in snowmelt water availability.

HIGH ELEVATION PRECIPITATION UNCERTAINTY AND INFERENCE OF SIERRA NEVADA PRECIPITATION PATTERNS FROM STREAMFLOW

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As is the case in most mountainous areas, observing precipitation across high-elevation basins of the Sierra Nevada of California is challenging, due to a relatively sparse network of precipitation gauges at these altitudes. Gridded datasets that estimate precipitation across the landscape likewise show larger uncertainties in mountainous areas, often complicating efforts to model hydrological processes. However, numerous observations of streamflow are also made in the Sierra, which offer additional information about the water balance of the basin with which to estimate precipitation. Here, we consider unimpaired streamflow observations from a dataset of >100 current and historic stream gauges across the Sierra from the mid-20th century to the present. We apply a Bayesian methodology for inferring basin-mean precipitation from these streamflow observations. To do this, we calibrate semi-lumped hydrologic models representing each basin, using streamflow to infer multiplicative corrections to gridded precipitation forcing data. We compare the resulting streamflow-based estimates of precipitation against widely-used precipitation gauge-based gridded datasets. From this analysis, we draw the following conclusions regarding Sierra Nevada precipitation patterns: 1) precipitation inferred from streamflow exhibits greater spatial variability than that seen in gridded precipitation datasets, with greater precipitation maxima on windward (southwest) facing basins and larger spatial gradients, 2) year-to-year variability is greater in streamflow-based estimates of precipitation than in gridded datasets, and 3) high-elevation trends in streamflow-based precipitation datasets differ from trends in gauge-based gridded datasets. These findings suggest that the incorporation of streamflow into precipitation datasets may improve representation of high-elevation hydrologic processes and trends.

ASSESSING HISTORICAL CLIMATE AND FINE FUEL DRIVERS OF REGIONAL-FIRE YEARS IN CENTRAL AND EASTERN OREGON

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Fire activity in the western US increased in the late 20th century in response to warming and earlier spring snow melt. Previous tree-ring studies have shown that historical fire activity varied with warm season temperature and drought, but spring snow and long-term fine fuel (i.e., vegetation productivity) records were not available. In the mountains of central and eastern Oregon, we inferred the climate drivers of forest fires from 17 fire occurrence chronologies reconstructed from tree rings (10 new plus 7 existing chronologies). Together, these chronologies span nearly 5 degrees of longitude and the period 1670 to 1900. We identified 28 regional-fire years as those exceeding the 90th percentile in number of sites with fire (i.e., during which 5 or more sites recorded fire). We compared these chronologies to existing independent tree-ring reconstructions of summer climate (Palmer Drought Severity Index and temperature), large-scale climate patterns (El Niño-Southern Oscillation), and new independent reconstructions of snowpack and fine fuels productivity (a rangeland yield index). Individually, all four climate parameters synchronized fire across the region during regional-fire years, but not during antecedent years. However, there was little indication of a significant influence of prior year fine fuel production on regional-fire years. Regional-fire years tended to occur when spring snowpack was low and summers were warm-dry, but were only weakly associated with El Niño years, when springs tend to be dry and warm in the region.

CLIMATE CHANGE ADAPTATION LIBRARY

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The Climate Change Adaptation Library was recently developed to assist resource managers and planners with responding to climate change effects. The Library was derived from seven (7) climate change vulnerability and adaptation projects encompassing 37 national forests and 28 national parks in the western United States. Adaptation strategies (general approaches) and tactics (on-the-ground actions) were developed for vegetation, hydrology and infrastructure, fisheries, wildlife, and recreation. More than 1200 participants in 21 workshops identified more than 200 adaptation strategies and 800 adaptation tactics. This collection of adaptation options can be used in a variety of applications, including planning documents (e.g., land management plans), resource management strategies (e.g., conservation plans), project design (e.g., activities at specific locations), and resource monitoring evaluations (e.g., monitoring objectives). In general, climate change adaptation is not intended to transform sustainable management, but to fine-tune and prioritize existing management tools and techniques in the light of projected climate change effects. Although federal agencies have been slow to develop organizational capacity to implement climate-smart management, we anticipate that this process will accelerate as the effects of climate change become more apparent (e.g., large wildfires, flooding) and disrupt agency operations.

SNOW VERSUS RAIN: DO CONIFER SPECIES DIFFER IN SOURCE WATER USE ACROSS A MONTANE ECOSYSTEM IN THE NORTHERN ROCKY MOUNTAINS?

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Across the western U.S., declining snowpacks have resulted in increased water limitations, increased fire frequency and disease outbreak, and reduced forest productivity. While total precipitation is predicted to increase in the future, the proportion of snow versus rain will likely decrease. However, what remains unknown is how forest trees will use these different sources of precipitation. In a watershed in western Montana, we linked the physical characteristics of the watershed (e.g. different elevations, aspect, and micro-topography) with source water use of the dominant conifers, including *Pinus ponderosa*, *Pseudotsuga menziezii*, *Picea engelmannii*, *Larix occidentalis*, and *Abies lasiocarpa*. We used oxygen and hydrogen isotopes to examine water source use by these different species at two-week intervals throughout the growing seasons of 2013, 2014, and 2015. We found that trees growing in the hollows used water with a more snowmelt signature than trees growing in the sideslopes. This was most likely due to upslope subsidies of snowmelt water to the hollow areas at the higher elevation sites. However, we found that trees growing at lower elevation sites (with shallower snowpacks) used proportionally more water with a snowmelt signature than trees at higher elevations (with a deeper snowpack). This was most likely due to the trees at lower elevation depending on deeper, more reliable water when the upper soils dried down during midsummer. These results suggest that lower elevation montane forests might depend more on snowmelt than previously believed and that summer precipitation might be a less important water source than winter snow.

DETECTING ATMOSPHERIC DEPOSITION OF NITRATE, ITS SOURCES AND EFFECTS ON LAKES IN THE UINTA MOUNTAINS, UTAH

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Mountain lakes in western North America are important water resources and biodiversity hotspots, which are commonly thought of as pristine. However, distant human activities resulting in atmospheric pollution, such as nitrate, could be impacting these sites. The Uinta Mountains in Utah, situated on the border of Wyoming and Utah, are characterized by hundreds of lakes, many of which are relatively remote and unaffected by direct human activity. This means that the effects of atmospheric deposition of nitrate are not confounded by local disturbances and are, therefore, more easily detected. Here we review our research findings, which combine a variety of isotopic and paleolimnological techniques, to determine the sources and effects of nitrate on these mountain systems. We use an isotopic approach ($\Delta^{17}O$, $\delta^{18}O$ and $\delta^{15}N$) to show that ~70% of nitrates in Uinta Mountain Lakes originate from distant human activities (10% from fossil fuel burning and 60% from fertilizers used in agriculture). Based on comparisons to the nitrate isotope compositions measured in lakes from other mountain ranges, we suggest that nitrate from fertilizers may be affecting many mountain regions of the western United States. Paleolimnological data indicate that nitrate deposition began in the mid-20th century, coincident with intensified fertilizer use, and this increase in nitrate caused an increase in the diatom *Asterionella formosa* and an increase in overall algal production. By quantifying the source of nitrates and its effects, we provide direction for effective mitigation, but also show challenges in balancing food production with protection of limited water resources.

THE MASSIVE NORWEST STREAM TEMPERATURE DATABASE AND HIGH-RESOLUTION CLIMATE SCENARIOS: HOW CROWD-SOURCING AND SOCIAL NETWORKING FORGED A USER-COMMUNITY ACROSS THE AMERICAN WEST TO PROTECT AQUATIC BIODIVERSITY

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Climate change is warming streams in mountain landscapes and threatens significant societal investments (billions of $US) to conserve iconic cold-water species like salmon and trout. The NorWeST (Northwest Stream Temperature) project began in 2011 to organize disparate stream temperature datasets within the Pacific Northwest into a database for developing stream climate scenarios because none existed. The project has since grown to encompass the American West and service the needs of >100 resource agencies as they adapt to climate change effects on aquatic biodiversity. Most of the data in the database (>150,000,000 hourly recordings at >20,000 stream sites) were "crowd-sourced" from 100s of fish biologists and hydrologists. Geostatistical models for stream networks were used with the database to develop accurate temperature models (r^2 = 0.90; RMSPE = 1.0°C; MAE = 0.65°C) and interpolate consistent 1-km resolution scenarios for >1,000,000 stream kilometers. Because of the NorWeST model's accuracy, availability of data products in user-friendly formats, and extensive empirical support based on data contributed by people working in local landscapes, the scenarios are rapidly adopted for decision making. Open access to the database and scenarios through the project website (http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.shtml) also facilitates inter-agency coordination of new monitoring efforts and stream temperature research. NorWeST was achieved by a small technical team (4-6 people) with complementary skillsets (i.e., relational and geospatial databases, spatial statistics, ecology, webdesign) that worked part-time on a limited budget ($100,000/year). Keys to project success were strong engagement with the management community, use of blogs and email chat for low-cost communication, and timely provision of data products, which created a project reputation that spread through social networks to enable subsequent successes in new geographic areas. The broader terrestrial mountain climate community may benefit from a similar science model as it seeks to develop information and engage users in climate adaptation this century.

ASPEN STAND VULNERABILITY AND UNDERSTORY COMPOSITION ALONG ENVIRONMENTAL GRADIENTS

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Quaking aspen (*Populus tremuloides*) woodland is an important community type in semi-arid mountains and woodlands of the western US. Although they constitute only a small portion of the landscape in this region, aspen communities provide critical food and cover resources for wildlife. Aspen is currently undergoing a region-wide decline, and climate predictions show that within 50 years approximately 40% of western aspen stands will no longer have a suitable climate. Drought within the past decade has been reported to cause mortality in western aspen. In Colorado, mature stands on south-facing slopes at low elevations were found to be particularly susceptible to disease and insects as a result of acute drought and high temperatures. Shifts from a snow to a rain dominated precipitation regime and subsequent loss of moisture through the growing season may prevent vegetative regeneration and cause aspen mortality. We are developing a methodology for classifying aspen stands on a drought continuum using gradient analysis of understory species composition and indicator species analysis with the goal of characterizing the hydrology of the aspen clone; vegetation indicator species will serve as a new metric for tracking response to climate change. At a broader scale we are assessing aspen stand vulnerability in relation to environmental data including topographic position, landscape curvature, topographic indicators of wetness, climate, and snow depth.

Microsites Promoting Seedling Regeneration in the Alpine Treeline Ecotone Worldwide

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Tree regeneration in alpine treeline ecotones (ATE) is associated with favorable microsites, earth surface sites ameliorating local stresses, but no known previous global summary has related microsite type with local climate. We differentiated five general ATE microsite form types ranging from mm to km in scale through extensive international literature review. We evaluated relationships among microsite type, tree genus, and mean annual precipitation and temperature and differentiated major climate zones. Most frequent microsite occurrence by zone was: concavities in cold/dry locations, shade in warm/wet locations, wood and convexities in cold/wet regions, and few locations with no microsite dominance in warm/dry zones. Topographic microsites occurred in all climate zones. Our summary elucidates both temperature and precipitation as limitations for seedling regeneration globally. Based on these findings, we hypothesize how impacts of climate change on tree regeneration pattern and forest advance potential might be realized.

INITIATING CLIMATE CHANGE SCENARIO PLANNING FOR WHITEBARK PINE AND AMERICAN PIKA

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Managing our montane national parks and protected areas necessitates strategic plans that acknowledge significant future uncertainty associated with climate change. Scenario planning integrates current knowledge with future uncertainty. By identifying key drivers of change and their related uncertainty we can prioritize resources, optimize preparedness, limit risk, and increase response efficiency. Effective scenario planning requires substantial initial preparation, through building partnerships, identifying strategic goals, compiling up-to-date information, and identifying challenges. We are initiating a climate change scenario planning program for montane ecosystems across three National Park Service Inventory & Monitoring Networks - Klamath, Sierra Nevada, and Upper Columbia Basin - focused on two species of conservation concern, whitebark pine (*Pinus albicaulus*) and American pika (*Ochotona princeps*). Through regional workshops we have identified a range of drivers in six major categories – climate, geological, biological, ecological, sociopolitical, and technological. Key climate uncertainties include precipitation and snow pack trends and their impacts on hydrology, phenology, diseases, and species interactions. Interacting geological, biological, and ecological factors that affect metapopulation connectivity, dynamics, and persistence are critical. Challenges facing both species include the scientific confusion over differing species-level model projections and the climate-model ‘genealogy’; identifying genetic and functional connectivity among populations; and local adaptation patterns. Technological and sociopolitical challenges include identifying adaptive genetic markers such as rust-resistance in WBP and monitoring physiological vital signs and survival of individual pika, issues of assisted migration, and how to fund long-term management strategies within short-term funding cycles. Conservation of both species will benefit from outreach and education to the public and resource managers and identifying near-term, low-risk management actions that will increase functional connectivity and maintain genetic diversity. Science communication may consider a paradigm shift, presenting these iconic species as emblems of persistence rather than peril to encourage an optimistic rather than fatalistic outlook.

