

Mountain Views

Chronicles of the Consortium for Integrated
Climate Research in Western Mountains

CIRMOUNT



Informing the Mountain Research Community

Volume 11, Number 2 • December 2017



Rocky Mountain juniper (*Juniperus scopulorum*) stem cross-sections. Top: "Thanksgiving Turkey" (1100 year ring circled). Bottom: "Taking a Rakish Appearance" (1200 yr old section). Prepared by John King

Front Cover: Remembering Kelly Redmond, who passed a year ago on November 2, 2016.
Kelly's photograph of Mono Lake, California

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Read about the contributing artists on page 57

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<i>Question:</i> First we have severe droughts in the West, then an epic snowpack winter of 2016-2017. In the systems and mountain regions where you work, did you observe any unusual or unexpected effects during the summer season that resulted from the heavy winter and/or the combined effect of prior drought and heavy winter(s)?	42
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EDITOR'S INTRODUCTION

When I was an undergraduate in the College of Forestry at the University of Washington in the early 1970s, I worked closely with recently hired Professor Linda Brubaker. Now lifelong friends, Linda introduced me to the world of the past. Linda was a Quaternary Scientist who used pollen and tree-cores to unravel the climate of the last 20,000 years and to investigate responses of forest communities to the dramatic climate changes that unfolded in the late Pleistocene. I was entranced by her research in the far-north land-bridge, Beringia. Linda's interpretations of pollen data there led her to propose the role of climate refugia, that is, locations where forests persisted despite frigid conditions that evolved in the region. Over the decades, the concept of climate refugia has become a central organizing theory to interpret Quaternary biogeography worldwide, paleohistoric migrations at deeper time periods, as well as more recent Holocene dynamics.

Only in the last decade has the refugium concept emerged as a potential strategy for climate adaptation. Mimicking prehistoric dynamics, resource managers can assist species or ecosystems vulnerable to contemporary climate change by evaluating and managing environmental contexts that serve as climatically safe havens. Toni Lyn Morelli (DOI) has taken a lead to focus a

science-based framework for refugia into the service of climate adaptation. Her guest editorial introduces a feature section on climate refugia for adaptation, drawing in efforts of two pioneers in the science-adaptation nexus, Dan Isaak (USFS) and Deanna Dulen (NPS), as well as summarizing her own work with climate refugia and Belding ground squirrels.

Our *Brevia* in this issue highlight recent articles on snow, snowmelt, and fire effects on snow, as well as a new study evaluating PRISM accuracies, and a 50-yr evaluation of alpine plant shifts in response to climate. The rollercoaster variability in recent years, from heavy snowpacks in the winter of 2016-2017 to extreme drought and warmth of years before, also features in sections of this issue, including the *Voices in the Wind* replies. As an ecologist looking always for patterns in the chaos of variability, more and more I find the role of legacy effects and interannual weather sequencing to be critical for unraveling responses.

With these and other topics, including a round-up of artwork from colleagues in the CIRMOUNT community, I send you my best wishes for the holiday season and the 2018 new year. See you at *MtnClim 2018* in Gothic, CO next September (page 40)!



Connie Millar

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GUEST EDITORIAL

Toni Lyn Morelli

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Because I can still remember when I first heard of the climate refugia concept, and it was less than a decade ago, I feel a bit shy to be tasked to speak as an authority on this topic here. But I'll set my imposter syndrome aside under Connie's request, who in fact was the one who made my introduction, back on an early summer day on the eastside of the Sierras, where the Great Basin finally runs out against the Range of Light. It was the perfect setting to first digest such an idea, as the landscape and the concept of protecting persistent climate spaces is both inspiring but daunting, and the hot, dry environment that surrounded me certainly made global warming projections feel urgent.

I've since had the great fortune to get to know the burgeoning field of climate change refugia. Like the Sierras that build from a vast plain, the field of climate change adaptation inevitably pushes forward into the idea of managing refugia. Though Europeans Hampe, Jump, and Rull made exceptional early contributions, perhaps it's no surprise that it was the Australians (Keppel, Ashcroft), coming from a hot, dry climate that was looking to become even hotter and drier, who helped transition the refugia focus from past climates to future ones. Here in the U.S. I have watched my colleagues respond with vision and brilliance, motivated by natural resource managers on the ground to move the conversation from the journal pages to the field to the state fish and wildlife office. In the right place at the right time, I was lucky to lead a diverse group of scientists and managers to develop a framework by which to operationalize the idea.

Dan Isaak has been one of these inspiring scientists, and in this issue Dan and Michael Young speak to using state-of-the-art technology and creative data sourcing (citizen science!) in response to the need for more fine-scale water temperature data to map climate refugia for salmonid conservation (Coldwater Climate Shield!) in the Pacific Northwest. They also push us to look to eDNA as the next frontier. You may think that all sounds challenging, but given Dan and colleagues are some of the only people doing it in the whole country, rest assured it's even harder than you think.

Likewise, a tale of inspiration can be found back where my story began, in the Sierra Nevada, where Superintendent Deanna Dulen has courageously adopted this idea for Devil's Postpile National Monument. With determination as well as warmth, she's brought top scientists together to determine how one would manage a climate change refugium for the unique and vulnerable fauna and

flora of the Monument and its watershed. It's certainly exciting for me to see the National Park Service apply the Climate Change Refugia Conservation Cycle, co-developed by scientists and managers, for the first time in such a thoughtful way.

To this impressive company I humbly add my own story, how I came to study a species that may be lost to the natural areas of California without climate change refugia management. With the foresight of naturalists a century ago, we have data to show that the Belding's ground squirrel is disappearing from California, and with the hard work and dedication of contemporary scientists we were able to produce maps for where they might hold out a while longer.

In some ways the climate change refugia work brings together the best parts of what we do – pure science, understanding gathered through hard, often isolated field work, matched against the critical management needs of the public and the natural world, moving forward together. The future often feels bleak, maybe more these days than ever before. But I'm sure I'm not alone in finding motivation, stimulation, joy on the good days, and solace on the others in my mountain enthusiast colleagues. Thanks for the inspiration!



ARTICLES

Delineating Climate Refugia for Native Aquatic Species with Big Crowd-Sourced Databases

Daniel Isaak and Michael Young

*USDA Forest Service, Rocky Mountain Research Station
Boise, Idaho (DI) and Missoula, MT (MY)*

Topographic diversity is the essence of mountain environments in western North America, a diversity that manifests itself hydrologically in a host of forms—rivers, streams, lakes, wetlands, and springs—that constitute habitats for a wealth of fish, amphibians, mussels, and insects. Some of those taxa, such as species of salmon and trout, are well studied icons of the region, whereas others are known only to dedicated naturalists or have yet to be described by science. Climatic controls on the distribution and abundance of aquatic taxa are of longstanding interest to aquatic ecologists and researchers given the aridity of much of the western U.S. and the strong environmental gradients driving biodiversity patterns from headwaters to lowlands. In fact, some of the first global research predicting how anthropogenic climate change could affect popular cold-water trout species occurred in the Rocky Mountains more than 20 years ago (Keleher and Rahel 1996). Early estimates of the potential habitat losses that warming could cause were a source of widespread concern and have stimulated ongoing research ever since. Most recently, historical resurvey efforts have confirmed that distributions of trout species are shifting coincident with warming (Eby et al. 2014), and these have heightened interest in identifying habitats that may serve as climate refugia for species preservation.

More Precision, Please

One limitation of early bioclimatic models that often persists to the present is their coarse resolution. That is, the models may be accurate in predicting an unbiased representation of species distributions and climatic conditions but are based on sparse underlying datasets that require extensive interpolation among observations to create the continuous prediction surfaces and maps that represent conditions during different climatic periods. The result is local imprecision that makes it difficult to use the information for guiding site or project-level climate adaptation responses and conservation investments. Compounding matters for many aquatic climate assessments is that air temperature has often been used as a surrogate for water temperature because data on the latter were lacking in many areas.

At about the same time that climate change awareness was dawning for aquatic professionals in the 1990s, inexpensive temperature sensors were developed, marketed, and adopted by many natural resource agencies as a basic habitat monitoring tool because of temperature's importance to ectothermic organisms. Temperature monitoring in the two decades since has occurred for many purposes but increasing climate concerns, combined with an accumulating mass of data, provided a need and an opportunity to develop a central database that would service the needs of multiple agencies and that could be used to develop precise climate scenarios across broad areas. Beginning with seed grant funding from the Landscape Conservation Cooperatives, the NorWeST (Northwest Stream Temperature) project was initiated in 2011 and recently completed scenarios for all flowing waters in the western U.S. (Fig. 1; Isaak et al. 2017). The database consists of >220,000,000 hourly recordings at >23,000 unique sites and was crowd-sourced from data collected by professional biologists and hydrologists with more than 100 state, federal, tribal, municipal, and private resource organizations. Geostatistical models for data on stream networks were fit to the temperature data and used to interpolate summer climate scenarios with 1-km resolution that are distributed as ArcGIS shapefile formats through the NorWeST website (<https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html>). Open access to the scenarios and database via a central repository has proven popular among resource professionals who visit the website >12,000 times annually, download hundreds of data products, and use the information in climate vulnerability assessments to improve the efficiency of new temperature monitoring, and for new research on water temperature and thermal ecology.

Climate Shield Native Trout Refugia

Developing more precise stream and river temperature scenarios was an important means but not the end of delineating climate refugia at an extent and grain sufficient for conservation planning. The thermal information still needed to be integrated with species ecology, so in 2014 we repeated the crowd-sourcing process but focused instead on compiling a biological database

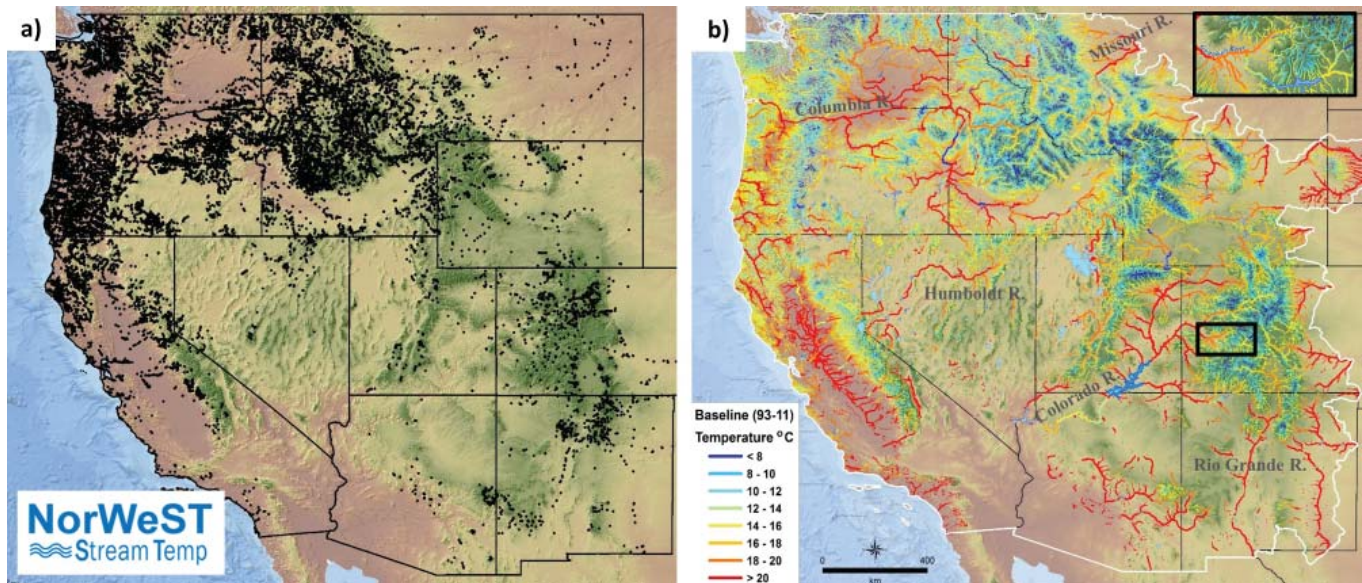


Figure 1. Locations of 23,000 sites in the western U.S. where stream and river temperature data were crowd-sourced from professionals working for more than 100 natural resource organizations to create the NorWeST database (a). The database is accessed by a large user-community through a project website and is used for many purposes, including the development of high-resolution temperature scenarios for rivers and streams (b).

of species occurrence records for two native trout species—bull trout and cutthroat trout—that are of conservation concern in the West. Here again, thousands of observations were available and professionals from state and federal biologists from management agencies were willing to share the data to develop a larger database. Once the database was complete, it was used to develop species distribution models that predicted the probability of trout occurrence as a function of the NorWeST scenarios and other environmental covariates that were obtained from regionally consistent geospatial datasets. Not surprisingly, temperature was a strong predictor of where trout populations occurred, the overall predictive accuracy of the models was good, and the modeled relationships were used to map probabilities of species occurrence for different climate scenarios throughout all streams within the geographic ranges of bull trout (Fig. 2; ~5,000 streams) and cutthroat trout (~20,000 streams).