Are climate-growth relationships at treeline changing?: Energy limitation and mountain hemlock in a warming climate.

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Climate-growth relationships in treeline forests can be particularly informative because they represent the upper limit of a species range where growth is especially sensitive to climatic variation. Radial growth response to climatic variables typically ranges from energy limited to water limited. In the Pacific Northwest (PNW) region of North America, treeline forests are typically energy limited, especially on north aspects. Results from a recent study (Marcinkowski et al. 2015) indicate a change in climate-growth relationships over time in treeline mountain hemlock (*Tsuga mertensiana*) in a portion of Washington State. We are investigating these changes throughout a large portion of the PNW. We will use tree cores collected during the summer of 2016 to examine the extent of change in limiting variables, including April 1 SWE, precipitation, and temperature. We will compare growth over time to the climate record, concentrating on trends in the past 20 years. We will also compare growth responses between north and south aspects for each site. Possible outcomes of this study include (1) a potential weakening of energy limitation in forest growth at treeline, and (2) a difference in growth-limiting variables between north and south aspects. Results can be used to inform where a change in limiting variables may be occurring in the PNW and improve our understanding of growth and productivity of subalpine forests at treeline.

DOES SNOWPACK AFFECT LOW FLOWS IN WESTERN MOUNTAIN RIVERS AND STREAMS?

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The Pacific Western US had exceptionally low snowpack and warm air temperatures in 2015. US Geological Survey documented streamflow responses to the 2105 drought across a six state region (CA, ID, NV, OR, UT, and WA) and analyzed how various factors influenced the severity of low flows. While snowmelt runoff was well below normal across the region, low flows were more variable reflecting factors other than snowpack including the length of the summer dry period and hydrogeology. The sensitivity of streams to particular factors can be used to assess where streams are likely to be most vulnerable to exceptionally low flows in a given year and to identify the important meteorological characteristics for forecasting low flows and for assessing climate change impacts.

SPATIAL HETEROGENEITY OF VEGETATION INCREASES FOREST RESISTANCE TO WILDFIRE, AND MODERN FORESTS HAVE A HIGH POTENTIAL FOR LARGE, STAND-REPLACING EVENTS

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Heterogeneity in vegetation spatial structure is widely thought to increase the resilience of California's Sierra Nevada forests to regular wildfire disturbance. However, direct empirical evidence of this phenomenon is limited due to the vast spatial and temporal time scales at which it manifests. We examined how vegetation spatial structure affects two components of resilience—resistance and precariousness—spanning a 30-year time period across the entire forested area of the Sierra Nevada range. We assessed forest heterogeneity, wildfire severity, and high-severity patch size distributions for 178 wildfires in Sierra Nevada forests using Landsat satellite imagery and Google Earth Engine. We found that greater variance of vegetation density within a 2-hectare neighborhood around a focal point correlates with reduced wildfire severity at that point. We also found that increasing numbers of large, high-severity patches in the past 30 years have shifted the distribution of high-severity patch size towards one more closely resembling a power law function. Power law patch size distributions are characteristic of a system that has a low potential for shifts in its defining processes (i.e., the system has low precariousness). Our results suggest that variable vegetation spatial structure increases the resistance of Sierra Nevada forests to wildfire, and that very large high severity patch sizes are an expected and stable outcome of current forest conditions.

PACIFIC CREST TREELINE: A TREELINE MONITORING TRANSECT

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Over the next century western North American conifer forests are predicted to experience distributional shifts and declines in coverage in response to climate change induced warming, droughts, fires, and insect and disease outbreaks. These responses will vary by species, latitude and elevation. Documenting the locations of current treelines, and the species that comprise them, across a broad gradient of latitude and elevation can act as a benchmark for monitoring future treeline shifts, as well as responses of associated understory species. In the western United States, the Pacific Crest Trail (PCT) forms a continuous 4,278 km transect from the Mexican to Canadian borders. This transect passes through a variety of ecosystems ranging from desert scrub to alpine tundra. In July and August of 2016, I traveled the northern 2,011 km of the PCT from near Burney, California to Manning Park, British Columbia. Along the way, I recorded the locations of all natural treelines (upper, lower, meadows, avalanche tracks, burn scars and lava flows). At each location I recorded the tree species forming the treeline, GPS coordinate, aspect, elevation, type of treeline, trail kilometer as well as photographs facing north, south, east and west. These data will be made available to other researchers via an online database. Future monitoring of these treelines, and potential new treelines, will be done via a citizen science initiative. I anticipate traveling the southern 2,267 km of the PCT in spring/summer 2017, completing this baseline dataset. Here I present a detailed description of the methods for this project, as well as preliminary data and observed patterns.

SNOW IN THE WESTERN US UNDER ANTHROPOGENIC WARMING

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Changes in snowpack arising from increasing greenhouse gases may have important consequences for water resources and ecosystems in the Western U.S. where the snowpack provides surface storage for water demand in summer when precipitation is low. We present results of an unprecedentedly large ensemble of climate simulations generated by weather@home, a citizen science computing platform, where Western U.S. climate was simulated for the recent past (1985-2014) and future (2030-2059) using a coupled regional/global model (HadRM3P/HadAM3P) at 25-km resolution. Our results show that, in winter and spring, snow albedo feedback is a dominant control on the spatial pattern of warming, and the largest temperature increase occur at mid-elevation sites, where substantial snowpack is first expected to disappear. We also investigate elevation control of precipitation falling as rain vs. snow in winter and spring, which could have important implications for water management decisions at different locations. Lastly, we will present projections of the length of the snowfall season.

ALASKA TREELINE AND FOREST CLIMATE: FROM THE PERHUMID TO THE ARCTIC

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I present multiple years of climatic observations from treelines and some related subalpine forests in Alaska along a gradient from the perhumid zone of Southeast Alaska to the interior Arctic. This gradient consists of eleven mountain sites including three maritime temperate, two transitional, and six continental boreal. Treelines are dominated primarily by mountain hemlock (*Tsuga mertensiana*) in the south and white spruce (*Picea glauca*) in the north.. I present seasonal comparisons of observed treeline climates and evaluate their relative positions in species' climate envelopes for the main conifer species present. Along this gradient, winter precipitation is greater in the south than in the north, though snowpack does not necessarily last longer – within-site variability in snowmelt timing and snow-free season is sometimes nearly as large as among-site variability within a region or among regions. During the winters of 2013/14-2015/16, winter temperatures above freezing occurred at least as high as 900m in the south but are comparatively rare in the north. Surface and near-surface (~10cm) soil temperatures generally remain near 0C in the maritime southeast and transitional southcentral climates, but snowpack is insufficient in the Arctic interior to buffer surface and near-surface soil temperatures, which are influenced by air temperature at weekly timescales. Unsurprisingly, growing seasons appear to vary in length and degree days both across the gradient and among years within regions, but in all cases, growing season frosts appear uncommon, likely because high solar loading limits the potential for outgoing infrared radiation. Frost-driven photoinhibition may be less important in limiting microsites than in comparable treelines in the mountain West. Taken together, these observations argue for a macroecological differentiation of treeline limiting factors, and as such, the responses of treelines to regional climatic change may be radically different than is often presumed.

PATTERNS OF POST-FIRE FOREST RECOVERY IN COMPLEX TOPOGRAPHY

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Understanding the drivers and spatial variability of post-fire forest recovery is critical to predicting both how ecosystems may respond to climate change and where management actions may best influence ecosystem resilience. Here, I will contribute to that understanding with initial results from a field-based assessment of how terrain-driven climate variability influences patterns of forest recovery. I inventoried juvenile conifers in areas that experienced complete overstory mortality in the 2006 Tripod Complex fire, which burned in the lower-elevation and montane mixed conifer forests of Washington's Okanogan-Wenatchee National Forest. I stratified sites by several topographic indices – topographic wetness index, heat load index, and elevation – to capture a range of emergent climatic conditions (or "topoclimates"). Using these indices, a remotely-sensed topoclimate dataset, weather station data, and *in situ* relative humidity and temperature measurements, I will characterize how the spatial pattern of juvenile trees that has emerged 10-years since the fire – including species composition, density, year of establishment, interannual growth – reflects terrain-driven climate variability. My results will highlight spatial configurations with relatively less robust juvenile recruitment where management that promotes recovery and reduces vulnerability to future disturbances may be desirable. On the other hand, spatial configurations with more robust juvenile recruitment – especially of higher-elevation species – may suggest the potential for climate microrefugia that may be considered for protection. With this research, I seek to inform the growing efforts to use topography as an efficient guide for resilience-enhancing management and conservation prioritizations across large landscapes and under climate change.

CHANGES FROM SNOW TO RAIN CAN INCREASE OR DECREASE STREAMFLOW AND GROUNDWATER RECHARGE DEPENDING ON LOCAL CLIMATE AND SOILS

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Snowpacks act as mountain reservoirs that store water and release it during periods of high ecological and human water demand. Changes from snow to rain threaten these critical snowpack reservoirs with relatively unknown effects on water budgets. New evidence is emerging that temperature-based phase thresholds are regionally biased. Part of this bias likely arises from humidity differences, with lower humidity leading to latent heat loss from hydrometeors that causes snow to occur at temperatures well above 0 C. We explore the role of humidity using gridded datasets from 1980-2015 across the Western U.S. We find the temperature-relative humidity (TRH) method leads to 10% to 40% more snow compared with typical 0 C and logistic based temperature thresholds. Moreover, applying the TRH method leads to increasing trends in snow fraction in many regions, while temperature-based methods predict decreasing trends. We apply a simple experiment turning all precipitation to rain within the Basin Characterization Model (BCM) to determine the potential effects on hydrologic partitioning. Shifting snow to rain increased annual infiltration and evapotranspiration in more than 90% of the Southwestern U.S. Shifting precipitation phase regimes generally increased saturation excess flow and decreased recharge and interflow in the western Sierra Nevada, but had opposite effects across most of the Southwest. Saturation excess flow, recharge, and interflow were most sensitive in regions with shallow soils and wet winters where the amount of winter precipitation exceeded the total soil water storage. There was a negative correlation between change in recharge/ interflow and change in maximum input intensity (i.e. less recharge/interflow with increasing precipitation intensity following changes from snow to rain) in the wettest regions, but a positive correlation in drier regions. These results demonstrate that water budgets are likely to have diverging responses to changes from snow to rain that will be mediated by precipitation regime (i.e. precipitation intensity), soil water storage, and local humidity and temperature. Efforts to link these results to water resource management will be discussed.

IMPACTS OF DECREASING SNOWPACK IN MEDITERRANEAN MOUNTAINS: THE EXAMPLE OF THE SPANISH PYRENEES

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The Spanish Pyrenees is the largest mountain system in Spain. Thanks to its location between the Atlantic Ocean and the Mediterranean Sea, the winter and spring is rather humid and it accumulates a rather thick and long lasting snowpack. Several studies has pointed out the Pyrenees as one of the most sensitives snowpack to climate change, and climate scenarios project a sharp decrease in snow accumulation and duration, especially in the transition zone (areas close to the 0ºC isotherm in winter). This study presents an overview of the current importance of snowpack on different environmental and socioeconomic sectors, and how they are expected to change at different levels of climate warming. An assessment of the main uncertainties of the currently available scenarios will be also presented. Analyzed sectors, includes the river flows, management of dams, glacier evolution, ecology and winter tourism.

THE FUNDAMENTAL IMPORTANCE OF CONTEXT: DISENTANGLING THE EFFECTS OF PRECIPITATION AND TEMPERATURE TRENDS IN MOUNTAINS OF THE NORTHWEST U.S.