Those probability maps are powerful tools for assessing the relative quality of current and future habitats throughout the ranges of these fishes. The maps show that not all habitats are created equal, nor do they decline at identical rates with future warming given the local nuances that arise from different combinations of habitat size, geomorphology, and temperature regimes. Most promisingly, some streams were predicted to have high probabilities of supporting trout populations even under the most extreme climate change scenarios, and therefore could serve as long-term climate refugia. Similar to the NorWeST project, all the data and scenario probability maps were organized into user-friendly digital formats and are distributed through a custom website for the Climate Shield project (<https://www.fs.fed.us/rm/>

[boise/AWAE/projects/ClimateShield.html](https://www.fs.fed.us/rm/boise/AWAE/projects/ClimateShield.html)). The information is broadly used by many agencies for bull trout and cutthroat trout conservation planning done in association with National Forest plan revisions, endangered species consultations, NEPA analyses, and climate adaptation projects (Isaak et al. 2015; Isaak et al. 2016; Young et al. 2018).

eDNA Opens the Way

Ongoing climate change means that information similar to that provided by the Climate Shield project is needed to delineate refugia for many taxa. Unfortunately, relatively few data exist for most aquatic species in the western U.S. that are not sport-fishes such as trout and salmon, and even information for those taxa is rarely collated into broad databases readily accessible to users. Both shortcomings need to be addressed to position society for informed management of aquatic taxa.

The primary limitation to gathering data on the distribution of aquatic species is methodological. We often rely on specialized techniques that only work for a handful of species in particular environments e.g., backpack electrofishing is suitable for describing small-stream fish communities, but little else. Learning about the presence of many species generally requires multiple visits, different techniques, and wide expertise, and rapidly becomes cost-prohibitive. A recent advance in aquatic species monitoring, however, may revolutionize our ability to sample across the taxonomic spectrum. Because all organisms release DNA into the surrounding environment, detecting that DNA can serve as a tool to infer species presence. This is the

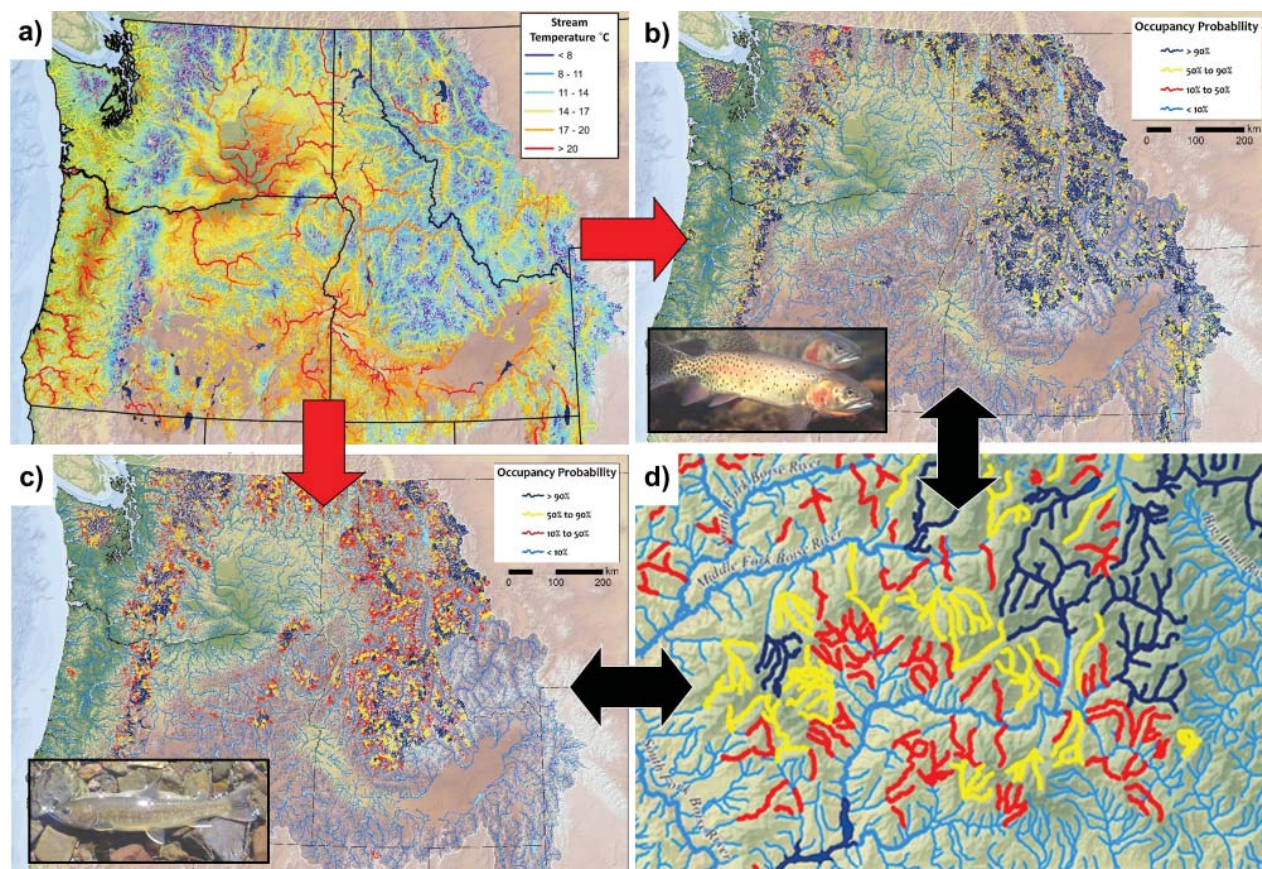


Figure 2. NorWeST temperature scenarios (a) were used with other environmental covariates from geospatial datasets to develop the Climate Shield species distribution models and predict the probabilities of habitat occupancy for cutthroat trout (b) and bull trout (c) throughout their ranges. Climate refuges are identified as those streams which retain high probabilities of supporting local populations during future climate change conditions (d).

premise of environmental DNA (eDNA) sampling, and interest in the field has exploded since its first application late in the last decade (Ficetola et al. 2008).

Much of the ongoing research into eDNA sampling has been in mountain environments in the western U.S. for taxa as diverse as amphibians (Goldberg et al. 2011), fishes (Wilcox et al. 2015), invasive snails, and even a mammal (Padgett-Stewart et al. 2016). Increasingly, this work is directed at characterizing the effectiveness of eDNA sampling relative to traditional methods, and many studies are concluding that eDNA sampling offers several-fold higher detection rates at lower costs (Wilcox et al. 2016). These advantages have led to a number of field applications, particularly to detect the distribution of species of conservation concern, whether rare native taxa or introduced invasive species (Carim et al. 2016a; McKelvey et al. 2016). Among the broadest approaches is the attempt to delineate the distribution of bull trout in natal habitats throughout their entire U.S. range (Young et al. 2017; https://www.fs.fed.us/rm/boise/AWAE/projects/BullTrout_eDNA.html), and similar efforts are underway for other species. And the value of these broad-scale

surveys is not limited to the species they are targeting. Each sample from a site has the potential to contain the DNA of all the taxa present at or upstream from that site, and these samples can be archived indefinitely. In essence, eDNA samples constitute a biodiversity archive that can be interrogated now to answer pressing questions about extant species, and stored to address questions that may arise in future decades.

As in any rapidly emerging field, there are growing pains. One is a concern about the comparability among projects, but this can be overcome if clear, straightforward sampling methods are adopted (Carim et al. 2016b). Perhaps a more pressing issue, however, is to raise consciousness among the community of professionals about those locations that have already been sampled (to avoid redundancy and redirect efforts to unsampled locations), and to make those existing data readily available to scientists, managers, and decision-makers. To foster that data sharing, we are developing the eDNAtlas (<https://www.researchgate.net/project/The-Aquatic-eDNAtlas-for-the-American-West>), an open-access online database that displays the site-specific results for all eDNA samples analyzed by the National Genomics Center for Wildlife and Fish Conservation (a prototype ArcGIS Online database tool

can be seen here: https://www.fs.fed.us/rm/boise/AWAE/projects/BullTrout_eDNA/SurveyStatus.html). A key feature is that users can filter the data for any species or location, and download that information in a variety of customizable formats. Although primarily focused on the West, for which there are data on over 8,000 samples, the eDNAAtlas will expand to the rest of U.S. in 2018 as samples arrive from throughout the country.

Our future efforts, and those of the eDNA sampling community, are being directed at a broader species pool—which will include a number of birds, mammals, pathogens, macroinvertebrates, and plants—and expanding into other environments e.g., snow and soil, as well as developing cost-effective methods to simultaneously analyze a host of species from each sample. Our overriding motivation, however, is to combine the increasingly sophisticated and comprehensive geospatial databases reflecting climate and hydrology with the growing eDNA databases to build more precise, accurate, and spatially specific models of species distributions, understand their responses to a changing climate, and map those areas which will serve as climate refugia for conservation planning and species preservation.

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Mapping Climate Change Refugia in the Sierra Nevada

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I, a “flatlander” from the great Lakes State of Michigan, probably don’t need to tell you that montane meadows in the western U.S. are remarkable. Unlike in the vast conifer forests of the upper Midwest and northern New England (not to mention Canada), where trees can stretch as far as the eye can see with only blowdowns or bogs naturally breaking up the view, I could return to a certain spot in the Sierra Nevada year after year, decade after decade, with confidence that I would find a nice spot to sit in the short grass, refill my water bottle, and watch for wildlife. Which is not to say that meadows are static over millennia, of course, as climate change reminds us. One only need pull up on the side of State Route 120 in Yosemite National Park (though please don’t, there are traffic problems enough as it is) and see that lodgepole pine seedlings and saplings are determined to turn Tuolumne Meadows back into the forest it once was.

Montane meadows are more than a nice place to eat your lunch. They are critical to hydrological function; for example, in California they have a big impact on water storage and ultimately the availability of drinking water to the majority of California that live on the coasts. They also contribute disproportionately to biodiversity. Raptors, weasels, small mammals, fish, countless invertebrates, plants that I don’t have the expertise to begin to enumerate...a huge variety of species benefit from, if not rely upon, the heterogeneity that these ecosystems bring. It was one of these species, the Belding’s ground squirrel (*Urocitellus beldingi*), that set me on the path that would forever embed the Sierras in my heart and climate change in my career.



Figure 1. Belding’s ground squirrel.