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Temperature has increased and precipitation has decreased in the mountains of the Pacific Northwest over the last 65 years. Attribution of changes in snowpack and streamflow through correlation to only air temperature is prone to errors due to spurious effects. Because future temperature increases are fairly certain and future precipitation is relatively uncertain, it is common to examine only temperature sensitivity of hydrological and ecological processes. Unfortunately, errors in interpretation and, consequently, projection can lead to maladaptative recommendations. Here we presents results from a series of examples addressing snowpack, low streamflows, and fire ecology to illustrate how thorough treatment of temperature and precipitation effects can lead to robust inferences, and how neglecting spurious relationships can lead to erroneous conclusions. We examine the issue in the context of both retrospective analysis and projections. Specifically, we look at the spatial distribution of snowfall and snowpack storage sensitivity across the west to consider the relative influence of precipitation uncertainty in future projections in different mountain ranges. We examine the relative contributions of historical precipitation and temperature changes on low flows and area burned by wildfire. The upshot is that there are many diverse mountain environments in the West and context is very important both for historical changes and future projections. The current state of climate change science is adequate to tailor site specific adaptation recommendations to account for both temperature and precipitation.

SNOW AND FOREST SURFACE TEMPERATURES: FEBRUARY 2016 YOSEMITE FIELD EXPERIMENT FROM POINT TO AIRPLANE TO SATELLITE

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The snow surface temperature mediates the exchange of energy between the snow and the atmosphere, determining when and where snow will melt and providing a key diagnostic tool for model analysis. On 5 to 8 February, 2016, we measured spatio-temporal patterns of snow and forest surface temperatures across the upper Tuolumne River Watershed, Yosemite, California, scaling from point measurements in a meadow, to ~5-m resolution aerial imagery, to ~100-m (ASTER and Landsat) and ~500-m (MODIS) satellite imagery. We illustrate how forests and topography control surface temperature patterns at different spatial scales and outline guidance for using available satellite data to improve modeling and understand surface temperatures in complex terrain.

TRANSFERABILITY OF SPACE-FOR-TIME MODELS OF SNOW

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The related challenges of predictions in ungauged basins and predictions in ungauged climates point to the need to develop environmental models that are transferable across both space and time. Hydrologic modeling has historically focused on modelling one or only a few basins using highly parameterized conceptual or physically based models. However, model parameters and structures have been shown to change significantly when calibrated to new basins or time periods, suggesting that model complexity and model transferability may be antithetical. Space-for-time models provide a simple framework within which to assess model transferability and any tradeoff with model complexity. Using 497 SNOTEL sites in the western U.S., we develop space-for-time models of April 1 SWE and Snow Residence Time based on mean winter temperature and cumulative winter precipitation. The transferability of the models to new conditions (in both space and time) is assessed using non-random cross-validation tests with consideration of the influence of model complexity on transferability. The models provide strong fits to the data and capture the nonlinear relationship between temperature, precipitation, and snow metrics. Transferability depends on the representation of temperature and precipitation observations in calibration and is generally more successful for more parsimonious model configurations than for complex configurations. The ability of the empirical space-for-time models to predict in new time periods and locations lends confidence to its application to gridded climate futures data for projecting future snow metrics across large areas.

Assessing Vulnerability to Hydroclimatic Change in the Tropical Peruvian Andes

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Climate change and accelerating glacier recession in the tropical Andes are transforming downstream hydrology, while increasing demands for water by end-users (even beyond the watershed limits) complicate the assessment of vulnerability. Future scenarios of hydroclimatic vulnerability require a better understanding of coupled hydrologic and human systems, involving both multiscale process studies and more robust models of glacier-climate interactions. We synthesize research from two proglacial valleys in different regions of Peru that are both in proximity to growing water demand from urban sectors, agriculture, hydroelectric generation, and mining. In both the Santa River watershed draining the Cordillera Blanca and the Shullcas River watershed below Hyuatapallana Mountain in Junin, glaciers have receded over 25% since the 1980s. Our regional modeling suggests glaciers remain sensitive to subtle temperature changes through lapse rates. Historical runoff and glacier data, combined with glacier-climate modeling, show a long-term decrease in discharge resulting from a net loss of stored water. We find evidence that this is transforming proglacial hydrology and water quality, even while water resource use has intensified. Beyond glaciers, our results show that over 60% of the dry season base flow in each watershed is groundwater sourced from heterogeneous aquifers. For example, municipal water supply in Huancayo already relies on 18 groundwater wells. Perceptions of water availability and actual water use practices remain relatively divorced from the actual quantity and quality of water from each mountain range. Critical changes in glacier volume and water supply are not perceived or acknowledged consistently amongst different water users, nor reflected in water management decisions. In order to identify, understand, model, and adapt to climate-glacier-water changes, it is vital to integrate the analysis of climate changes, water availability and groundwater processes (the focus of physical scientists) with that of water use (the focus for social scientists). Attention must be drawn to evaluating risks and adaptation options with scenarios of how management decisions impact all end users.

The Phenology of Wilderness Use

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Phenology studies have been a critical tool for learning about the ways that changing climate affects individual species and ecosystems. In this study, we apply a phenological framework to human interactions with mountainous ecosystems in a changing climate. Specifically, we quantify the relationships between changing snowpack and streamflow and the timing of human visitation to the mountainous Sierra Nevada. Data on human visitation to these areas was collected using two methods: behavior of visitors who obtained permits through the National Park Service (NPS) was assessed through analysis of backcountry permits. Long-distance hikers on the Pacific Crest Trail (PCT) do not obtain permits directly from the NPS, so the timing of their visitation has been previously undocumented. We obtained data on these hikers through the use of weblogs, or blogs. Timing of visitation for both groups was regressed against streamflow and snowpack variables: snow water equivalent (SWE) in spring months, center of timing (CT) of streamflow, and total annual streamflow. PCT hikers and NPS permit-holders were both sensitive to these hydroclimate variables. The mean timing of each group advanced by 0.24-0.28 days for each day of advance in streamflow, depending on the stream used as a predictor. Both groups were also sensitive to April and May SWE, arriving earlier in years with lower SWE. Projected changes in CT from the published literature were applied to these regression models, and suggested a 4-13 day advance in timing through the 21st century, depending on scenario used. Visitors appear to be partially sensitive to hydroclimate variables, suggesting that timing of visitation may change, but also that as temperatures warm, visitors may interact with ecosystems in a different phenological stage than they did historically.

UPPER MISSOURI RIVER BASIN STREAMFLOW RECONSTRUCTIONS FOR IMPROVED HYDROLOGIC OPERATIONS

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The Upper Missouri River Basin (UMRB) is the only major river headwaters in the western U.S. for which hydrologic reconstructions from tree rings have not been generated in any systematic way. This knowledge gap is critical given that the region is facing an array of water resource issues that are challenged by climate change and natural hydrologic variability, and has experienced both severe floods and droughts in the recent past. Providing a longer context for understanding past variability of flow and the corresponding climatic controls, particularly at decadal and longer time scales, is critical for anticipating and managing future water supplies. Here we present recent progress in a collaborative research project with the Bureau of Reclamation (BOR) and Montana Department of Natural Resources that seeks to address this data and knowledge gap by producing up to millennial-length reconstructions of streamflow for a network of 30 major UMRB gages that capture inflows to BOR and state water management infrastructure. Streamflow reconstructions were performed using a “climate-informed” best subsets regression approach, and the more traditional principal component based point-by-point regression. Reconstructions were extended back in time using a statistical nesting procedure, with the best models achieving high-quality calibration and validation statistics against the naturalized records of streamflow (average R^2=0.58, RE=0.5, NSE =0.4). The next step will be to statistically disaggregate to daily flows, then route the flow time series through a BOR constructed RIverWare™ operations model to test current operational rules against the sequence of historic flood and drought events. In conjunction with results from modeled future hydrology, information generated from this study will help guide operational improvements under severe drought and flood conditions across a complex network of reservoirs and diversions.

REGIONAL CLIMATE MODELS: WHAT DO THEY SAY ABOUT MOUNTAIN PRECIPITATION?

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Winter precipitation in the Northwest is a primary driver of both flood risk and summer water availability. Modeling the effect of climate change on these processes requires high spatial resolution to represent the effects of medium-scale weather systems and terrain on rain events. To date, most studies have used statistical methods (e.g. Hamlet et al., 2013) to produce “downscaled” (fine-scale) information on precipitation and temperature from the coarse resolution global climate model simulations that are used to project future climate. Prior downscaling approaches used for these studies have been based on projected changes in monthly-mean statistics, without considering shifts in daily extreme statistics. However, recent research has shown that regional climate models, which simulate the interactions in the earth system at fine spatial scales, project very different future flooding scenarios than suggested by estimates derived from statistical downscaling (Salathé et al., 2010; 2014). This presentation will review recent results and progress in applying regional climate models to understanding changes in high elevation precipitation, including model evaluations, comparisons with statistical methods, and ongoing work using models to identify the large-scale mechanisms governing mountain precipitation.

INVESTIGATING SUMMER LAPSE RATES IN DENALI NATIONAL PARK

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Multiple networks of temperature sensors have been deployed in Denali National Park over the last several years to track local lapse rates. Five summers' of daily minimum and mean temperature from sensors spanning almost 1000 meters elevation were explored with a large set of mixed-effects models. Surprisingly, elevation did not seem to be the strongest predictor of minimum or mean daily temperature along these slopes, even after accounting for seasonal and synoptic-scale temperature changes. Ambient conditions, tracked using 700-hPa temperatures from the NCEP/NCAR reanalysis, drove much of the day-to-day variability across all sites. While temperatures were generally cooler at higher elevations, differences in temperature between sites were more consistently related to differences in aspect and topographic configuration. Lapse rates were not consistent across the data set, differing by aspect and topographic position, as well as with synoptic conditions. Only on the steepest slopes, did daily average lapse rates approach the average environmental lapse rate of 6.5°C/1000m. Moreover, lapse rates differed for minimum and mean temperatures, with minimum temperature lapse rates about half that predicted by daily means. These preliminary analyses suggest that topoclimatic relationships developed in the mid-latitudes may not be applicable at higher latitudes and underscore the importance of representative monitoring.

SEASONAL AND INTERDECADAL VARIABILITY IN ENSO-INFLUENCE ON THE PACIFIC NORTHWEST

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Climatologists have long considered the El Niño/Southern Oscillation (ENSO) to be a robust predictor of winter temperature and precipitation in the Pacific Northwest, making last winter’s warm, but very wet El Niño something of a surprise. A recent analysis of 138 Global Historical Climatology Network stations in Washington, Oregon, Idaho and western Montana identified substantial geographic, seasonal, and inter-decadal differences in ENSO influence on temperature and precipitation, as well as asymmetries in the response to El Niño versus La Niña conditions. Throughout the 20th century, ENSO has had remarkably little impact on mid-winter (December/January) temperature or precipitation. Its influence was more pronounced in the autumn (October/November) prior to the 1960s. Currently, the most significant ENSO impacts occur during the late winter and early spring (February/March). The increasing importance of spring relationships, particularly for temperature, may be related to the fact that El Niño and La Niña tend to have opposite impacts at this time, whereas in the fall, the La Niña response appears to be more widespread than El Niño signal. These subtleties in ENSO influence on climate in the Pacific Northwest, combined with the increasing use of seasonal forecasts in management decisions, suggest that we need to take a more nuanced approach in our assessment of and communication about teleconnections. Such instabilities also highlight the need for high-quality paleoclimatic data that can be leveraged to better understand shifts in the influence of ENSO, and other modes of ocean and/or atmosphere variability, over time.

From n=3 to n=200,000: Application of GPR to measure snow accumulation on glaciers

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A quantitative understanding of snow thickness and snow water equivalent (SWE) on glaciers is essential to a wide range of scientific and resource management topics. However, robust SWE estimates are observationally challenging, in part because SWE can vary abruptly over short distances in complex terrain due to interactions between topography and meteorological processes. In this presentation, we will summarize recent efforts to measure SWE using both ground- and helicopter-based ground-penetrating radar (GPR) surveys over a range of spatio-temporal scales.   Highlights include GPR surveys at seven glaciers in Alaska in spring 2013, temporal variability at two glaciers from 2013–2016, and a high spatial resolution 250-m grid at one glacier in 2015. We will discuss spatio-temporal variability, describe implications for glacier mass balance modeling, and share insights for planning additional field surveys.

KEY DRIVERS OF HOLOCENE VEGETATION CHANGE AND FIRE ACTIVITY, MISSION MOUNTAINS, NORTHWESTERN MONTANA.

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We set out to better understand historical drivers of ecosystem dynamics in mixed-conifer tribal forests of the northern US Rocky Mountains. Here we report on preliminary reconstructions from a network of lake sediment cores of fire and vegetation history at mid-elevation mixed-conifer stands in the Mission Mountains of northwestern Montana. Pollen and charcoal records from East Twin Lake (1261 masl) and Moss Peak Lake (1486 masl) show mixed-conifer forests (*Pinus, Abies, Picea, Pseudotsuga, Larix*) dominated forest cover at these sites throughout the Holocene but that periods of warmer and drier conditions were associated with increased fire activity and increased dominance of *Pseudotsuga/Larix* forest cover. Increases in fire activity and *Pseudotsuga/Larix* forests were particularly pronounced during the early-Holocene summer insolation maximum c. 7-9 ka cal BP and the Medieval Warm Period c. 1,250-950 cal yr BP. Fire activity also increased during the past several hundred years when human activity may have promoted fires despite generally cooler and wetter climatic conditions. Results from these sites illustrate how both climate and fire played an integral role in shaping millennial-scale vegetation dynamics in the Mission Mountains and suggest some level of human influence, especially in recent decades to centuries. These records are the first to be analyzed among a network of sites that experienced different intensities of human activity in the past. A final meta analysis of climate/fire dynamics of the entire suite of lake sediment sites, and the inclusion of gridded tree-ring based fire histories currently being developed, will help clarify the role of human influence on centennial to millennial-scale fire activity.

Genetic Classification and Identification of old apple genotypes in the Kwina Estate – a move towards food sovereignty and security

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Lummi Tribal Nation is acknowledged for having a distinguished tribal fishing history, but little is known about the historical data regarding the early agriculture in the area. Northwest Indian College (NWIC) was founded on the Kwina Estate in 1973, which was formerly the Lummi Indian School of Aquaculture. Originally a training program developed to prepare technicians for employment in tribal based aquaculture operations; currently the only tribal college in the Pacific Northwest serving Washington, Oregon, and Idaho. Food security is a critical concern of national magnitude as global climate change continues to impact the economy of agriculture. In order to make well informed decisions for their community, it is imperative for Lummi Nation to establish a clear record of agriculture history which is conducive to their community development. This is also an issue which concerns tribal sovereignty by influencing tribal leadership decisions with respect to food sovereignty initiatives, environmental policy – furthermore responding to the emerging needs in the progressive advancement of NWIC's environmental science program. This study is being conducted to genetically classify and identify the old apple varieties growing in abandoned orchards on the NWIC campus. DNA was isolated from leaf tissue collected from trees in the Kwina estate grove using Promega's © Wizard Magnetic 96 DNA Plant System. DNA was used for Target Region Amplified Polymorphism (TRAP) reactions. TRAP analysis is used to identify polymorphic markers from established database information of expressed sequence tags around targeted candidate gene sequences. For each TRAP reaction, scorable fragments are generated when separated on a polyacrylamide sequencing gel. This method has proven to be beneficial in genotyping and interpreting the structure and genetic diversity of a given population. It is our intention to fill in the missing gaps of agricultural history of the Lummi Indian Reservation in hopes to build upon the cultural and historical knowledge base of the past, as well as provide a preliminary study which may contribute to further studies relating to plant phenology and climate change.

DO HIGH ELEVATION CONIFERS FIND REFUGIA AT LOW ELEVATIONS AND ON NORTH ASPECTS DURING WARM CLIMATES IN THE GREAT BASIN, USA?

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Twenty-six conifer species occur in the Great Basin (GB) of SW USA, a 520,000 km^2 region of internal drainage containing ~635 mountain ranges. Mostly small in area, ranges are isolated from each other in a sea of low basins, inhospitable to conifers under present climates. Unlike the flanking major cordillera, where conifers grow widely across elevational gradients, conifers of many GB mountain ranges are sparsely and chaotically distributed, reflecting idiosyncratic biogeographic histories. Whereas mountain species are expected to shift upward with warming climates, conifers of the GB suggest diverse responses. We present updates of our study to investigate hypotheses that GB conifers can persist in low-elevation ravine and/or north-slope refugia during unfavorably warm climates, where cold-air drainage, protection from solar radiation, and higher soil moisture provide suitable habitat. We develop three lines of evidence:

1. Upland Conifers. Current occurrence records for 12 upland conifers across 50 Nevada mountain ranges yield a mean of 60.1% of all records in extra-marginal low-elevation, riparian, ravine, or other cold-air contexts and a mean of 40.1% of all records on north aspects.

2. Limber Pine. Thermochron temperatures in ranges currently containing limber pine document expected warmer temperatures at extra-marginal low-elevation riparian sites relative to uplands. However, temperatures were colder than expected from standard lapse rates, and rates for these locations were larger (sometimes positive) than the standard rate, and larger than upland slope rates.

3. Late-Holocene Limber Pine. Abundant relict wood of limber pine, scattered across aspects of the Wassuk Range, contrasts with the present sparse distribution of live trees, limited to N slopes and ravines. Tree-ring analyses indicate that pines grew throughout the late-Holocene at elevations similar to present. Pines extirpated from all but north aspects during warm dry intervals of the late Holocene. Low-elevation ravine and north-aspect locations are implicated as mid-Holocene and other warm-period refugia, serving as source populations for re-colonization when climates ameliorated.

IMPACTS OF FORECASTED CLIMATE CHANGE ON SNOWPACK IN THE NOOKSACK RIVER BASIN

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The Nooksack River drains an approximately 2000 km^2 watershed in the North Cascades in Whatcom County, Washington and is a valuable freshwater resource for regional municipalities, industry, and agriculture, and provides critical habitat for endangered salmon species. Historically, streamflow in the high relief basin is largely influenced by precipitation and snowmelt in the spring, and glacial melt throughout the warmer summer months. Due to a maritime climate, the basin is classified as a transient rain-snow basin, thus assessing its response to forecasted warming climates is important for water resources planning purposes. We apply publically available statistically derived 1/16-degree gridded surface data along with the distributed-hydrology-soil-vegetation model (DHSVM) with a newly developed coupled dynamic-glacier model to simulate hydrologic processes in the Nooksack River basin. For the historical period, we model using a gridded meteorological forcing data set (1950-2010; Livneh et al., 2012). We simulate forecasted climate change impacts using gridded daily statistically downscaled data from 20 global climate models of the CMIP5 with RCP4.5 and RCP8.5 forcing scenarios developed using the multivariate adaptive constructed analogs method (Abatzoglou and Brown, 2011). To examine the evolution of snowpack in the basin, we average snow water equivalent (SWE) raster outputs over 30 year simulations surrounding the years 1995, 2050, and 2075. Average historical simulations (1981-2010) indicate that winter snow dominates regions above 500-600 meters in the Nooksack River basin. As temperatures increase near the end of the century, the average SWE (2064-2090) decreases and is restricted to regions above 1100-1300 meters. With more snow-free basin area exposed to rainfall, winter runoff increases, thus increasing the flood and mass-wasting risk during the wetter winter months. The projected decrease in SWE also significantly reduces the spring runoff in the Nooksack River.

RELATIONSHIP OF VEGETATION COMMUNITY AND SOIL MOISTURE PATTERNS TO WILDFIRE RE-BURN FREQUENCY: ECOSYSTEM VULNERABILITY FRAMEWORK AND PRELIMINARY FIELD RESULTS FROM MT. ADAMS

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We present a novel analysis framework and preliminary results from a study of the intersections of recent wildfire burn perimeters on the southern slope of Mt. Adams in Yakima county, WA, to begin to assess the overlapping burns' influences on hillslope patterns of soil moisture and ecosystem regeneration. Considering the number of recent burns, time since most recent burn, and regrowth intervals between burns, we propose an aggregate index of how vulnerable the ecosystem may be to a burn-influenced non-forested state change. Considering the specific geographic overlaps of wildfires in 2004, 2008, and 2015, we identify six field sites spanning the gradient of recent re-burn influences and possible state change vulnerabilities (unburned control, burned in 2008 only, 2004 and 2008 only, 2004 and 2008 and 2015, 2008 and 2015, 2015 only). The six selected sites hold fire severity constant within a given fire and also control for regional and local slope, aspect, and elevation. We present preliminary data on differences among these six sites in vegetation community, tree seedling density, soil infiltration capacity, and spatial soil moisture patterns. Future work will examine spatially-explicit influences of fire frequency and micro-climate conditions (mediated by hillslope edaphic factors) on departures of plant community composition and functional plant types from unburned forests, as metrics of vulnerability to ecosystem transition to potential alternative states. The presented results are the first steps toward a thorough assessment of linked ecological and hydrological differences in hillslopes subjected to different re-burn influences, as well as longer-term investigation of the role of re-burns and subsequent plant-water interactions on forest ecosystem regeneration.

VEGETATION MORTALITY, RESILIENCY AND RECOVERY FOLLOWING LARGE WILDFIRES IN THE METHOW VALLEY AND ADJACENT MOUNTAINS (WA)

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The influence of climate change on fire regimes and vegetation communities is a current concern. Increased frequency and intensity of fires coupled with drought and heat stress may inhibit or alter recovery of native ecosystems. As a result, plant communities may experience phase shifts, with some forests becoming shrub-steppe, and some shrub-steppe converting to grassland. The Methow Valley (WA) experienced record-breaking wildfires in 2014. Fuel buildups from fire exclusion compounded the effects of extreme fire weather. We studied the mortality, survival, recovery and vegetation dynamics following these fires and abnormal climatic conditions. We assessed fire effects and vegetation recovery through analysis of an extensive network of post-burn field plots and pre-burn vegetation data as well as a chronosequence of satellite images and aerial photography. 75% of the 2014 Carlton Complex fire burned non-forested vegetation (mostly shrub-steppe). Ponderosa pine (*Pinus ponderosa*) forests comprised most of the rest of the burn area. The response of native vegetation after the fires is complex and requires further study. The shrub-steppe recovered rapidly in most areas, but has shifted from shrub dominated communities to grass/forb dominated communities. Our analysis indicates that the forests experienced about 70% initial mortality. There are large areas of high mortality mixed with patches of medium and low mortality. Recovery of the forest appears slower than in the shrub-steppe. We are collecting data on tree seedling germination and survival. Seedling germination and survival during the first year was poor due to an extremely hot, dry spring and summer. Seedling survival the second year appears much better due to a cool, moist spring and summer. The combination of severe fire and extreme heat and drought may result in range contraction of the ponderosa pine forests. The study reveals the importance of subsequent climatic conditions on vegetation recovery after a fire.

Ecophysiological Responses of Southwest Sky Island Forests to Seasonal and Topographic Variability

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Our study investigates the controls of topography on the net primary productivity of three species (*P. menziesii, P. ponderosa, P. strobiformis*) in a southern Arizona montane ecosystem. The mixed conifer ecosystems found on Madrean Sky Islands are characterized by low precipitation, high annual variation in temperature, and heterogeneous topography. Though the carbon (C) cycle in southwestern forests is a topic of extensive study, these studies tend not to include topography. Eddy covariance measurements of NEE show distinct seasonal trends due to temperature and bi-modal precipitation patterns, but these measurements are unable to capture the potential differences in primary productivity on opposing north and south aspects within the footprint of the tower. North aspects generally receive less energy input due to the oblique angle of incoming solar radiation, leading to a divergence in soil moistures and temperatures. However, overall movement of energy and material is much higher on the north aspects on an annual basis. How this relates to primary productivity remains poorly studied. We use leaf-level measurements of photosynthesis and transpiration to investigate how the dominant vegetation functions as a result of microclimatic conditions. A comparison of species within the same catchment will highlight species-specific tolerances of temperature and water stress, while a comparison of aspects will explain topographical controls on the C cycle. Initial results from the spring and summer measurement periods suggest differences in microclimate depending on aspect, leading to a divergence in rates of productivity. In addition, samples of the three species on the same aspect respond to the same microclimatic conditions differently. A more complete picture of seasonal behavior will be developed with the addition of fall and winter measurements. The results of this project will begin to unravel the complexity of characterizing montane forest ecology and attempt to quantify the contributions from topographic features.

Evidence for slower snowmelt in a warmer world

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We present snowpack observations from western North America that show that shallower snowpack melts earlier and at lower rates than deeper, later-lying snow-cover. The observations provide the context for a hypothesis that reduced snowpack in a warmer world will melt at lower rates. We test this hypothesis using high-resolution Weather Research and Forecasting model simulations over much of North America for a historical decade (2000-2010), verified against snowpack and precipitation observations, and then re-run with a pseudo-global-warming technique. Results show that high snowmelt rates are greatly reduced in a warmer climate. The reduction is caused by substantial late-season snow-cover depletion at a time of high seasonal energy availability. Regions of largest reductions in high melt rates include the Sierra Nevada, Pacific Northwest, and lower elevations of northern Idaho, Montana and the Canadian Pacific Ranges. Increases in snowmelt rates were small, exhibited greater regional and elevational variability, and generally impacted low historical melt rates in winter and early-spring. The large reduction of high spring snowmelt rates in a warmer world has unresolved but important implications on future streamflow as catchment wetness thresholds may be exceeded less frequently, contributing to soil moisture deficits, vegetation stress and streamflow declines.