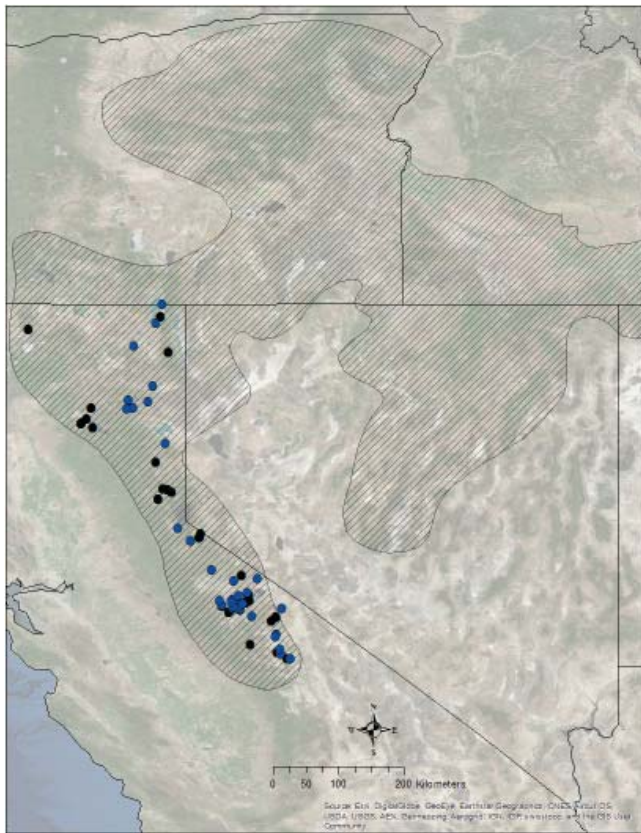
As far as rodents go, social ground squirrels are among the most charismatic, and Belding’s are no exception (Fig. 1). In addition to being found in the right place (montane meadows, see above) and the right time (they’re diurnal, unlike most rodents), they are noisy and curious and indiscreet, making them easy to survey and study. But I didn’t know most of this when my postdoctoral

supervisor, Craig Moritz, eminent evolutionary biologist and then-Director of U.C. Berkeley’s Museum of Vertebrate Zoology, suggested that I study them. In fact, I had never seen one. Once he convinced me there was more prestige, or at least more data, in ground squirrels than in anything else I could name, I took to YouTube to figure out what they looked like. I had recently graduated with a PhD studying lemur behavior and ecology in Madagascar, so even though I could tell you how to distinguish a red-bellied from a red-ruffed lemur, and, the difference between a fosa and a fossa, not to mention how to get a leech out of your eye (tip: get help from a friend), I didn’t know much about California flora and fauna.

But I quickly learned to love hiking and driving around the whole state (Fig. 2), using old maps and atlases to chase historical occurrences of Belding’s ground squirrels recorded in the loopy cursive of early 20th century natural history pioneers like Joseph Grinnell. The question started as: What caused the contraction of the Belding’s range in Yosemite NP over the last hundred years? It eventually morphed into a broad examination of a startling revelation of extirpations across nearly half of the species’ recorded California range (Fig. 3).



Figure 2. The author, Toni Lyn Morelli (left), with her fantastic field technicians, Christina Kastely and Ilaria Mastroserio, handling ground squirrels at the Mono Lake County Park “anthropogenic refugium”. Photo: Max Keeler



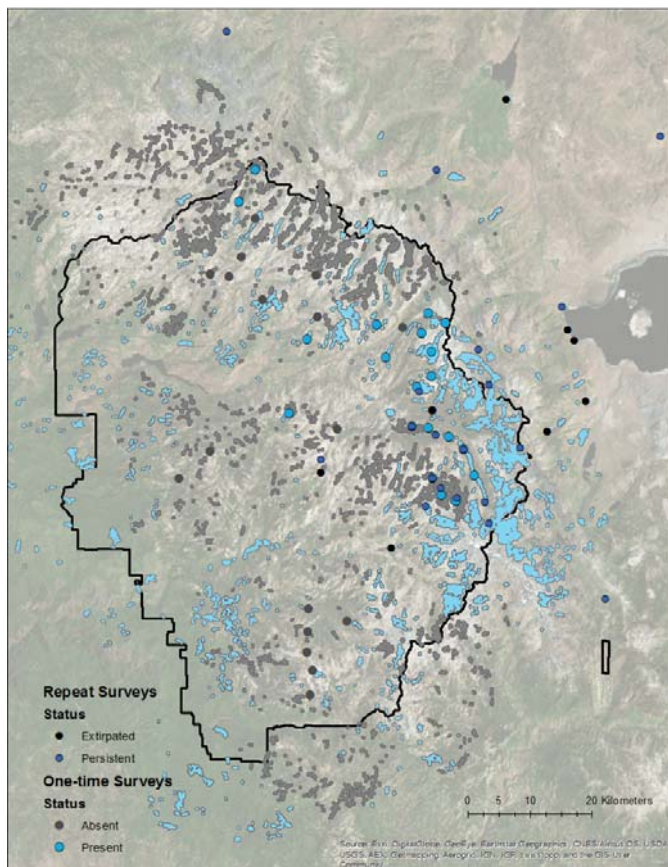
As an inherent optimist, an investigation into the cause of this statewide pattern of extirpations was quickly flipped to look at the minority of locations where populations had persisted over the last century. Could we connect these to climate change refugia, areas relatively buffered from contemporary climate change over time that enable persistence (Fig. 4)?

Fortunately, with funding from the California Landscape Conservation Cooperative, support from supervisor Steve Beissinger, incredibly fine-scaled hydrological data from Lorrie and Alan Flint, and the brains of then-postdoc-now-Missouri-State-Assistant-Professor Sean Maher, we were able to develop a map of meadows that were climate change refugia across the Sierra Nevada, as well as the connectivity among those refugia (Fig. 5). There are complications with this kind of analysis, including how to define refugia in the first place. The conceptual

Figure 3. Results of Belding's ground squirrel surveys—circles indicate extirpation (black) or persistence (blue) between California surveys in the early 20th and early 21st centuries. Hatching indicates the species' approximate range (from IUCN Red List 2010).



Figure 4. Halfmoon Meadow, Yosemite National Park, is a potential refugium.



framework that my fantastic colleagues (Steve, Connie Millar, Kelly Redmond, Jessica Lundquist, Chris Daly, Deana Dulen, Solomon Dobrowski, Koren Nydick, among others) developed for our *PLOS ONE* paper last year was specific enough for discussion and general enough to cover nearly everything (Fig. 6). Once you're actually coloring polygons on a map, you have to decide on variables and cutoffs. In the case of the meadow refugia work that Sean led, which was published earlier this year in *Ecosphere*, we decided to use some logical, albeit arbitrary, thresholds: 1°C temperature changes and 10% precipitation changes from the historical (1970-1999) period, for example.

Figure 5. Map of refugia meadows (in blue) in the area of Yosemite National Park (YNP, black outline). Blue circles indicate sites where Belding's ground squirrels were present (from one-time YNP surveys; light blue dots) or persistent (revisit after 50-100 years, smaller dark blue dots). Dark circles indicate sites where Belding's ground squirrels were absent (from one-time YNP surveys; gray dots) or extirpated (from revisit after 50-100 years, black dots). The Mono Lake County Park site can be seen on the right at the edge of Mono Lake.

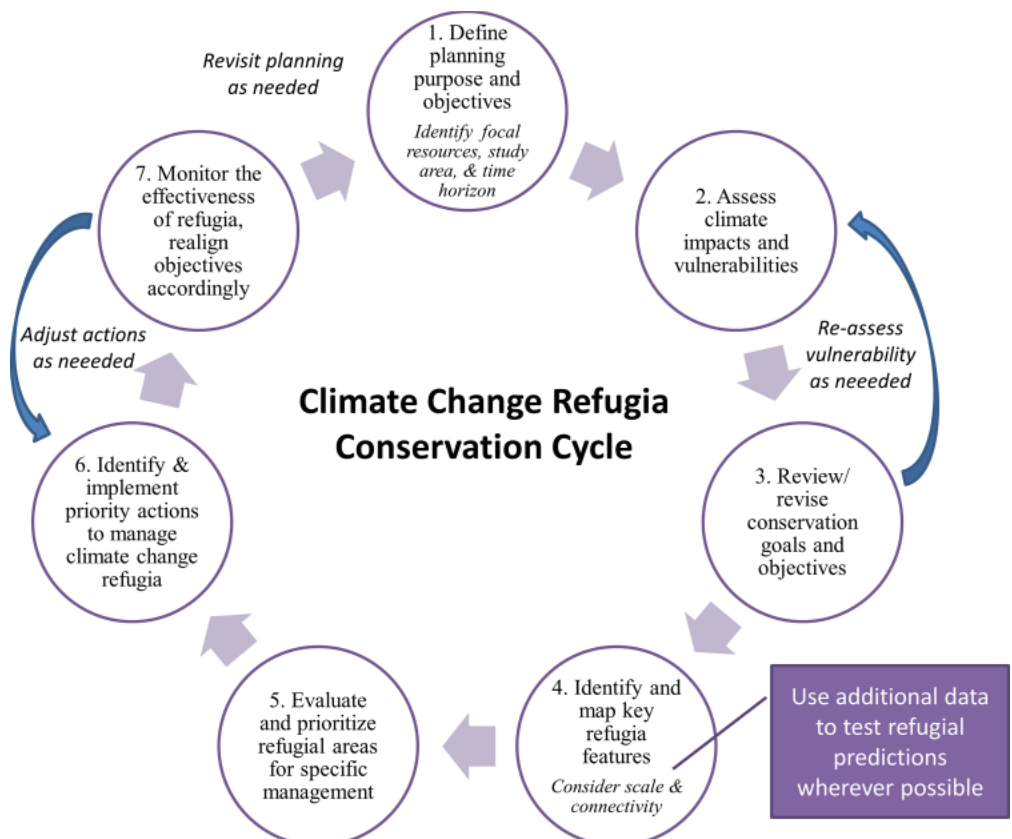


Figure 6. Climate change refugia conservation cycle, from Morelli et al. 2016

Our Sierra Nevada refugial meadows map was built generically, with 15 climate variables and thresholds considered, broadly applicable and essentially agnostic to species (e.g., increases in extreme wet or extreme dry periods could exclude refugia status). However, one point we highlighted in the climate change refugia conservation cycle framework we developed in our *PLOS ONE* paper, refugia maps are just hypotheses that need to be tested. So we tested whether our Belding's extirpation data could be explained by the refugia maps: were Belding's more likely to persist in sites that had been buffered from climate changes over the last 30 years?

Indeed, our hypotheses were supported (whew!). In work that has just been accepted for publication in *Climate Change Responses*, we show that Belding's ground squirrels were less likely to disappear from sites that had changed little in terms of temperature, precipitation, and, in some cases, snowpack over the last century. Moreover, there was higher persistence, signified by both occupancy over time and genetic diversity, in meadows with higher connectivity.

The result was one of the first maps of climate change refugia (rare in itself) that had been tested with an independent dataset. There's some personal persistence to explain that success (those results took nearly a decade from daydream to publication), but we were also lucky to have multiple visit occurrence data over a long time period (in this case 50-100 years) for species in sites that have seen *relatively* little change outside of climate.

Of course these maps are just a rough approximation. The next step of understanding what specifically is driving the species to extinction is hopefully right around the corner. We suspect the answer may be similar to one of the explanations for pika extirpations; climate change is increasing winter cold stress. The decrease in snowpack in recent decades means the ground is that much colder, the Belding's need to burn through more fat reserves while hibernating through the long winter, and some just can't make it to spring. Indeed we found that warmer, lower elevation sites were much more likely to blink out, unless they had been modified by humans as campgrounds or agricultural fields. In that case, such as at Mono Lake County Park, abundances were high and persistence was exceptional, possibly due to the increased availability of food (due to irrigation or just crop raiding). However, these sites may be acting as ecological traps; we found that populations in these rare "anthropogenic refugia" oases seemed cut off from neighboring populations and thus had less gene flow and lower genetic diversity.

Nevertheless, I would love to see these maps used for other species, not to mention conservation and management applications. For example, an LCC-funded project led by the

California Invasive Species Council is currently using them to inform meadow restoration prioritizations. But beyond that, it would be fantastic to see such research carried out in other regions and ecosystems. In fact, to encourage just such initiatives and the broad collaborations they require, the Northwest Climate Science Center developed the Refugia Research Coalition (see climaterefugia.org) with regional efforts led by Aaron Ramirez and myself (in the northeast) to bring together scientists and natural resource managers around target ecosystems—cold-water streams, sagebrush, boreal forests, glacial lakes—to discuss relevant management needs, identify existing spatial data, and move forward on climate change refugia conservation. Ultimately, the science is intended for action—one more tool in the kit for conservation practitioners, natural resource managers, and all of us to put to work.

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All photos by the author unless otherwise noted.

Climate Change Refugia at Devils Postpile National Monument: Workshop Report

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Over two perfect summer days in August 2017, 18 agency and academic scientists along with agency managers and interns gathered at Devils Postpile National Monument in the Sierra Nevada of California to discuss climate change refugia management as an adaptation strategy (Fig. 1). A shared passion for the Sierra Nevada and a strong resolve to understand and maintain the high biodiversity, ecosystem function, beauty, and wildness in a changing climate brought this group together.

Given the topography and steep elevational gradients, the Sierra Nevada harbors numerous potential climate change refugia. To begin exploring how to manage these areas and apply the seven-step Climate Change Refugia Conservation Strategy (Morelli et. al. 2016), Devils Postpile National Monument—described by Superintendent Deanna Dulen as, “large enough to be meaningful and small enough to be manageable”—was chosen as a case study (Fig. 2). Soda Springs Meadow has both physical and biological attributes including cold air pooling, a river fed by high elevation snow melt, complex topography, and substantial tree canopy that contribute to its potential as a climate



Figure 1. Workshop attendees deep in thought, August 24, 2017. Photo: Dan Cayan

change refugium (Fig. 3). In addition, Belding ground squirrel (*Uroditellus beldingi*), a species that is extirpated from many other lower elevation sites, still occurs in Soda Springs Meadow. Superintendent Dulen added that, “With the wealth of scientific partnerships at the monument and the manageable scale to plan

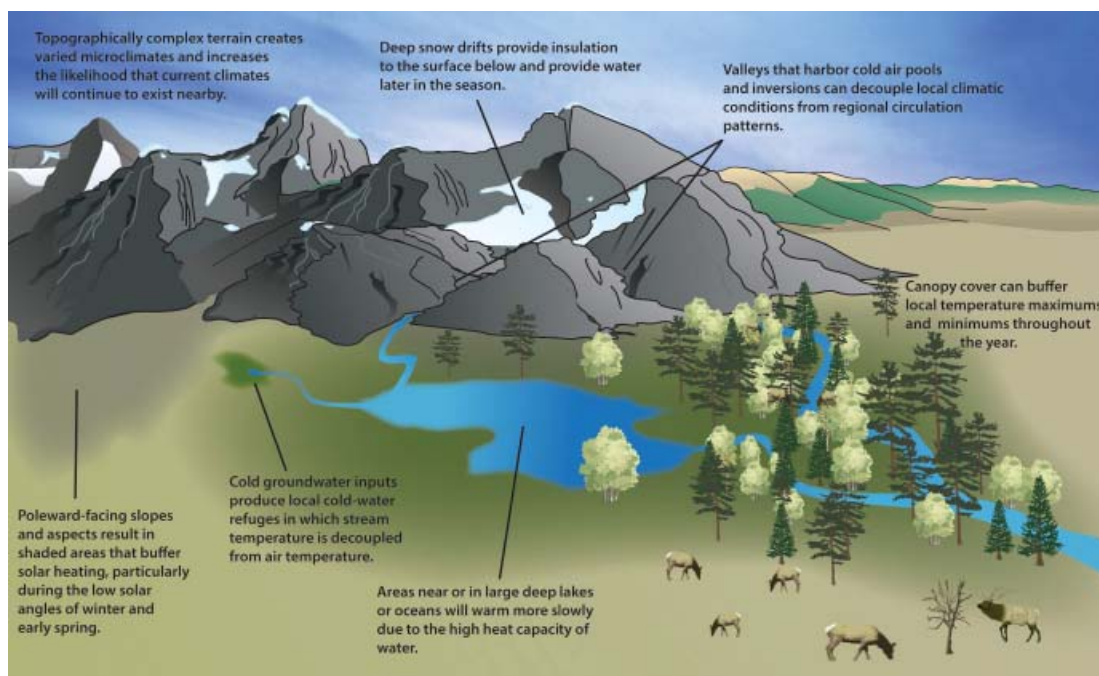


Figure 2. Attributes of climate change refugia, from Morelli et al. 2016



Figure 3. Upper Middle Fork of the San Joaquin River and Soda Springs Meadow. Photo: National Park Service

and apply actions, the efforts here will contribute to scientific learning and provide reference studies that may be transferable to developing adaptation strategies for larger meadow systems” (Fig. 4).

Following the seven step process, the group focused on the overall purpose of the workshop, reviewed climate impacts and vulnerabilities, developed several management goals, discussed refugial features of the area, identified key features, summarized current and needed data, and brainstormed potential actions. Using the case study approach, questions were discussed extensively exploring desired goals and appropriate time scales to develop action plans. For example, the effects of fire on the landscape and the necessity of integrating fire management strategies into the adaptation strategy were considered in the short and long term. Actions discussed included reducing the risk of catastrophic fires in the adjacent forest and to use fire management as a tool for managing lodgepole pine (*Pinus contorta*) migration into the shrinking meadow habitat as well as on the greater landscape to restore fire as a disturbance process.

As expected, the group also discussed obstacles including lack of knowledge, resistance to experimentation, changing hydrology, catastrophic natural disturbance (e.g., severe wildfire), conifer encroachment (related to changing hydrology), politics, encroachment of native species that aren’t usually found in

meadows, effective monitoring and, increasing visitor impacts. For example, with warmer and dryer periods, non-native species such as Kentucky bluegrass (*Poa pratensis*) that are not currently a concern may expand in range and require management actions to maintain diverse flora.



Figure 4. Superintendent Deanna Dulen leads discussion on the role of science at Devils Postpile National Monument. Photo: Sylvia Haultain

Most approaches to resource management focus on increasing *resistance* and *resilience* but the group found that when thinking about climate change refugium management, the focus is more on *persistence*. Therefore, when managing these areas, scientists and managers alike benefit by thinking outside the box and a willingness to get out of the comfort zone. In managing a climate change refugium for persistence managers might intervene more than is typical. However, they will need to acknowledge that at some point there may be a tipping point where management actions to resist change may be too heavy-handed or are futile and they need to step back. As the team gathers more information and develops a 10-15 year action plan, we will use science to inform management but hope that management can also inform science for application on larger landscapes.

The Presidential Proclamation of 1911 that designated Devils Postpile National Monument and the 2015 General Management Plan highlighted the importance of “scientific interest.” One of the goals we developed was to, “Continue to build on the legacy of science focused on Soda Springs Meadow as a ‘natural laboratory’ to inform management and serve as a model

for potential climate change refugium” (Fig. 5). The efforts to explore climate change impacts and adaptation strategies at Devils Postpile provide many opportunities for current and potential partners to join the monument in gathering and analyzing data, developing science communication materials, and reporting on the results. In a time when land managers are tasked with developing climate change adaptation strategies, the lessons learned as the monument develops and applies an action plan will be invaluable.

Reference

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Figure 5. Soda Springs Meadow and surrounding mixed conifer forest. Photo: National Park Service

What's Blooming in the Cold Air Pool?

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Climate change is leading to earlier spring snowmelt, drought, and shifting species ranges and phenology in the Sierra Nevada. Climate scientists are investigating the potential of cold air pools—temperature inversions where cold, dense air concentrates in areas of high topographic variation—to maintain refugia that are buffered from climate change and enable the persistence of valued resources. The cooler and moister conditions in cold air pools may help maintain biodiverse areas such as wet meadows and riparian habitats. Although much is known about the physical dynamics of cold air pools, an understanding of the ecological response is lacking.

During my summer internship I linked plant phenology to temperature at Devils Postpile National Monument to inform efforts to manage the monument as a potential climate change refuge. My supervisor, Monica Buhler, and other interns joined me in the field to monitor phenology in and out of the cold air

pool (CAP; Fig. 1). Our team also downloaded temperature data from iButtons, monitors the size of a thumbnail.

The number of male pollen cones on a lodgepole pine is one trait used to monitor phenology throughout the season (Fig. 2). Additionally, I developed a pilot Plant Phenology Monitoring Citizen Science Program for the monument by creating outreach materials, instruction booklets, and providing a set of recommended next steps. I prepared a report summarizing our phenology observations and the temperature dynamics in the cold air pool, e.g., its intensity and frequency. I then collaborated with park staff and scientists to develop climate change adaptation strategies for the monument.

Based on the data collection, we did not observe a clear phenological response to the CAP, but there was a trend of later phenology within the CAP in eight out of fourteen phenophases.



Figure 1. Sophia prepares monitoring plots in Devils Postpile National Monument

Plant phenology may be a poor indicator of a biological response to the cooler conditions within CAPs. Potential explanations for why we did not observe a clear phenological difference between CAP and non-CAP sites include:

- Microclimate, sun exposure, and nutrient availability are variables aside from temperature that also influenced plant phenology, potentially masking a clear phenological response;
- Wildlife browsing interfered with phenology monitoring;
- Drought conditions likely influenced phenology in all species, causing fruits and flowers to wilt and leaves to change color prematurely;
- Cooler night-time conditions within the CAP may not be sufficient for eliciting a clear phenological response in plants;
- The current phenology monitoring protocol is likely too complicated for citizen scientists to follow and could also be revised to potentially reveal a clearer phenological response to cold air pooling.

My internship allowed me to experience firsthand how science can inform natural resource management, particularly climate change adaptation strategies, and vice versa. I am so grateful to everyone at Devils Postpile National Monument for their support and providing me with the opportunity to work and learn in a beautiful landscape!



Figure 2. Pollen cone flowering stage was one useful indicator of phenology

Slower Snowmelt in a Warmer World

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Musselman, K. N., Clark, M. P., Liu, C., Ikeda, K., & Rasmussen, R. 2017. Slower snowmelt in a warmer world. *Nature Climate Change* 7(3):214-219.

Abstract

There is consensus that projected warming will cause earlier snowmelt, but how snowmelt rates will respond to climate change is poorly known. We present snowpack observations from western North America illustrating that shallower snowpack melts earlier, and at lower rates, than deeper, later-lying snow-cover. The observations provide the context for a hypothesis that snowmelt will be slower in a warmer world. We test this hypothesis using high-resolution climate model runs for a control period and an end of century business-as-usual future climate scenario. We find that the fraction of meltwater volume produced at high snowmelt rates is greatly reduced in a warmer climate. The reduction is caused by a contraction of the snowmelt season to a time of lower available energy, reducing by as much as 64%

the snow-covered area exposed to energy sufficient to drive high snowmelt rates. Our results have unresolved implications on soil moisture deficits, vegetation stress, and streamflow declines.

Overview

We use a mix of historical data analysis and controlled regional climate model simulations to test the hypothesis of *slower snowmelt in a warmer world*. We have five summarizing points:

- Analysis of historical daily snowpack depletion over western North America demonstrate lower ablation rates in locations with less snow water equivalent (SWE; Fig. 1). The positive relationship between ablation rates and SWE occurs because deeper snowpack persists to late spring and summer when energy availability is high. The empirical relationship suggests that melt could be slower in a warmer climate characterized by reduced SWE, earlier snowmelt, and less spring snow-cover.