NEW METRICS FOR CHARACTERIZING MOUNTAIN SNOWPACKS IN A WARMING WORLD

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The variability of mountain snowpack affects multiple sectors from water, energy, and forest management to transportation planning to winter tourism. We have developed a suite of snow metrics as key climate indicators to support the goals and needs of current stakeholders as well as the National Climate Assessment process. These new snow metrics augment the traditional "April 1 SWE" metric that uses ground-based measurements from stations whose spatial distributions are sparse and not necessarily representative snow spatial distributions. The specific snow metrics include seasonal snow cover frequency (SCF), snow disappearance date (SDD), snow cover duration (SCD), the ratio of snow water equivalent to total winter precipitation (SWE:P), snowstorm temperature, the frequency of warm winters, and "at-risk" snow. We use a novel combination of remote sensing, *in situ*, and modeling data including the NASA/MODIS snow cover product, snow data from observations, and model output (NASA Earth Exchange Downscaled Climate Projections and the VIC hydrologic model) to look both retrospectively (lagged indicators) and prognostically (leading indicators). In addition, we have developed an innovative interactive geovisual analytics tool using Google Earth Engine that allows users to explore spatial and temporal snowcover patterns from 2000—present. Here, we demonstrate the utility of these products for analyzing intraseasonal and interannual snowpack variations in the Oregon and Washington Cascades, and California Sierra Nevada. Comparing winter SCF for 2011 (an average winter) with SCF for 2015 (an extremely warm winter), we see distinct spatial patterns not evident in the station-based snow data. For instance, below 1500 m the SCF for 2015 was very low compared with SCF for 2011; however, for elevations above 1500 m the SCF for 2015 was not significantly different from that of 2011. Station data in 2015 were unable to detect distinct snowline and the consistent, longer lasting high elevation snow cover.

Treaties, Tribes, and Fish: How Indigenous rights to harvest can influence global climate change and environmental policy

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Global climate change has disproportionate impacts on coastal Indigenous communities, where fishing and shellfish harvesting is central to traditional ways of life and cultural self-identity. Furthermore, increased risks of flooding – in relation to glacial melt and sea level rise – is projected to severely impact traditional harvest sites and reduce the land base of coastal Tribal reservations. Given the Federal trust responsibilities of the United States government to protect Indigenous treaty rights – specifically usual and accustomed hunting and gathering areas – tribes are in a unique and powerful position to advocate for ecosystem and cultural health. This paper examines the complex relationship between ecosystem health, Indigenous rights and Federal treaty trust responsibilities. In the paper, I show how Coast Salish tribes of the Pacific Northwest are leveraging treaty rights to influence environmental and climate policy. Specifically, I point to Article 5 of the 1855 Treaty of Point Elliot, subsequent Federal court decisions (Boldt, Rafeedie, and Culvert cases), as well as recent decisions by federal agencies (such as the Army Corps of Engineers) to uphold treaty rights and demonstrate trust responsibility. Although these trends are encouraging, I outline the need to adopt wider and more proactive polices to protect endangered ecosystems that are jeopardizing Indigenous ways of life.

RANGE-WIDE DEMOGRAPHIC RESPONSES OF AN ALPINE PLANT TO MUTIPLE CLIMATE DRIVERS

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Predictions of range shifts in response to a changing climate can be refined with an understanding of how demography and climate interact to drive population expansion and decline across a species range. The demographic rates (*e.g.,* germination, growth, survival) that coalesce to form the population growth rate may be idiosyncratically sensitive to multiple climate conditions (*e.g.,* temperature, soil moisture, snowpack duration), and these sensitivities may change across a species range. Since 2013, I have monitored 16 populations of a long-lived alpine plant, *Ivesia lycopodioides* var. *scandularis* (Rosaceae) across the entirety of its altitudinal range in the White Mountains, CA (3350 – 4420m). In each population I quantified both demographic rates and microclimatic soil moisture and temperature. In addition, I have experimentally manipulated summertime temperature and precipitation in nine populations. Demographic rates in populations across this species range exhibit sensitivity to accumulated degree-days, soil volumetric water content or the interaction between these climate variables. Demographic rates also differed in their response to the climate manipulations and the effect depended on the population's location within the range (lower elevation limit (LE), upper elevation limit (UE), and range center (C)). For example, heating had a negative effect on reproductive output of LE and C populations, but a positive effect in the UE. The combination of watering and heating increased flowering in C populations, ameliorating the negative effect of the heating. However, the manipulations had minimal effect on the population growth rate, except in the lowest elevation experimental site where heating reduced the population growth rate by 64%. The inverse response of demographic rates to the manipulations may allow populations to demographically buffer against the experimental change in climate conditions. However, for the lowest elevation population, the negative effect of heating on survival overwhelmed the positive effect on germination leading to predictions of population collapse.

Is there a history of eutrophication preserved in the sediments of The Loch, Rocky Mountain National Park?

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Mats of green algae have been observed in the subalpine Loch and alpine Sky Pond in the Colorado Front Range. These algal mats were not observed prior to 2010. *Zygnema spp*. are common green algae in nutrient-rich waters, and Loch Vale watershed has been nitrogen (N) rich but phosphorus poor since mid-20th century. The fact that the algal mats are only recently observed suggests N alone is not the cause of increased productivity; some other forcing factor may facilitate attached algal growth. Summer lake water temperatures have increased steadily by more than 2 degrees Celsius since the 1980s. Phosphorus concentrations may also have increased from either dust inputs or increased weathering rates. We present data from a 26 cm sediment core obtained from The Loch in March 2016. Analysis is ongoing, and includes ^{210}Pb, C:N ratios, □^{13}C, □^{15}N, total organic matter content, sediment P, spectrofluorescence of sediment humic substances, and major algal pigments to assess changes in primary production through time. Percent organic carbon has increased in recent time while C:N has decreased, consistent with results from other lakes affected by N deposition. These results are part of a larger study involving experiments and monitoring that addresses the hypothesis is that lakes that were heretofore oligotrophic and characterized by very low nutrient waters may be transitioning to a different trophic state induced by changing climatic drivers.

Biophysical linkages in coastal Alaska's icefield-to-ocean ecosystem

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Rates of glacier mass loss in the Alaska Region are among the highest on Earth. Changes in glacier volume and extent will impact the flow regime and chemistry of coastal rivers, as well as the nearshore marine ecosystem of the Gulf of Alaska. Here we synthesize physical, chemical and biological linkages that characterize the glacierized basins of coastal Alaska, with particular emphasis on the potential impacts of glacier change on the surface-water hydrology, biogeochemistry, coastal oceanography and aquatic ecology. We focus on a newly initiated interdisciplinary study at Wolverine Glacier, where glacier mass balance and streamflow have been measured for 50 years. During 2016, we complimented these core observations with off glacier snow measurements, seasonal DEMs, ground penetrating radar, expanded and continuous ablation, snow and stream chemistry, vegetation and freshwater ecology surveys and hydrography of the nearshore ocean. This presentation will focus on a physically-based approach to partition the water budget between ice-covered and ice-free portions of the basin, including new constraints on assumptions required in DEM differencing of glacier surfaces. Additionally, we will highlight how such process-based studies may be integrated in modelling efforts to improve science-based resource management and economic decision-making.

ADVANCES IN SNOW HYDROLOGY AND WATER MANAGEMENT WITH THE NASA AIRBORNE SNOW OBSERVATORY

Painter, Thomas H. (1), and the ASO Team (many)
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We present scientific and water resource applications of data and modeling from the NASA Airborne Snow Observatory (ASO) in the Western US. ASO is a measurement and modeling system developed to breakthrough to comprehensive snow water equivalent mapping and quantitative physically based runoff forecasting. The measurement component combines scanning lidar, imaging spectrometer, and snow physical modeling to produce unprecedented distributed mapping of snow water equivalent and snow albedo across mountain basins. The modeling component assimilates these data into distributed snowmelt and runoff models of varying complexities and purposes. We present results from the Sierra Nevada, Colorado River and Rio Grande River, Olympic Peninsula, and the Oregon Cascades. These results show the first examples of marked improvements in understanding of snow distribution, snowmelt distribution, water allocation, runoff forecasting, and ecosystem functioning.

NORTH AMERICAN 0.5 DEGREE GRIDDED SUMMER TEMPERATURE RECONSTRUCTIONS

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Prior efforts to reconstruct summer or annual temperatures across North America from tree rings have incorporated both positive and negative growth responders. Consequently, paleotemperature reconstructions integrate a blend of the direct effects of growing-season temperatures on tree growth and indirect effects mediated though moisture stress; making it questionable whether these records retain a time-stable and frequency-appropriate response to temperature. To circumvent this problem, and to allow the independent investigation of long-term co-variability between temperature and precipitation, we have produced a new dataset of publicly available and investigator-contributed tree ring-width and maximum latewood density records. The initial set of tree-ring records (n=316) were screened to include only those that exhibited a significant ($p \leq 0.1$) and positive correlation with the target temperature dataset (CRU TS3.2) at local and/or regional scales, and had at least 5 series prior to 1700 CE (n=185 retained after screening). In comparison with the previous NAM2k dataset, geographic coverage improves substantially across western North America and the Arctic, but degrades across the plains and the southeastern United States. Records were standardized using a suite of detrending methods (e.g. negative exponential, signal-free, and regional curve standardization) providing n=1,110 chronology variants for testing. We have applied the new dataset to produce an ensemble of gridded 0.5° North American summer (June-August) temperature reconstructions that extend back more than 1000 years over most of the West. We used nested point-by-point principle component regression (PPR) on each of the differentially detrended datasets to reconstruct summer temperatures in space and time. The ensemble of reconstructions is most skillful in western North America and across the northern boreal forest region. The choice of detrending method and PPR search radius exert the largest influence on the uncertainty of the final reconstruction, as well as the ability of the reconstruction to retain potential climate information at low frequencies.

Avalanches as a driver of landscape change and a hazard in Glacier National Park, Montana.

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Avalanches affect mountainous areas around the world as both a hazard and a landscape disturbance. Glacier National Park (GNP), Montana, USA, is such an area where infrastructure and human safety are at risk from avalanches, and where avalanches shape the landscape from the alpine to riparian zones. Avalanche research in GNP thus far has focused on both wet snow hazards as well as dendrochronological records of frequency and magnitude. Wet snow avalanches will potentially become more common as air temperature rises and spring onset arrives earlier.

Recently, we examined meteorological parameters associated with 192 wet snow avalanches as well as terrain components across the landscape and devised simple models that allow for better wet snow avalanche forecasting. Results of a classification tree analysis included a 73 percent overall predictive accuracy using meteorological variables and a 99 percent probability of detection of terrain capable of producing a glide avalanche. We also applied the photogrammetric technique Structure from Motion (SfM) to investigate wet snow avalanche size. Results indicate that air temperature and snowpack settlement are useful indicators of wet snow avalanche occurrence. This work has fostered our general understanding of wet snow avalanche occurrence, timing and improved operational decision making for the Going-to-the-Sun Road avalanche forecasting program.

We also examined dendrochronological data from a number of avalanche paths to investigate large magnitude avalanches. These types of avalanches are large, destructive, and affect landscape characteristics, such as vegetation, along a large elevation gradient. We examined frequency of avalanches in a single avalanche path, and also examined large magnitude avalanches over time and compared them to climate parameters. Rain-on-snow events and the presence of arctic air intrusions followed by warm, wet storms may be the strongest drivers of such large magnitude events. Overall, GNP serves as a ripe, natural laboratory to study avalanches, a major mountain and landscape driver, from both a hazard and an ecological perspective.

Adapting natural resource management to climate change in the Rocky Mountains: The Northern Rocky Mountain and Intermountain Adaptation Partnerships

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Science-based adaptation to climate change is needed to help natural resource managers incorporate climate change into management and minimize potentially negative effects. We recently initiated science-management partnerships for climate change in the Rocky Mountains, encompassing 27 national forests and adjacent federal lands. The partnerships synthesized published information and data for the effects of climate change on water resources, fisheries, vegetation, ecological disturbance, wildlife, infrastructure, recreation, ecosystem services, and cultural resources. An initial vulnerability assessment was used as the basis for developing adaptation strategies and tactics in a series of 10 workshops. The assessment was used to develop science-based adaptation strategies and tactics that will help mitigate the negative effects of climate change and assist the transition of biological systems and management to a warmer climate. The U.S. Forest Service is now implementing adaptation options in relevant planning documents and on-the-ground projects. The success of the partnerships illustrates the utility of place-based vulnerability assessments and scientist-management partnerships in adapting to climate change.