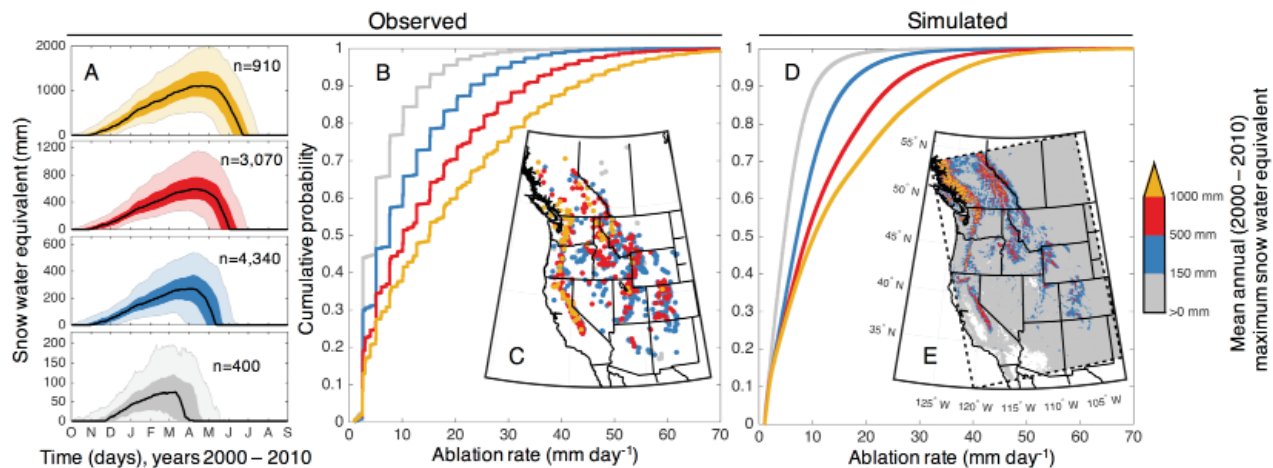


Figure 1. Observations and model simulations of snow water equivalent (SWE) across western North America, for the period October 2000 until September 2010, demonstrate lower ablation rates in places with less SWE. Shown are (A) time series of daily SWE (mm) observed at 975 telemetry stations for 10 years presented as the 5th and 95th (light color shading) and 25th and 75th (solid colors) percentiles and binned by the mean annual maximum SWE corresponding to the peak of the bold lines; (B) cumulative probability distributions of observed SWE ablation rates (mm per day) at the telemetry station locations (see inset map in C), (D) the cumulative probability distribution of SWE ablation rates simulated by the WRF model using the same four snow classes (see inset map of model grid cells). Ablation rates shown are restricted to values ≥ 1 mm per day. In panel (A), n represents the number of station-years of daily SWE.

- The ablation rate distributions from the Weather Research and Forecasting (WRF) model simulations support results from the observational analysis—that in regions with deeper, more persistent snow-cover, ablation rates are higher than in regions with shallower snowpack. The similarities between the observed (Fig. 1b) and modeled (Fig. 1d) ablation rate distribution provide confidence in the ability of WRF to simulate the snowmelt dynamics explained in this paper.
- The widespread simulated reduction of annual meltwater volume over western North America (Fig. 2) is associated with small regional increases in low snowmelt rates, and, critically, a large reduction in high snowmelt rates (see Fig. 3). This is an important new finding that contradicts the intuitive notion that snowmelt rates in a warmer climate will exceed historical values, suggesting a tendency for *slower* snowmelt in a *warmer* world.
- The reduction in high melt rates occurs during spring and early summer, and the increase in low melt rates occurs in mid-winter. The reduction in high snowmelt rates is associated with a contraction of the snow season, where reductions in daily snow-cover percentage are skewed toward spring and summer.
- Put simply, much more of the land area in the warmer climate scenario is snow-free at times of high energy

availability. In a warmer climate, the contraction of spring snow-cover reduces by as much as 64% the snow-covered area that is exposed to net energy sufficient to drive moderate to high snowmelt rates, resulting in slower snowmelt in a warmer world.

Implications

Hydrologic implications of slower snowmelt in a warmer world are likely to vary substantially with regional climate, elevation, soil properties, evapotranspirative demand, and climate response to greenhouse gas emissions. We report large projected declines in spring snowmelt rates over great spatial extents and averaged over a decade—the impact of warming on individual (e.g., extreme) melt events may differ (Fig. 4). Additionally, warming effects on snowmelt will likely have more pronounced spatial variability than can be simulated at 4 km grid spacing. Given the critical need to better understand the impact of climate change on water resources, future studies are needed to address hydrological and ecological consequences of less snowfall, reduced seasonal snowpack and a shift toward slower melt. The implications on streamflow and ecology of large-scale changes in the magnitude of this critical water flux must be better understood to inform mitigation strategies and increase our resilience to climate change.

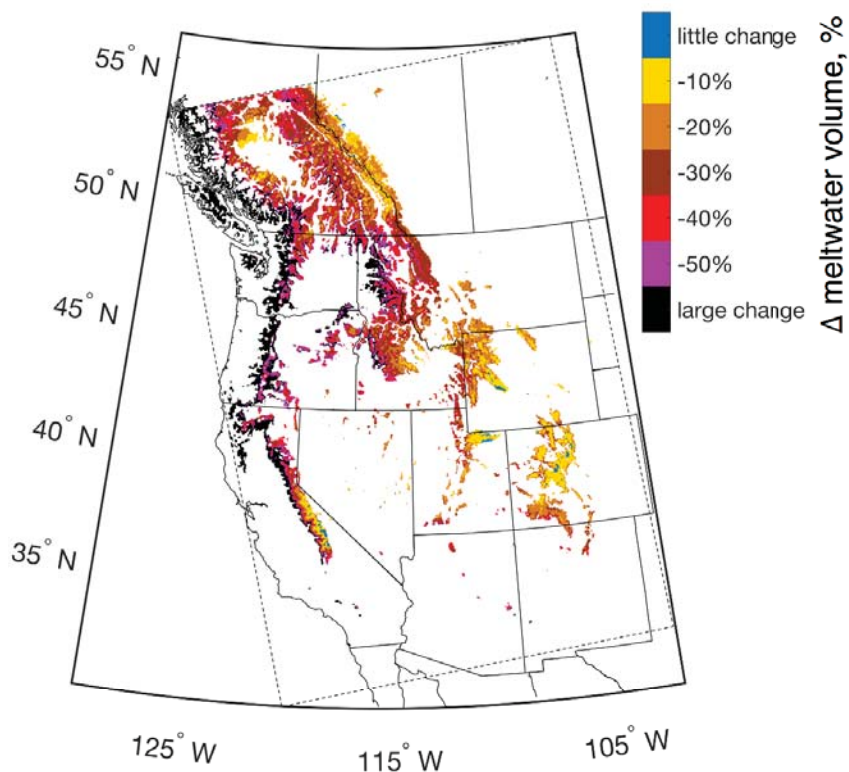


Figure 2. Model projections of end of century changes in meltwater volume (percent) under a business-as-usual greenhouse gas emissions scenario. The metric can be interpreted as ‘changes in accumulating snowfall’ between the historical and warmer climate. Excluded from the analysis are regions with the historical (2000 – 2010) mean annual maximum SWE < 150 mm (see Fig. 1E).

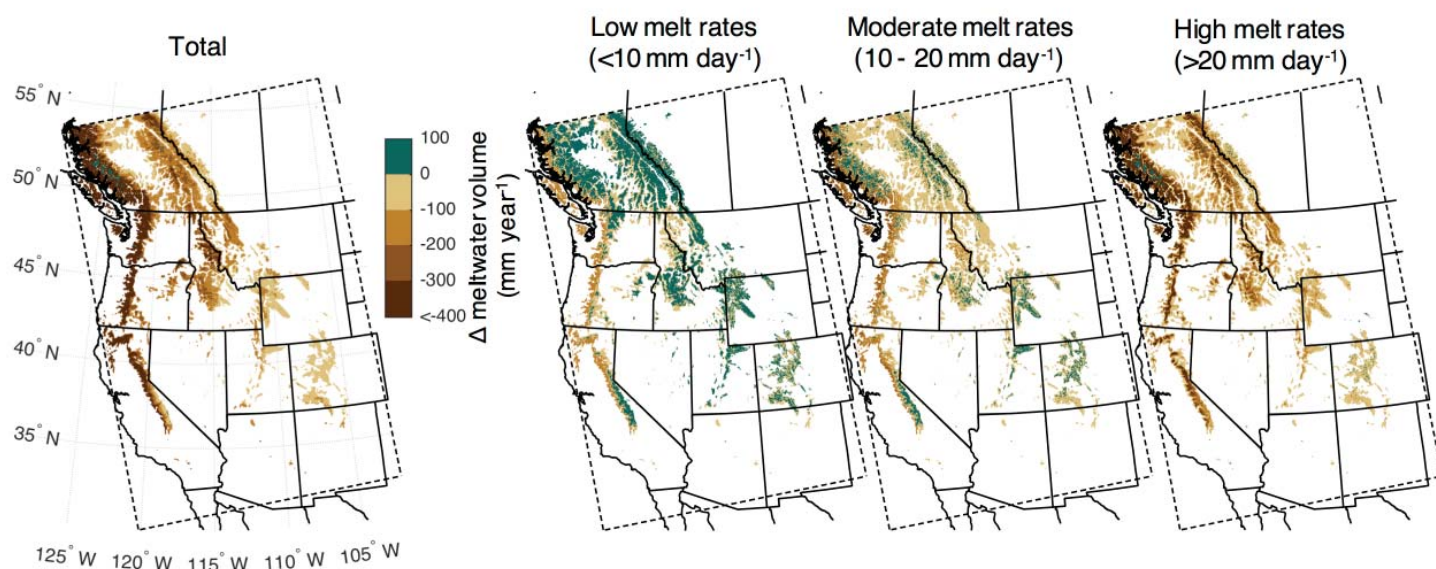


Figure 3. Reductions in total meltwater volume are primarily associated with reductions in high melt rates. Shown are maps of the mean annual projected changes in total meltwater volume (mm) and the changes that occur at low (<10 mm day⁻¹), moderate (10 - 20 mm day⁻¹) and high (>20 mm day⁻¹) snowmelt rates.

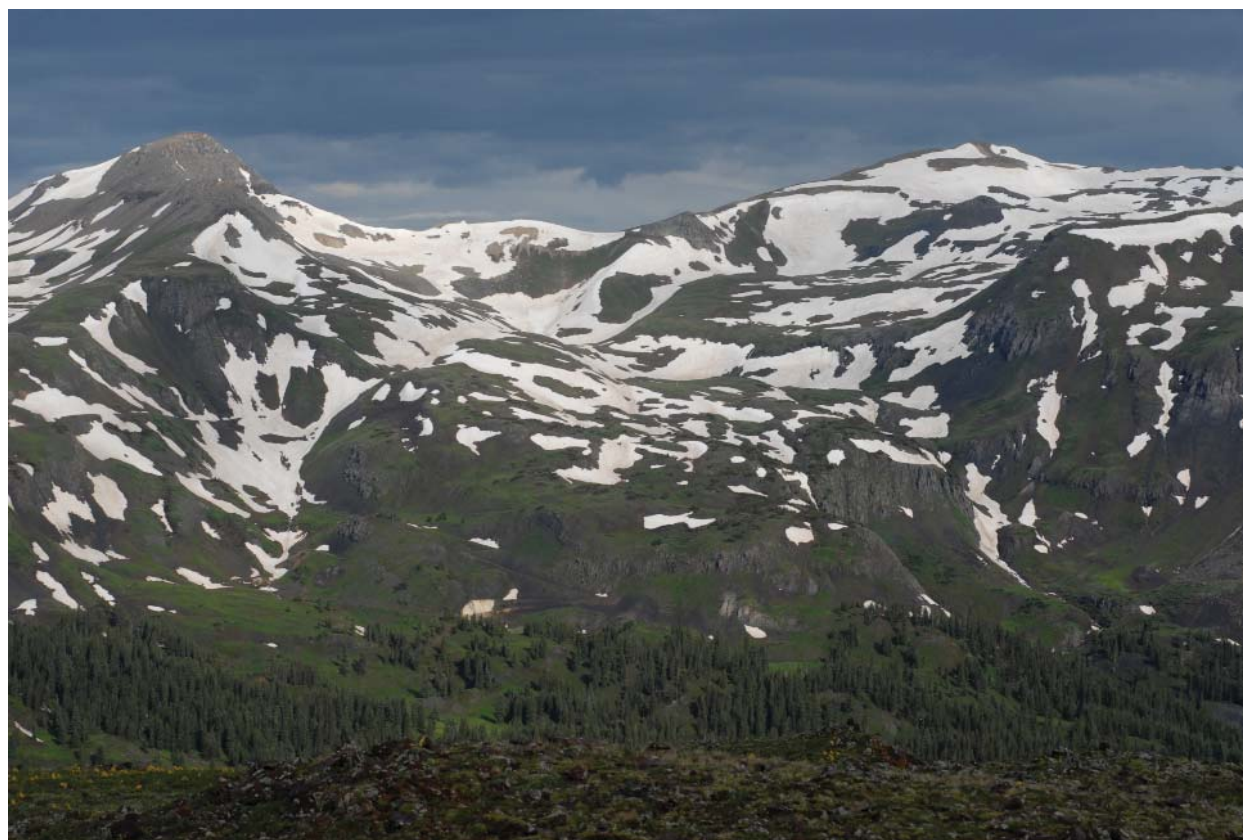


Figure 4. Spring melt season in the Senator Beck Basin Study Area (<https://snowstudies.org>) in the San Juan Mountains of Colorado. Photo: Jeffrey Deems and Matthew Kennedy

Terrain-Based Downscaling of Fractional Snow Covered Area Datasets for Mapping Snow Cover at High Spatial Resolutions

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Cristea, N. C., Breckheimer, I., Raleigh, M. S., HilleRisLambers, J., & Lundquist, J. D. 2017. An evaluation of terrain-based downscaling of fractional snow covered area datasets based on Lidar-derived snow data and orthoimagery. Water Resources Research 53:6802–6820.