STRATEGIES FOR CONSERVING MONTANE AMPHIBIANS IN A LESS SNOWY FUTURE

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Climate change is an important threat to montane amphibians throughout the world. This threat is particularly pronounced in western North America, where changing climatic conditions interact with other important threats – primarily disease and introduced fish. We present results from a series of ongoing studies investigating the interactive effects of climate, disease, and introduced trout on the Cascades frog (*Rana cascadae*) in the mountains of northern California, and explore conservation measures that are being developed for this species. Cascades frogs were historically widespread in the southern Cascade Range, but have dwindled to a handful of small populations inhabiting montane meadows. This regional decline is likely due to a combination of introduced trout and disease, which are more likely to affect populations inhabiting large, permanent bodies of water. These remnant populations are threatened by decreasing water availability, as breeding ponds must maintain water long enough for larval amphibians to complete metamorphosis. Thus, warm dry years with limited snowpack can affect frog populations by decreasing survival through metamorphosis. The fungal pathogen *Batrachochytrium dendrobatidis* (Bd), which has had devastating impacts on montane amphibians around the world, affects Cascades frog populations by increasing mortality in recently-metamorphosed frogs. However, the effects of this pathogen are diminished in warm conditions. Thus, warm dry years may enhance the survival of frogs once they metamorphose. We are developing conservation strategies focused on: 1) enhancing breeding conditions by increasing wetland hydroperiod, and 2) treating diseased juvenile frogs to enhance survivorship. It is hoped that these strategies will increase the viability of remnant Cascades frog populations in a less snowy future and stave off regional extirpation of the species.

CLIMATE REGULATES ALPINE LAKE ICE COVER PHENOLOGY AND AQUATIC ECOSYSTEM STRUCTURE

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High-elevation aquatic ecosystems are highly vulnerable to climate change, yet relatively few records are available to characterize shifts in ecosystem structure or their underlying mechanisms. Using a long-term dataset on seven alpine lakes (3126 to 3620 m) in Colorado, USA, we show that ice-off dates have shifted seven days earlier over the past 33 years and that spring weather conditions – especially snowfall – drive yearly variation in ice-off timing. In the most well-studied lake, earlier ice-off associated with increases in water residence times, thermal stratification, ion concentrations, dissolved nitrogen, pH, and chlorophyll-a. Mechanistically, observed changes in lake ecosystem structure are likely explained by the effects of climate on hydrology: warming and drying reduced summer stream flow (increasing lake residence times) but enhanced local glacial and permafrost ablation (increasing lake solute inputs). The observed links among hydrological, chemical and biological responses to climate warming highlight the ability of lakes to integrate larger-scale ecosystem change and the potential for major shifts in the functioning of alpine lakes due to forecasted climate trends.

RESPONSE OF DOUGLAS FIR NITROGEN UPTAKE TO CHANGES IN SOIL MOISTURE AND NITROGEN AVAILABILITY THROUGHOUT THE GROWING SEASON

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Human activity has reduced mountain snowpack in the Rocky Mountains since 1950. Higher temperatures, earlier snowmelt, and less snow are projected to further alter terrestrial productivity. Because most precipitation falls as snow in temperate mountainous ecosystems, decreased snowpack could have drastic ecological, sociological, economical implications. Nitrogen (N) immobilization is one crucial process affected by changes in snowpack. In temperate western forests, snow insulates soil and promotes microbial N mineralization throughout the winter. During snowmelt, a pulse of N from this winter microbial activity is made available. In N limited ecosystems, plants are expected to take N from this large pool, but some evidence suggests that evergreen trees instead use N stored from the previous year during this time. This study addresses whether trees are accessing this readily available N pool directly after snowmelt. In order to evaluate when trees are taking in N most readily, we measured N uptake throughout the growing season. We collected N uptake rates using the in situ depletion method with fine roots from eight Douglas fir (*Pseudotpsuga menziesii*) trees. We also calculated a Douglas fir N mass balance by measuring total N and $\delta^{15}N$ concentrations in current and previous years' stems and leaves from 10 trees. This study reports tree N uptake rates measured throughout the growing season and total N and $\delta^{15}N$ concentrations from stems and leaves. We address how variation in N availability and soil moisture throughout the growing season influences Douglas fir N uptake. Because tree N uptake is indirectly linked to the timing of snowmelt, we can begin to predict how lower snowpack and earlier snowmelt may affect N dynamics in forested ecosystems under a changing climate. These results will refine our knowledge of temporal variation in N pools in snow dominated ecosystems.

Trends in snow, rain and streamflow in Wyoming's Wind River Mountain Range

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Climate warming is expected to affect the hydrologic cycle in mountain regions by influencing the timing of snowmelt and the amount of precipitation falling as snow. We examine daily observed station data, between water years 1979 and 2015, on snow water equivalent and precipitation from Snow Telemetry (SNOTEL) stations and stream discharge from US Geological Survey gages in the Wind River Mountain Range and the surrounding region of Wind River Indian Reservation (WRIR) to evaluate trends in snow processes, phase of precipitation and streamflow. We use homogenized daily SNOTEL temperature data to estimate the proportion of precipitation falling as rain on a daily basis based on the method proposed by Kienzle (2008). We also examine the year 2015 separately, when the WRIR and surrounding mountain region had near or above average precipitation but recorded the second warmest temperature anomalies (after 2012), and WRIR experienced drought-like conditions during the growing season. Our results show that the WRIR region has warmed by 2^{o}F since the mid-1990s and the period since 2000 has been relatively drier compared to the earlier period. However, there is no clear consensus between the stations on an earlier shift in the timing of rain during that period. For 2015, however, the snow to rain shift occurred 3 to 7 weeks earlier in spring. Streamflow gages generally show that the day when half the water-year discharge occurs has shifted earlier in recent decades by a few days to a week. For 2015, the shift was also earlier by a week. Since the station data provide a very limited coverage of the region for quantifying changes in snowfall and snowmelt processes, including their elevation depdendency, we supplement those with remotely sensed gridded data. Results from that analysis will also be presented at the meeting.

Climate Change from an Indigenous Perspective: Looking at the indigenous aspects of climate change to help prepare tribal communities.

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Global climate change is impacting tribal communities in the Pacific Northwest by depleting their food resources. This depletion will prevent continuing traditional practices of harvesting and keeping ones identity. This poster used cartography to not only map traditional land, also known as usual and accustomed areas, but also bridge Indigenous methodology into research studies with tribes. After undergoing traditional protocol with tribes, the research displayed digitally mapped vegetation, traditional harvesting areas, and glacial melt so tribes are able to see the impacts of global climate change on their homelands in the Pacific Northwest.

Understanding Western USA Mountain Hydroclimatology Under Present and Future Conditions Using a Next-Generation Variable-Resolution Global Climate Model

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The western USA is fundamentally reliant upon winter season snowpack, which supplies 3/4 of the region's fresh water and buffers against seasonal aridity on agricultural, ecosystem, and urban water demands. By the end of the 21st century, western USA snowpack (SWE) could decline by 40-70%, snowfall by 25-40%, more winter storms could tend towards rain rather than snow, and the peak timing of snowmelt will shift several weeks earlier in the season. Further, there has been evidence that mountain ranges could face more accelerated warming (elevational dependent warming) due to climate change. Thus, the grid-scale and sub-grid-scale resolution of topography in climate models is critical to accurately resolve winter season hydroclimate trends, such as precipitation distribution, intensity, and phase and the snowpack life cycle. Due to computational constraints, even today's most cutting-edge global climate models rarely push to resolutions higher than 28km, resulting in inadequate resolution of local topographic features that can have a pronounced impact on precipitation/snowpack statistics. Therefore, due to the importance of atmospheric rivers, orographic uplift, and eastern Pacific sea-surface temperature anomalies, high-resolution global scale modeling techniques are necessary to understand western USA mountain range climatology. Variable-resolution global climate models (VRGCMs) are a next-generation technique to do this. VRGCMs bridge the gap between regional and global models by providing high-resolution in areas of interest, eliminating lateral boundary forcings (and resultant model biases), allowing for more dynamically inclusive large-scale climate teleconnections, and requiring smaller simulation times and lower data storage demand (compared to conventional global models). This poster highlights the ongoing research to validate these next-generation models and project future climate change scenarios (RCP8.5) for key western USA hydroclimate metrics (e.g., precipitation, two-meter surface temperature, snow cover, SWE, and snowfall) with the goal to help inform water managers/policy makers and resilience to hydroclimate change facing the region.

Glacial Mass Balance in Washington's National Parks

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More than 520 glaciers larger than 0.1km^2 grace the summits of Washington's three large national parks. We started a mass balance monitoring program in 1993 on four glaciers at North Cascades NP using standardized methods that were applied to two glaciers at Olympic NP beginning in 2014. New protocols were developed for two glaciers at Mount Rainier NP in 2003, where ice falls, extensive debris cover, high winter winds, and access present considerable challenges. The eight glaciers span nearly 3000m of elevation, occur in maritime and continental climate regimes, range in size from 11.6 to 0.2km^2, and exhibit sensitive responses to the region's variable and warming climate. All of these glaciers have negative cumulative mass balances ranging from -3.7 to -13.0m w.e. (water equivalent) over their periods of record with the greatest losses at lower elevations in the Olympic Mountains and on the west slope of the North Cascades. Water year 2015 was an extremely negative year for many glaciers in this region because of low winter accumulation and high summer melt that reached 9m w.e. Low-elevation Eel and Noisy glaciers had the most negative annual balances at -3.50±0.3m and -4.5±0.3 m w.e., respectively. Higher elevation glaciers had less negative annual balances in 2015 that ranged from -0.9±0.7m w.e at Nisqually Glacier, to -2.30±0.4m w.e at Blue Glacier, and -2.3±0.3m w.e. at North Klawatti Glacier. These measurements were used to produce empirical estimates of total glacial surface melt runoff on select rivers at each park. Glaciers contribute from 3-46% of the water at downstream gages, depending on weather, basin hypsometry, and glacial cover. High inter-annual variability and short records preclude identification of trends, but extended records in North Cascades identified a 24±9% decline in total summer glacial runoff on the Skagit River at Concrete between 1959 and 2009.

Effects of a shifting snowmelt regime on inflow mixing in a large alpine lake

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We investigate how a shifting snowmelt regime may change inflow mixing dynamics in a large alpine lake. A decrease in annual-average Secchi depth during a warm and dry year (2015) at Lake Tahoe (CA-NV) motivates our investigation into how climate-induced changes in the snowmelt regime may change how and in what quantities fine particles and nutrients are introduced into the nearshore and surface mixed layer (SML) of the lake.

Spring snowmelt is the primary driver of inflows that transport terrestrial carbon, nutrients, and sediments into lakes in the Sierra Nevada, USA. The thermal stratification of receiving lakes and their temperature relative to inflowing water control how these inflows mix and the fate of transported particulates and solutes. Peak inflows at Lake Tahoe generally occur in late-May and early-June during the onset of summer stratification; cold snowmelt inflows enter a comparatively warm lake and plunge downslope. Reduced winter snowpack could affect the timing and temperature of these inflows. Earlier snowmelt may mean inflows will enter cooler, un-stratified receiving waters, potentially resulting in greater nearshore and SML mixing of inflow constituents. A shift toward a more rain-dominated precipitation regime may lead to more frequent incidence of warmer, positively buoyant inflows, resulting in the same effect.

We hypothesize that clarity loss in 2015 may be due to comparatively warmer, more buoyant inflows introducing suspended sediment and nutrient loads into the nearshore and SML rather than plunging and carrying these loads to depth. However, streamflow data indicate near-record-low stream loads in 2015. Thus we pose the question: if a low-snow year causes more nearshore and SML mixing of snowmelt inflows but also leads to lower inflow constituent loads, then what is the net effect of a shifting snowmelt regime on inflow loads to the SML?

This investigation reviews trends in the timing and nature of snowmelt regimes in western North America and, more specifically, the Lake Tahoe basin. We review the trend toward a warmer, longer-stratified thermal regime at Lake Tahoe. We present a theoretical analysis of the combined effects of these climate change-induced trends on inflow mixing dynamics. And we analyze stream and nearshore water quality data from a warm drought year, 2015, and an average snow year, 2016, to comparatively highlight potential effects of a shifting climate on inflow mixing and transport processes. We aim to determine the effect of a shifting snowmelt regime on inflow mixing dynamics in large alpine lakes and the subsequent effect on nearshore and SML water quality.