Accurate snow cover area (SCA) maps at fine spatial scales are highly desired by ecologists and conservation biologists studying how snow presence or absence influences local ecosystems sensitive to snow at scales of meters or tens of meters (Kudo 1991, Walker et al. 1993, Ford et al. 2013). Shrinking snow cover areas has important implications for mountain ecosystems, affecting organisms ranging from bacteria and fungi to plant communities, invertebrates, and other animals (Williams et al. 2015 and Pauli et al. 2013). As an example, in the high mountains of western North America, peak wildflower season closely follows snow disappearance day each year, and is therefore likely to respond strongly to declining snowpack associated with ongoing climate change (CaraDonna et al. 2014). While *in situ* monitoring can be performed to detect presence or absence of snow (Lundquist and Lott 2008, Dickerson-Lange et al. 2015, and Raleigh et al. 2013), the spatial and temporal extent of these field observations is limited. Moderate Resolution Imaging Spectroradiometer (MODIS)-derived binary SCA (snow presence/absence) and fractional SCA (fSCA) products have an appropriate temporal resolution (1 day); however, the spatial resolution (~500 m) is too coarse to map the snow and determine snow disappearance date at ecological scales. To address this issue, we developed and applied a terrain-based downscaling procedure that uses coarse resolution fSCA data to assign binary snow data (presence/absence) to higher resolution grids, based on the assumptions that snow disappears first on the steep insolated slopes and persists longer in the depressions.

Previously-developed downscaling methods have been primarily based on ablation drivers of snow cover spatial variability (Walters et al. 2015, Li et al. 2015). However, snow accumulation processes are at least as important as ablation processes in determining the date of snow disappearance (see Raleigh and Lundquist 2012). Our approach builds on previous research and propose a modified downscaling method that incorporates both

ablation and accumulation effects on snow spatial variability. To account for spatial variability in accumulation processes, our method uses the topographic position index (Weiss 2001), *TPI*, to identify areas of depressions and fissures in the landscape. The *TPI* index was found the strongest explanatory variable of snow depth spatial variability (Revuelto et al., 2014). A terrain-derived index combining slope and aspect, the diurnal anisotropic heat (*DAH*) index, is used to identify areas where snow is likely to disappear first (ablation effects). The *DAH* accounts also for differential warming on different aspects, which is important for snow spatial variability during the ablation season (Jost et al. 2007, Revuelto et al. 2014, Anderson et al. 2014). We derive these two indices from a higher resolution digital elevation model (DEM), and combine them to inform the spatial distribution of binary snow based on fSCA values from the coarser resolution grids. Our study specifically aims to 1) evaluate and test the new downscaling routine to map seasonal snow from fractional snow cover area products across multiple years and regions separately over forested and exposed areas, and 2) downscale to very fine spatial resolution (3 m) over both areas (the scale at which many organisms operate—and thus of interest to ecohydrology).

We focus our analysis on two different geographic regions: 1) the upper Tuolumne River Watershed, CA, and, 2) Mount Rainier, WA. We evaluate the method using the 2014 Tuolumne snow data, and demonstrate that the procedure is robust when applied over the same area in different years, 2013 and 2015. We then apply the method over the Mt. Rainier area, which has different topography and very different climatic conditions, to test for spatial transferability of our method for downscaling from 500 m resolution to 30 m and 3 m resolutions.

We use a framework based on airborne-derived (LiDAR and orthoimagery) high-resolution snow datasets. We derive 500 m-scale fSCA from the high-resolution binary data (snow presence/ absence) for input to the downscaling routine. These inputs are more certain than satellite-derived imagery, which could be affected by the topographic and sensor-viewing angle effects, and are uncertain over forested areas (Raleigh et al. 2013, Rittger et al. 2013). This ensures that we focus our testing on the skill of the downscaling methodology, when provided with reliable input data. The downscaling method can be applied to

any existing MODIS-based (or VIIRS-based) fSCA products (e.g. Salomonson and Appel 2004, Painter et al. 2009), and can be automated and used routinely by users to develop high-resolution maps of the seasonal progression of snowmelt in complex terrain.

The upper Tuolumne River watershed is located on the western slopes of the Sierra Nevada, California (Fig. 1a). It spans about ~3000 m in elevation, covering an area of 1190 km² above the Hetch Hetchy reservoir. Complex features characterize the landscape. The higher elevation areas are covered by granitic bedrock and shallow, erodible soils, while the subalpine areas are forested with interspersed meadows. The climate is Mediterranean, with mild winter temperatures, low annual precipitation, and warm and dry summers.

The Mount Rainier National Park area, located in the Cascade Mountains of the United States (Fig. 1b), covers a topographically complex and large elevation gradient (600–4390 m) with heterogeneous snow cover. Between the lowest and the highest elevation weather stations located in the Park, the mean annual precipitation varies from 1905 mm (at 579 m) to 3200 mm (at 1646 m), respectively. The region's climate is Maritime, with dry summers and very wet winters, making the snowpack on Mt. Rainier significant. The climate is influenced by the proximity to the Pacific Ocean and varies with elevation.

The testing framework consists of the following steps: 1)

derivation of high resolution 30-m and 3-m binary snow/no-snow from the LiDAR-derived snow depth data (Tuolumne area) and orthophotography (Mt. Rainier area), 2) reconstruction of MODIS-scale (~500 m) fSCA using data from the previous step, 3) downscaling of the 500-m fSCA data to spatially-explicit binary maps, and 4) comparison of the downscaled results with the data from step 1). These steps are illustrated in Fig. 2 for the Tuolumne area.

The downscaling algorithm assigns presence/absence snow data to a higher resolution grid based on the likelihood of snow presence informed by a composite topographic index and fSCA from a coarser resolution grid (e.g. ~500 m for a MODIS size pixel). Our composite index is a linear combination of independently-derived terrain indices balancing representations of ablation and accumulation effects:

$$SVI = DAH * w + (1 - w) * TPI, \quad (1)$$

where *SVI* (-) is the snow variability index, *DAH* (-) is the diurnal anisotropic heating index (Böhner and Antonić 2009), used to represent ablation effects, *TPI* (-) is the topographic position index (Weiss, 2001) used to represent accumulation effects, and *w* is a calibrated weighting factor. Snow water equivalent, SWE, was found to relate with terrain curvature (which is similar in concept with the *TPI*) at near-peak snow accumulation (Sextone and Fassnacht 2014).

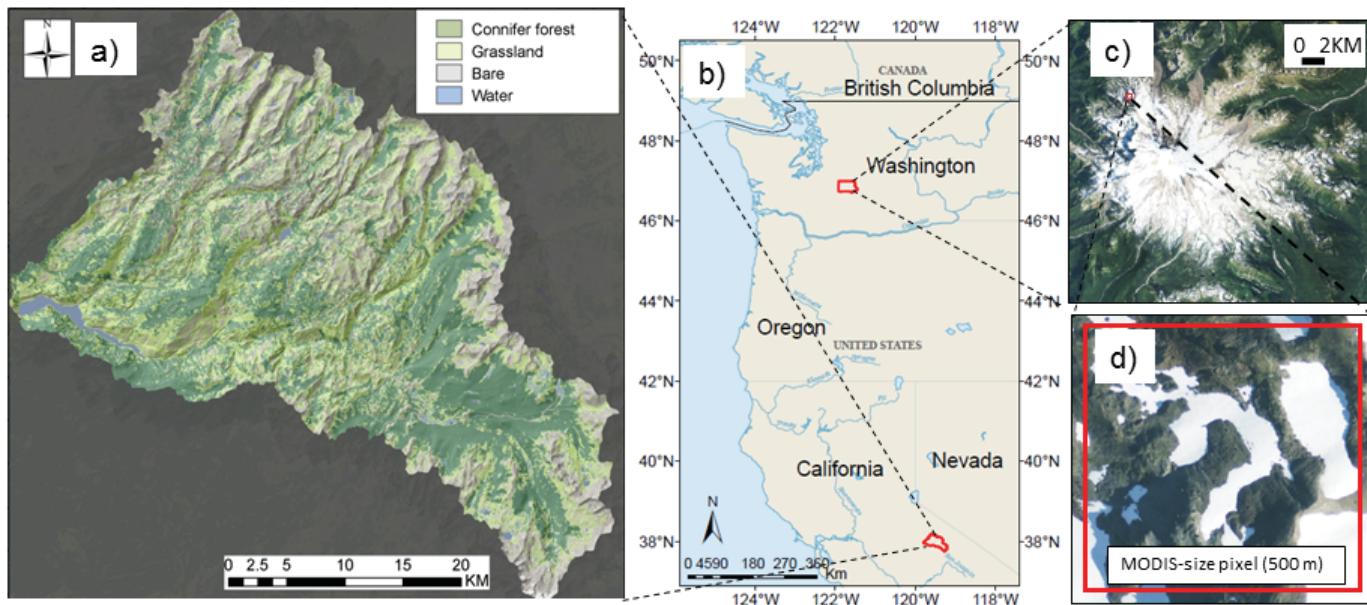


Figure 1. a) Tuolumne River watershed, CA; b) Locations of Tuolumne River watershed, CA and Mt. Rainier, WA; c) Snow cover as captured by orthoimagery 16 August 2011, and d) example of the spatial distribution of snow covered areas across the surface of a MODIS pixel on Mt. Rainier (red square).

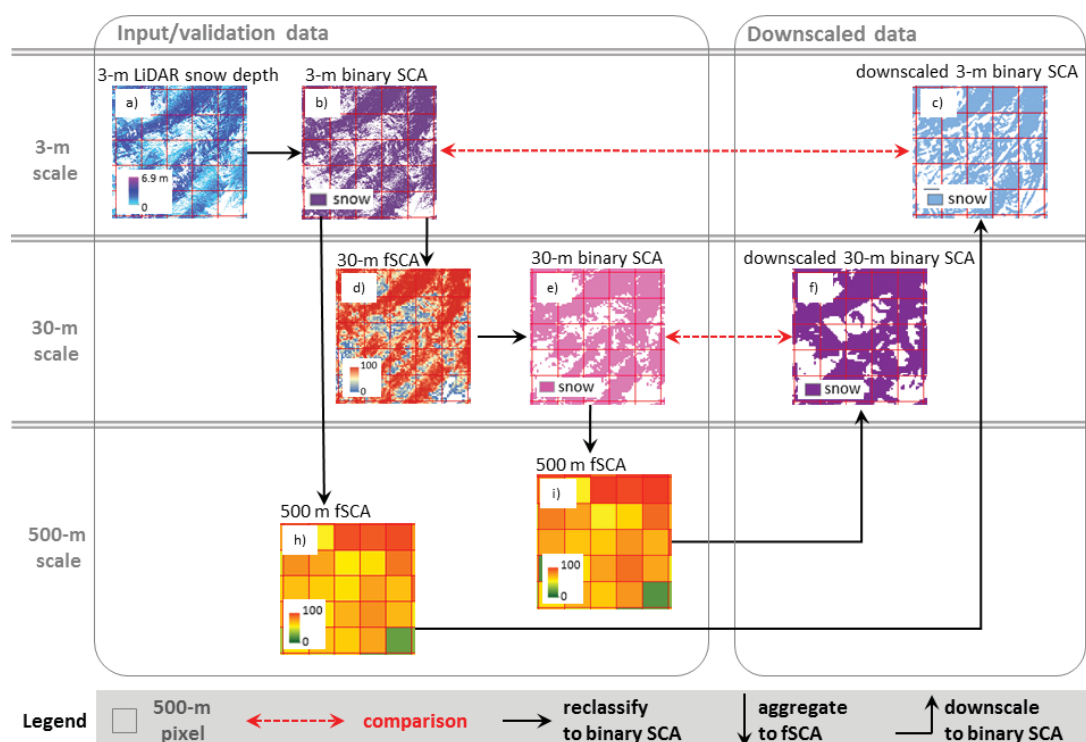


Figure 2. Framework and workflow for downscaling at 30-m scale and 3-m scale. Figures shown on May 2, 2014 for a subset of the Tuolumne watershed.

We evaluate the procedure for downscaling at 30 m resolution as a function of the weight w , and TPI neighborhood size and shape. We use the Tuolumne 2014 data, which had the most scenes over the melt season (11), for model development. We test the sensitivity to ablation and accumulation representation. We use the F score derived using contingency table metrics for binary data (Olson and Delen 2008) as an overall measure of matching performance, accounting for both commission and omission errors. For each image we determine *true negatives* (TN) as the number of pixels that are snow-free in both downscaled and validation data, *false positives* (FP) as the number of “snow” pixels present only in downscaled but not in the validation image, *false negatives* (FN) as the number of “snow” pixels present in the validation data but not in the downscaled product, and *true positives* (TP) as the “snow” pixels common in both downscaled and validation datasets. The F score is then estimated as:

$$F = \frac{2TP}{2TP + FP + FN}$$

The weight w and the TPI circular neighborhood size have variable effects on the downscaling efficiency as a function of day of year and snow cover variability (Fig. 3). The matching performance scores are higher by 15-30% for the LiDAR-

derived fSCA datasets than for the MODIS-based fSCA product, MODSCAG. This is expected as the MODSCAG fSCA datasets are likely more uncertain than the reconstructed fSCA from the high resolution data. MODIS-derived data are affected by vegetation cover, terrain attributes and sensor view angle effects (Cristea and Lundquist 2016).

To investigate vegetation effects, we downscaled all scenes in 2013, 2014 and 2015 and estimated binary metrics separately for forested and non-forested areas. All runs applied Eq. 1 configured for TPI with a search radius of 60 m and $w = 0.7$. The method performed worse in forested than in exposed areas (Fig. 4). For days when the percentage of snow in forested areas was below 20%, the F score dropped below 0.6, and as low as 0.3, albeit for cases when very little snow remained in the forest (less than 5-6%).

When downscaling to 3 m resolution, a TPI with a 27 m searching distance provided the best matching F scores (Fig. 5). However, for $w = 0.7$, the most effective weight, the F scores for all TPI options varied within the second digit. The matching scores were similar to the 30-m downscaling, demonstrating the method’s robustness to downscaling at very high spatial resolutions (meters). All $Kappa$ scores showed strong agreement (0.61-0.8).

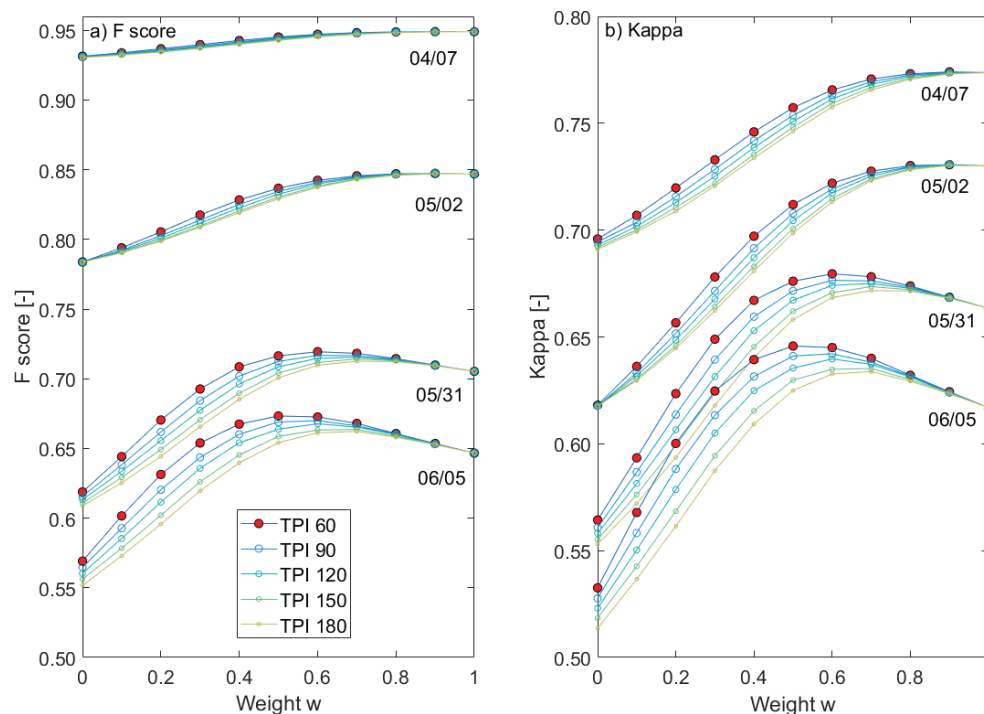
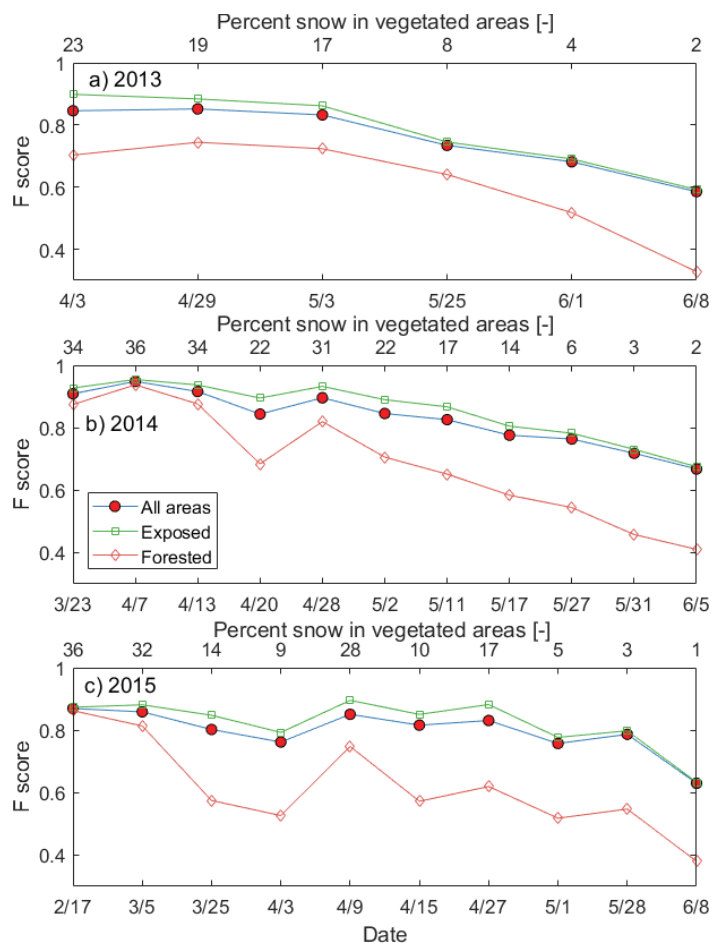


Figure 3. a) F scores and, b) $Kappa$ scores for downscaling at 30 m resolution as a function of weight w and circular TPI size for four days in 2014. TPI searching distance is expressed in meters; $w = 0$ means TPI controls the distribution, and $w = 1$ means DAH controls the distribution.



Results from downscaling to 30 m and 3 m resolution from both the Tuolumne and Mt. Rainier areas showed that variations in F scores for different TPI sizes at their most effective weights are relatively small, within 1%, and larger up to 2-3% for other weights. Differences in F scores are larger, within 15% for the weight factor range of variation (0 to 1). Examining this variation pattern for both areas, we concluded that using $w = 0.5$ provides good downscaling results without major deductions in F scores from the peak values (1% for Tuolumne, and 2% for the Mt. Rainier). Close range neighborhoods proved effective for mapping snow; therefore we recommend using circular TPI neighborhoods with 60 m and 27 m search radius for downscaling to 30 m and 3 m, respectively, combined with a $w = 0.5$ weight factor. The diurnal anisotropic index, DAH (Eq. 2) is optimized for mid-latitudes in the Northern Hemisphere but can be modified for the southern hemisphere, by replacing N with S, and for areas north of the Arctic Circle (by reducing the E-W importance).

Figure 4. F scores for evaluating forested and exposed areas separately during a) 2013, b) 2014 and, c) 2015.

The results from downscaling MODIS-scale fSCA products for the Tuolumne and Mt. Rainier areas indicate potential for applying the downscaling method to finer spatial scales (meters) using both MODIS-based fSCA products and other SCAG products under current development (30 m, from Landsat platforms). Launched in 2013, Landsat 8 circles the entire Globe every 16 days and has an 8-day offset to Landsat 7, which can help increase the temporal resolution from the combined Landsat platforms. Successful application of the proposed downscaling technique depends on the quality of both the fSCA and DEM datasets, as well as the ability to co-register the remotely-sensed fSCA value with the specific area on the DEM it is looking at. DEM accuracy is especially important for downscaling at high spatial resolutions (meters). The method can be directly applied to other mountain systems in northern

hemisphere using the above default recommendations. If fine-resolution validation data are available for comparison, the method can be further tuned to find the optimal balance between accumulation and ablation representation, and the *TPI* size as a function of terrain complexity. High resolution data from the newly launched satellites such as Sentinel 2 or 3, and/or data from manual observations and terrestrial laser scans can assist the comparisons.

The downscaling procedure is coded in Matlab and can be downloaded from the following Github account, along with additional description about the input files using an example from this study: <https://github.com/NCristea/Downscale-fractional-snow-covered-area-datasets>.

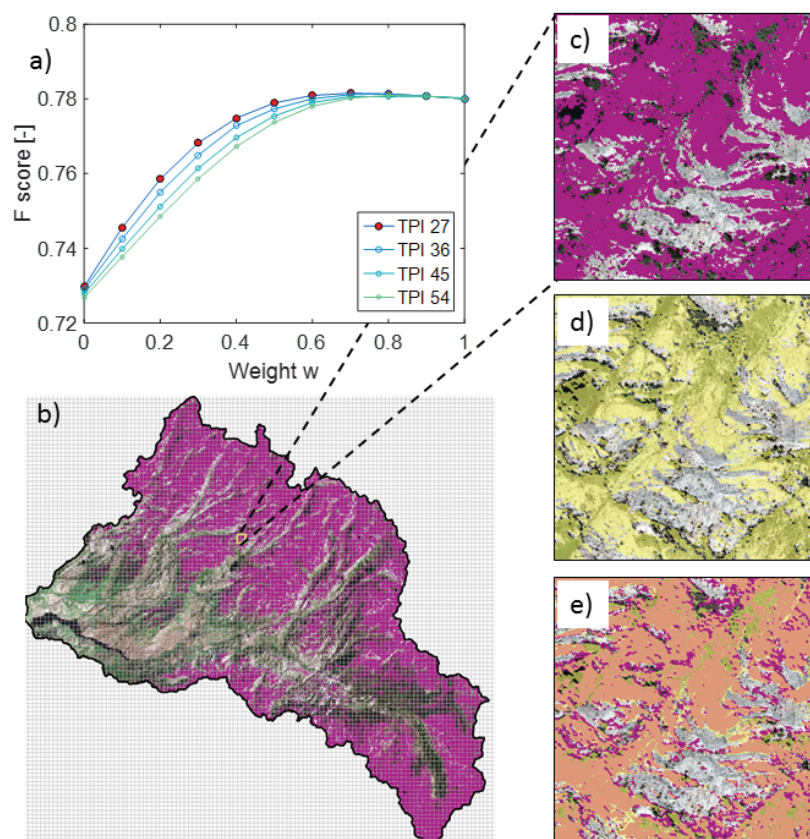


Figure 5. a) F scores for downscaling to 3 m resolution as a function of weight w and TPI searching distance in meters, with $w = 0$ meaning *TPI* controls the distribution and $w = 1$ meaning no weight on the *TPI*, b) spatial distribution of 3-m downscaled snow covered areas for *TPI* 27 m (pink color), c) zoomed-in downscaled map (pink color), d) zoomed-in snow covered areas derived from snow depth (yellow color), e) zoomed-in overlaid maps from c) and d), where orange represents snow in both, pink represents downscaled snow that was not observed, yellow represents observed snow that was not downscaled, and clear (underlying rock and forest) represent no snow in either. The zoomed-in area is approximately four MODIS pixels (~2 km on a side). Data shown for May 2, 2014.