CLIMATE CHANGE IN THE SOUTHERN SIERRA NEVADA: EFFECTS OF DROUGHT AND CLIMATE WARMING ON WATER TEMPERATURE IN A SNOWMELT DOMINATED LAKE

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We analyzed three decades of climate and lake temperature data from a high-elevation catchment in the southern Sierra Nevada of California to illustrate the magnitude of warming taking place during different seasons and the role of precipitation in regulating lake temperatures. Significant climate warming trends were evident in all seasons except spring. There were consistent diel patterns in warming, with rates ~25% higher at night than during the day. Annual rates of warming were higher at sites above tree-line than below, similar to patterns of elevation dependent warming in other mountain regions. Although interannual variation in snow deposition was high, the frequency and severity of recent droughts has contributed to a significant 3.4 mm $year^{-1}$ decline in snow water equivalent over the last century. Despite rates of climate warming considerably higher than global averages, 94% of variation in summer lake temperature was regulated by precipitation as snow: for every 100 mm decrease in snow water equivalent there was a 0.62 ℃ increase in lake temperature. Drought years amplify warming in lakes by reducing the role of cold spring meltwaters in lake energy budgets and prolonging the ice-free period during which lakes warm. The combination of declining winter snowpack and warming air temperatures has the capacity to amplify the effect of climate warming on lake temperatures during drought years. Interactions among climatic factors need to be considered when evaluating ecosystem level effects, especially in mountain regions. For mountain lakes already affected by drought, continued climate warming during spring and autumn has the greatest potential to impact mean lake temperatures.

Modernizing Glacier Mass Balance Research

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Abstract: Watersheds with even modest glacier cover tend to have distinct hydrological and ecological characteristics, and even small changes in glacier cover could have broad implications both locally and regionally. The US Geological Survey began seasonal measurements of glacier mass balance at South Cascade Glacier, Washington in 1957; Gulkana and Wolverine glaciers, Alaska in 1967; and Sperry Glacier, Montana in 2005. However, different field and analysis methodologies limit spatial and temporal comparisons at these sites. We are working towards homogenizing the methods to make each record internally consistent and comparable across glaciers. We are using the same analysis methods both through time and on each glacier to estimate glacier-wide changes in mass balance from the point observations, and we are calibrating each glacier record with volume changes calculated from differencing subsequent digital elevation models. Both the previously calculated mass balances and the reanalyzed time-series at Wolverine and Gulkana glaciers show continuing trends of mass loss. Higher interannual variability is observed at the more coastal glacier (Wolverine) and more monotonic losses on the interior continental glacier (Gulkana). The reanalysis effort resulted in slight decreases in interannual variability and slight increases in mean annual balance amplitudes for the homogenized time-series at both glaciers. Results at South Cascade and Sperry Glaciers will be available soon. We are implementing new technologies to understand the mass balance processes in greater spatial and temporal detail, including using high resolution satellite imagery to quantify changes in glacier extent and thickness, high frequency radar to map snow thickness distribution, and modernized high altitude weather stations. We are using our improved understanding of the linkage between climate and glacier mass balance to explore the impacts on water resources and downstream ecology.

Water Conservation Challenges in Mountain Communities in the Columbia Basin in Canada

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To adapt to increased climatic variability twenty mountain communities in the Columbia Basin in Canada committed themselves in 2009 to reduce their water consumption by 20% over a 7 year period. The project was sponsored by the Columbia Basin Trust (CBT) and at the end of 2015 fourteen communities had comparable data that revealed how complex and challenging it is to adapt to climate change. Over the seven year period the majority of communities experienced the two wettest and the hottest summer months since recorded climate records that go back over 100 years. June rainfall events in 2012 and 2013 were 30-70% higher than the highest recorded event in 1963 and resulted in major destruction to infrastructure. In contrast the extended drought in 2015 created major water supply challenges and widespread water use restrictions. Each community faced different challenges as a result of highly diverse climates (covering a mountain area of 70000 km^2), old infrastructure problems resulting in leaky pipes, winter water pipe bleeding measures to prevent freezing, and excessive outdoor water use during hot summers. The climate data showed that the largest temperature changes occurred during January-March with extreme minimum and mean minimum temperatures increasing by 6-10 degree C in those communities with a 100 year record. There is a clear shift from snow to rain in all climate stations particularly in late winter and precipitation increased in 8 of the 10 climate stations in the summer. The mean maximum monthly summer temperatures were found to be a good predictor of water consumption and the results showed how sensitive the water use is to temperature increases. The range in summer consumption between communities varied from 19-80 L/P/D for every 1 degree increase in mean maximum summer temperatures above 14 ^{o} C. The project provided a fascinating view of the diversity of water problems in mountain communities, the different approaches taking to achieve the conservation targets and the challenges we will face with increasing climatic variability.

TEMPORAL SHIFTS IN CARNIVORE DISTRIBUTION ALONG ELEVATIONAL GRADIENTS IN NEW ENGLAND: AN INVESTIGATION OF THE CONSEQUENCES OF CLIMATE CHANGE

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Increasing temperatures and shifting precipitation regimes is decreasing snow cover across most of the world's mountains. It is not well understood how these changes, in addition to the shifts in land cover that result from climate change, will affect species interactions and community dynamics. The montane boreal forests of the northeastern United States mark the distributional intersection of the cold-adapted carnivores, American marten (*Martes americana*) and Canada lynx (*Lynx canadensis*), and more generalist, southerly-distributed fishers (*Pekani pennanti*), bobcats (*Lynx rufus*), and coyotes (*Canis latrans*). We used 91 remote cameras, programmed to collect climate data, to evaluate the influence of snowpack on carnivore species' distributions along elevational (335 m–1,917 m) and latitudinal (43.9° N–45.3° N) gradients for 2 winters. Elevation was the best predictor of occupancy for most species, with maximum snow depth also acting as an important predictor. Martens were positively associated with sites that contained deep snow whereas fisher, bobcats, and coyotes were primarily detected at low elevations with shallow snowpack during mid-winter. However, as snowpack receded during spring, these generalist carnivores were more frequently detected at high elevations. Our results highlight that changes in snow cover are reverberating through wildlife communities across elevational and latitudinal gradients and that dramatic shifts can occur within a few years. We are increasing sampling in the region to estimate occupancy for additional carnivores, multiple seasons, and changes in phenology, and to reduce confounding among habitat and climate variables.

RAPID DEMOGRAPHIC SHIFTS AT TREELINE IN GREAT BASIN BRISTLECONE AND LIMBER PINE FORESTS

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Recent rapid climate change has given us a unique human timescale-proxy to study very slow processes like changes in the elevation of treeline which can be both a response to and a cause of mountains without snow. Using the mountains of the Great Basin as a study system, we have put in over 400 paired above-treeline and mid-stand plots to examine the demographics of tree establishment above historical Great Basin bristlecone and limber pine treeline. These plots show that it is fairly easy to model adult tree species distribution based on a couple of metrics like aspect and soil type. However, despite differential species dominance by adults, above-treeline establishment appears to be largely due to typically downslope limber pine whose establishment does not correlate well with any of the measured metrics. This limber pine above-treeline takeover is happening throughout the Great Basin on all soil types and aspects, even when adult treeline forests are dominated by other species like bristlecone pine. While the long-term consequences of this treeline demographic shift are hard to determine, the near-term consequences are clear: a shift from bristlecone pine-dominated treeline to a higher limber pine-dominated treeline in the next 50-100 years. For species with individuals that can live for more than 5000 years, this is a fantastically fast demographic shift. While this likely does not spell doom for bristlecone pine, it is quite possible for limber pine's rapid colonization to result in local extirpations, and is certain to result in forests that look very different than those that have persisted at treeline for thousands of years.

THE EFFECT OF BATHYMETRY IN SMALL LAKES ON THE COMPOSITION OF THE DIATOM FLORA: APPLICATIONS FOR EVALUATING PAST CLIMATE VARIABILITY

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Small lakes at middle- to high-elevations (1,500-3,500 m asl) can be sensitive recorders of regional climate change, but these lakes can also be sensitive to local factors. For example, basin morphology of these small lakes is known to have a significant effect on the thermal structure of the water column, as well as the duration and spatial extent of winter ice cover. In turn, these conditions may affect the species composition of the diatom flora found in alpine lakes. In an effort to better characterize diatom microfossil variability in small lakes; this presentation explores the relationships between lake bathymetry and diatom assemblages. The lakes in this study have been divided into three categories: Type I - shallow (< 1 m deep), flat-bottomed; Type II - deep central basin (>5 m deep), surrounded by a shallow shelf ("inverted sombrero"); and Type III - deep (>6 m deep) with steep sides. Shallow, flat-bottomed lakes are characterized by a diverse benthic assemblage including motile, non-motile, and prostrate epiphytic species. Lakes with a shallow shelf and deep basin are often dominated by tychoplanktonic taxa which form large mats in shallow water. As these mats break up, and the constituent diatoms are then deposited in deeper water. Deep lakes with steep sides are often dominated by planktic diatoms. Therefore, as lake levels change over time, the basin morphology of individual lakes can also change (*eg*. a lake can begin as a Type I which, over time, becomes a Type III lake as it fills, culminating in a Type II lake), leading to variations in the timing and magnitude of thermal stratification and ice cover, which in turn can lead to changes in the dominant members of the diatom assemblage. The major conclusions from this analysis are that (1) bathymetry in modern lakes affects the composition of the diatom assemblage; and (2) changes in the diatom assemblage can be used to infer past variations in lake levels. Data from lakes in California, eastern Nevada, and Idaho will be presented as examples of modern variability and as potential archives of lake level change.

USING CALIFORNIA'S HOTTER DROUGHT AS A PREVIEW OF THE FUTURE: THE *LEAF TO LANDSCAPE* FOREST VULNERABILITY PROJECT

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"Hotter droughts" (otherwise normal droughts whose effects on ecosystems are exacerbated by higher temperatures) are an emerging climate change threat to forests, with some of their earliest and strongest manifestations in the American West. Managers can increase forest resistance to hotter droughts, such as by thinning forests to reduce competition for water among the remaining trees. However, the task is so vast that managers often need to perform triage, deciding where on the landscape their limited funds will be best applied; that is, they need forest vulnerability maps to help them strategically target treatments. But at the spatial and temporal scales that matter most to trees and forest managers, our ability to use commonly-available data sources to produce spatially-explicit maps of forest vulnerability is, at best, quite poor. We have thus launched the collaborative "Leaf to Landscape" project, which applies a fundamentally different approach to mapping forest vulnerability to hotter droughts. By using California's 2012-2015 hotter drought as a preview of the future, we let the trees themselves provide a direct empirical basis for vulnerability maps and for improving our basic mechanistic understanding of the effects of hotter droughts on forests. Leaf to Landscape thus has three main data-collection components, designed to be integrated across scales – from tree leaves to entire forested landscapes: (1) tree physiology and chemistry (directly measured by climbing hundreds of trees of the Sierra's 10 dominant tree species), which is strategically co-located with (2) population monitoring (ground surveys of foliage dieback and tree death in permanent forest plots), thus providing calibration and validation for (3) high-resolution LiDAR + hyperspectral remote imagery. The remote imagery will allow us to scale up to determine spatial patterns of drought effects, and their correlates. Early results already provide some unexpected insights.

Precipitation characteristics, soil moisture deficit, and conifer response during the 2012-2015 drought as observed across instrumented mountain life zones in the Great Basin, USA.

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We present the daily evolution of near-surface ecohydrological processes across a representative Great Basin mountain gradient during the significant 2012-2015 drought. Hourly-to-seasonal precipitation volume, phase, and intensities are highlighted, and the roles of individual storms in moderating root-zone drought stress are demonstrated in case examples. Two dominant seasonal patterns of water input are evident during this timeframe, with varying soil drought duration across the different life zones. In three of the four years, relatively dry winters with low snowpack were offset by persistent summertime moisture input that recharged shallow soil moisture and mitigated conifer water stress as measured by diurnal sap velocity patterns. Consistent winter snow capture occurred in upper elevations even during this significant drought, demonstrating elevationally-driven buffering of mountain life zones against drier winters. Xylem sap flow was measured in *Pinus flexilis* and *Pinus longaeva* within 100 m of treeline throughout the peak water stress periods of the drought sequence. *P.longaeva* appears more resilient to soil drying than *P.flexilis* in this scenario, and both species leveraged summertime moisture input to maintain positive daytime sap flow. Summertime hail at high elevation was observed to provide substantial rooting-depth moisture recharge during high-energy convective storms as opposed to rainfall only. These results underscore the need for fine-scale monitoring across elevational gradients in order to observe critical hydroclimatic mechanisms in temperate and semi-arid mountains, refining our concepts of processes related to ecosystem health, species adaptability, and biogeography.

SIMULATED IMPACT OF PALEOCLIMATE CHANGE ON FREMONT NATIVE AMERICAN MAIZE FARMING IN UTAH AT THE MCA-LIA TRANSITION, CA. 12-13TH C. CE

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We present the results of a computational crop modeling experiment for ancient Fremont Native American *Zea mays* farming in the Uinta Basin, Utah, at the Medieval Climate Anomaly to Little Ice Age (MCA-LIA) transition, ca. 850-1450 CE. The crop model (the Environment Policy Impact Calculator, EPIC) was driven by statistically downscaled precipitation, temperature and shortwave radiative flux from the Community Earth System Model (CESM) produced by NCAR. We found that maize yield responded to changes in the model-reconstructed climate; and periods of reduced maize yields corresponded to the abandonment of higher elevation Fremont ^{14}C-dated archaeological sites. EPIC produces good agreement between modeled and historically reported maize yields for the 19th century. This work was carried out during a Young Scientists Summer Program fellowship at the International Institute of Applied Systems Analysis near Vienna, Austria.

PAST AND ONGOING OBSERVATIONS OF *PINUS PONDEROSA* TREE-RING GROWTH IN THE SHEEP RANGE, NV, USA

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The Sheep Range of southern Nevada is located at the northwest edge of the North American Monsoon System (NAMS), which affects summertime precipitation in the US and could be highly sensitive to future climate change. On this mountain range there are extensive stands of *Pinus ponderosa*, which are being studied using data from a long-term mountain observatory, the Nevada Climate-ecohydrological Assessment Network (NevCAN). Tree-ring records from *P. ponderosa* have been used to statistically reconstruct monsoonal precipitation, and we have now completed a *P. ponderosa* tree-ring chronology spanning 1590 – 2015 for the Sheep Range. Earlywood/latewood measurements were correlated against seasonal climate variables from PRISM datasets (1895-2015). In addition, sub-daily images from remotely operated webcams and sub-hourly precipitation measurements were used to determine the onset of snowfall and snowpack duration in relation to earlywood/latewood growth between 2011 and 2015. Finally, interannual variability of $\delta^{13}C$ and $\delta^{18}O$ in cellulose was compared to $\delta^{18}O$ of precipitation collected at the NevCAN station from March 2015 until June 2016.

Visualization of Plant Functional Traits Along a Gradient of Elevation in the Cairngorm Mountains of Scotland

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The distributions of alpine plant species and their functional traits are predicted to change with climate change in alpine environments. We used R and the interactive Shiny application in RStudio to visualize the distribution of plant functional traits and species with the goal of developing predictive scenarios of changes in these attributes of plants in response to changes in the environmental variables associated with alpine climate change. These predictive scenarios are based on *in-situ* field data of species and trait distribution from the RAPT (Researching Alpine Plant Traits) project on Sgòran Dubh Mòr, (57°04'49.76"N, 3°48'28.85"W), a mountain of the Allt a' Mharcaidh Catchment in the Cairngorm Mountains of Scotland. Utilizing R and Shiny, we placed plant functional trait and species values on topographic Google Maps along a gradient of elevation from 750 m to the 1111 m summit of Sgòran Dubh Mòr. The slider options within Shiny were used to generate if-then scenarios of the responses of alpine plants to climate change with Sgòran Dubh Mòr as a model system. For example, if temperatures increase, then does species distribution change? Do the distributions of trait values within and between species change with elevation and with increased temperature? The resulting predictive scenarios can be linked with long-term observatories such as GLORIA and those included in the GNOMO group, especially since Sgòran Dubh Mòr is the highest summit of the Scottish Cairngorms GLORIA site. The scenarios can be applied to other mountain systems and the visual and interactive nature of the R Shiny models gives them great value in illustrating and predicting the effects of climate change on alpine plants.

TEMPERATURE SENSOR NETWORKS: SAMPLING, ANALYSIS, AND INTERPRETATION

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Inexpensive temperature sensors have revolutionized measurement and mapping of topoclimate and microclimate. Drawing on more than a decade of deployments in subalpine forests/shrublands, coastal woodlands/grasslands, streams, and vineyards, this presentation explores how to effectively deploy sensors, analyze data, map results, and extrapolate local models. Deployment issues include microclimate positioning, key topoclimatic gradients, and sensor density/replication. Data analysis issues include averaging periods, temperature differentials, and derivation of ecologically relevant temperature indices. Mapping options include direct interpolation of dense networks, multivariate predictions of temperature indices from topographic variables, and GIS projections across complex terrain. Daily and hourly time series of individual sensors can be tied to local weather stations via empirical transfer functions that incorporate temperature, humidity, wind speed/direction, and insolation, allowing simulations under weather conditions beyond the sampling period. These examples aim to stimulate and encourage MtnClim dialog on how to best use this exciting technology to answer fundamental and applied questions of topo- and microclimatology.

COMPARISON OF NITRATE CHEMISTRY AND PHYTOPLANKTON BETWEEN GLACIER-FED AND SNOW-FED MOUNTAIN LAKES WITHIN NORTH CASCADES NATIONAL PARK

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We compared nitrate concentrations, phytoplankton biomass, and phytoplankton community structure in lakes fed by glacier melt and snowmelt (GSF lakes) and by snowmelt only (SF lakes) within North Cascades National Park (NOCA) in Washington State, USA. In the U.S. Rocky Mountains, glacier melting has increased nitrate concentrations 40-200 times in GSF lakes relative to SF lakes and thereby stimulated phytoplankton changes in GSF lakes. Considering NOCA contains approximately one third of the glaciers in the continental U.S., and many mountain lakes that receive glacier meltwater inputs, we hypothesized that NOCA GSF lakes would have greater nitrate concentrations, greater phytoplankton biomass, and greater abundance of nitrogen-sensitive diatom species than NOCA SF lakes. However, there were relatively small differences between GSF and SF lakes at NOCA compared to those observed in the Rockies. At NOCA, nitrate concentrations were on average only 2-3 times higher in GSF relative to SF lakes, and a nitrate difference was not detectable in several individual years. There also was no difference in phytoplankton biomass or abundance of nitrogen-sensitive diatoms between lake types at NOCA. In contrast to the Rockies, nitrate concentrations in NOCA GSF lakes were an order of magnitude lower, and there was not a significant positive relationship between watershed percent glacier area and lake nitrate. Reasons for inter-regional differences are not clear but may relate to differing climate, geology, and microbial processes occurring in glacier environments.

Effects of Climate Change on Traditional Medicinal Plants

Carol Wilson, Northwest Indian College, Department of Science, Bellingham, WA 98226

Traditional Medicinal plants are highly valuable and well recognized within Native communities. There is evidence that climate change is causing noticeable effects on life cycles and distribution of the traditional plant species. This evidence leads me to pose the following questions: as plants move to higher elevations have their medicinal potency and effects changed, or do they stay the same? It is unclear whether climate change effects secondary chemicals production in plants. The mountainous ecosystems these plants are migrating to effect not only the plants functions, including chemical processes, but also their availability to Native peoples. This perspective has been given renewed attention recently; there is a need for research to improve our understanding of the effects of climate change on traditional medicinal plants. I would like to stress the importance and urgency of this work. This work includes the need for a comprehensive literature review of the scholarly work on the Western hemisphere on this important issue.

CONNECTING WITH CITIZEN SCIENCE TO TRACE STABLE ISOTOPES IN RAIN AND SNOW IN THE COLUMBIA RIVER BASIN

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Citizen science, a technique to gather scientific information through public participation, has increasingly been used in environmental sciences to both advance scientific knowledge and yield positive outreach and educational benefits. As part of a larger project to characterize moisture delivery pathways to the U.S. Pacific Northwest over multi-century time scales, we connected with an ongoing citizen science project, the Community Collaborative Rain, Hail & Snow (CoCoRaHS) network, to better understand storm-level variation in precipitation isotopes. Working with the CoCoRaHS Education Coordinator, we identified four observers around the Columbia River Basin who were affiliated with K-12 or non-profit education, had excellent records of participation, and were willing to transfer weekly samples from their CoCoRaHS gauges to vials and send them in for δ18O analysis. As part of these collaborations, which have been ongoing since 2012, we have provided informational flyers to share results and have conducted outreach with K-12 schools and non-profit organizations. These collaborations have in turn provided us with high-resolution precipitation sampling for δ18O that will help us understand event-scale isotope patterns and confirm isotopic precipitation patterns at our tree-ring sampling sites. Data obtained from these samples have already allowed us to test hypotheses concerning isotopic differences between high- and low-snow years and between northerly and southerly storm-track positions. When combined with soil moisture and tree-ring sampling conducted over the same time period, we will be able to track the movement of stable isotopes from precipitation through the soil and into the trees.

PALEOCLIMATE PERSPECTIVES ON RAIN AND SNOW IN THE PACIFIC NORTHWEST

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Seasonal biases in paleoclimate proxies remain a major challenge for the reconstruction and interpretation of past climates. Questions have been raised concerning the ability of the tree-ring record to capture cool-season precipitation, with implications for the interpretation of past climate events, particularly in the Pacific Northwest. This presentation will outline ongoing work to address these concerns, focusing on our recent reconstruction of the mid-latitude, westerly storm track, which represents the primary moisture-delivery pathway to the Pacific Northwest. This reconstruction of cool-season (Oct-Mar) storm-track position over 1693-2011 CE shows strong variability in storm-track position and trajectory throughout the past 319 years. Decadal and longer drought periods are consistently associated with a north-shifted storm track, and our comparison with an independent El Niño – Southern Oscillation reconstruction demonstrates the long-term influence of El Niño on storm tracks. This study and others being undertaken by paleoclimate researchers in the Pacific Northwest will help provide a more complete understanding of long-term variability on rain and snow in this region.

MANAGING AN ELECTRIC UTILITY IN A TIME OF CLIMATE CHANGE

Steve Wright, *General Manager Chelan PUD and former BPA Administrator*

Climate change is likely to have tremendous impacts on electric utilities in the Pacific Northwest. The PNW gets a relatively large amount of electricity from weather dependent hydropower, is a large consumer of weather dependent electricity due to its low cost supply, and hydropower's greatest environmental challenge is impacts on salmon that will be affected by changes to temperature and water. Steve Wright has 35 years experience in PNW electric utility industry including 12 as CEO of the Bonneville Power Administration and 3 as General Manger of Chelan PUD, both of which manage hydropower resources on the Columbia River. Steve will speak to the operational and policy challenges for the Northwest utility industry resulting from an uncertain climate future.

TOPOGRAPHIC AND SEASONAL CONTROL ON N AVAILABILITY IN WESTERN MONTANE FOREST ECOSYSTEM

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In the montane ecosystems of the western US, winter snowpack is predicted to decline with rising air temperature. Because winter snowpack both provides a major source of water as well as insulates the soils for N mineralization, the decline in snowpack is expected to affect forest productivity. However, while N availability is known to influence forest productivity, it is not clear how declining snowpack would alter current N availability across complex mountain topography. We examined how elevation, aspects (north-facing vs. south-facing), and micro-topography (slope vs. hollow) affect the distribution of plant-available N across season at the Lubrecht Experimental Forest in western Montana. We hypothesized that N availability is highest following spring snowmelt and fall, when soil moisture is highest, and that sites with a deeper snowpack (high elevation, north aspect sites) results in higher N availability during summer than those with thinner snowpack. We measured ammonium (NH_4^+) and nitrate (NO_3^-) in soil KCl-extracts and in soil water collected by lysimeters for over a year, immediately following the spring snowmelt of 2015. Soil temperature and moisture were recorded continuously during this time using data loggers. Our results show that soil N availability was generally greater at higher elevation sites and in the hollows, where the winter snowpack is deepest. In contrast, the effect of elevation was less pronounced on the slope. While N availability changed greatly across season, the seasonal patterns differed between high vs. low elevation sites as well as hollow vs. slope. Our findings suggest that seasonal N availability in the western montane forests differ greatly across elevation and microtopography. This implies that shifts in snowpack regime in the future would alter the amount and timing of N available to the plants.