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Fire Severity Impacts on Winter Snowpack

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Stevens, Jens T. 2017. Scale-dependent effects of post-fire canopy cover on snowpack depth in montane coniferous forests. *Ecological Applications* 27:1888-1900. <http://dx.doi.org/10.1002/eap.1575>

Research Summary

Spring snowpack depth was highest in areas of unburned forest and low severity fire effects. Within unburned and low severity areas, canopy gaps had the deepest snowpack. Fine-scale forest variability with < 1 ha gaps that are created or maintained by fire may have benefits for water storage in snow. Weather is the primary control over snowpack, and may influence how fire affects snow.

Overview

Mountains in western North America provide much of the water in this region through winter snowfall and spring snowmelt. These mountainous regions are generally dominated by conifer forest. The evergreen foliage of conifer forests means that forest structure in this region influences how much snow accumulates on the ground during winter, and how quickly that snowpack disappears. Evergreen tree canopies intercept falling snow, so

areas with greater tree cover often have less snow reaching the ground. However, tree canopies also increase shading from solar radiation and reduce wind speeds, so areas with greater tree cover can also extend the duration of snowpack. These counteracting effects of forest canopy create uncertainty in forecasting how montane snowpack will respond to future changes in forest structure.

Fire can strongly influence montane forest structure. Our recent study in California's Sierra Nevada examined how fire can influence snowpack depth. Field crews sampled snowpack depth across the footprint of three montane fires for a total of 11 times during winter of 2013-14. At each fire, they sampled four different levels of burn severity, as well as unburned forest. The categories of burn severity were mapped as very low (0% canopy cover loss), low (1-20% canopy loss), moderate (20-90% canopy loss) and high severity (> 90% canopy loss). At each sampling point, they also recorded overhead canopy cover, as either open, edge, or under canopy (Fig. 1).

The effect of canopy cover on snow depth depended on the spatial scale of canopy measurement. Snow depth was greater at lower burn severities on average, but snow depth was also greater in canopy gaps than directly under canopy (controlling for burn severity; Fig. 2).

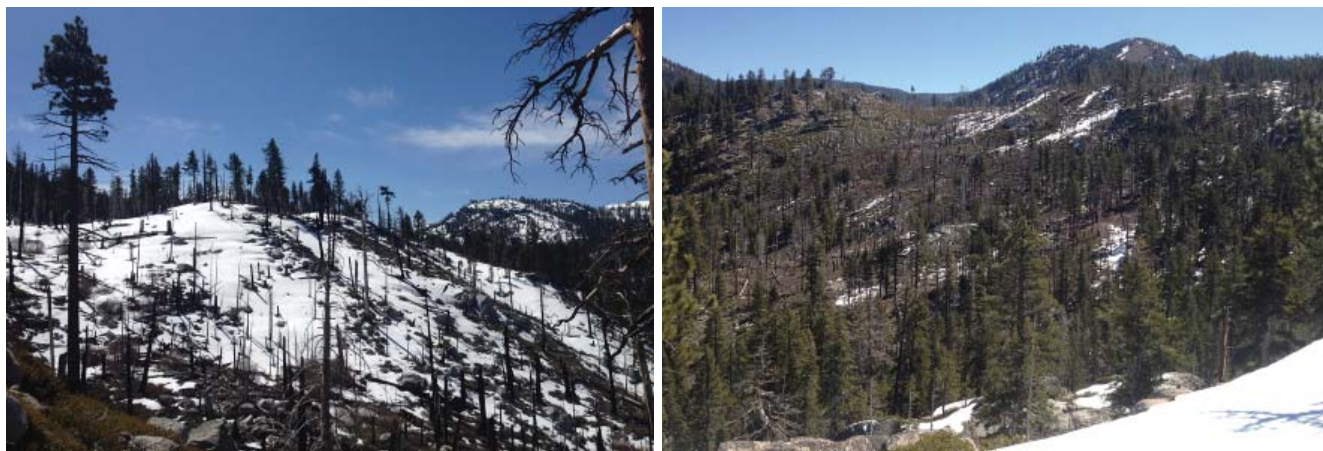


Figure 1. Snowpack variation at the Showers Fire, Lake Tahoe Basin, CA on April 07, 2014. Snowpack levels were generally higher in smaller gaps of stand-replacing fire adjacent to live trees, and lower in larger gaps of stand-replacing fire and directly under live trees. Photo: Amy Jirka.

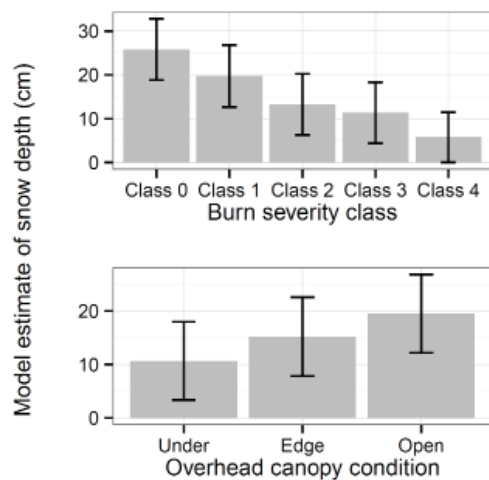


Figure 2. Estimate of snow depth across all site visits as a function of burn severity and overhead canopy. Class 0 is unburned forest, and Class 4 is high-severity.

The size of post-fire canopy gaps therefore appears to influence the depth of spring snowpack. Although more snow may initially hit the ground in larger gaps associated with more severely burned stands, the increase in snowmelt in these larger openings appears to control snowpack duration. However, smaller openings at the scale of one to several tree crowns surrounded by live forest, commonly observed in unburned and low severity stands (where canopy cover in this study was 57% and 42%, respectively) appear to act as important reservoirs for snowpack water storage (Fig. 3).

Specifically, canopy gaps in the unburned and very low-severity areas were only 34% of the total sampled area, but contributed 78% of the total snowpack water storage (Fig. 3). In contrast, large canopy gaps in high-severity stands (ranging from ~0.5 to 16 ha) accounted for 20% of the sampled area but only 2% of total water storage.

It should be noted that the data in this paper come from winter 2013-14, when most of the Sierra Nevada and southern Cascades were in a historic multi-year drought. With abnormally low winter snowfall totals, greater accumulation in larger canopy gaps may have mattered less to snowpack duration. The benefits of larger gaps for snowpack may therefore be greater in wetter years (Boisramé et al 2016, and unpublished data), raising further questions about how interactions between fire, forest structure and climate change will regulate montane winter snowpack.

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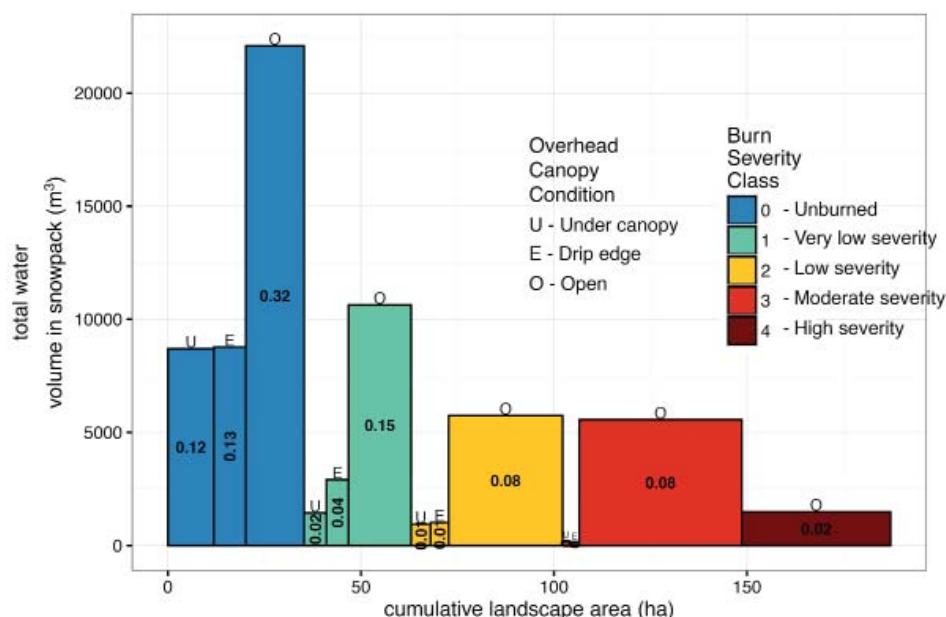


Figure 3. Distribution of water in snowpack at the Reading Fire on April 14 2017 (bar height), by overhead canopy and burn severity combination. Bar widths reflect cumulative area in a given class.

Modeling Air Temperature on Mountain Slopes: A Conversation on Key Sources of Bias at the Watershed Scale

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Strachan, S., and Daly, C. 2017. Testing the daily PRISM air temperature model on semi-arid mountain slopes. *Journal of Geophysical Research: Atmospheres*, <http://dx.doi.org/10.1002/2016JD025920>.

Gridded models of air temperature in mountain areas remain a mainstay input to many resource-related applications, e.g., watershed hydrology, bioclimatic envelope estimation, and climate projection downscaling. We think that's fantastic, and expect this to remain the case for many years into the future! The temporal and spatial resolution of these models is constantly improving, but accuracy assessments remain a challenge in a world of few, scattered ground observations and imperfect remote sensing. This creates a classic conundrum of management applicability, where increased resolution is often mistaken by users as increases in accuracy. The Parameter-elevation Regression on Independent Slopes Model (PRISM; PRISM Climate Group 2016) has been in development and use across the USA for over 20 years now, and has in recent years moved from monthly to daily resolution. Because both science and management practices across the Intermountain West frequently leverage climate models such as PRISM in lieu of making expensive and time-consuming original observations, we felt it a useful exercise to evaluate the PRISM temperature accuracy

in mountainous terrain, focusing especially on that topographic category that often comprises the bulk of watershed area: slopes (Fig. 1).

We piggybacked in-situ temperature observations with a palaeoclimate study in the Walker River Basin, a semi-arid watershed on the border of California and Nevada (Fig. 2). A total of sixteen sites were used, as paired opposing-slope installations of temperature sensors housed in Gill-type radiation shields at 1.7 m above ground level (Fig. 3). Study sites were all open-canopy woodland environments, spanning both the lower (pinyon pine) and upper (limber pine) elevation forest types. Monitoring locations minimized cold-air pooling, ridgetop exposure, and other topoclimatic idiosyncrasies (monitored snow accumulation on the sites was minimal during the 2012-2015 drought period). Analysis was performed over nearly two full water-years (1 October 2013 to 1 September 2015) of daily maximum ($T_{\max}$) and minimum ($T_{\min}$) values extracted from hourly data. Site characteristics and error statistics for the PRISM 800 m gridded daily product are shown in Table 1 (after shredding boots and bottoms on these rugged hillsides while maintaining data collection, we are recalling why gridded models are so nice and observations are less prevalent).



Figure 1. Mountain slopes are the most exciting part of the watershed—they are where all of the action is, at least for ecohydrologists. Slopes are also the least-represented part of the topography for instrumentation (because it's difficult to get there!).

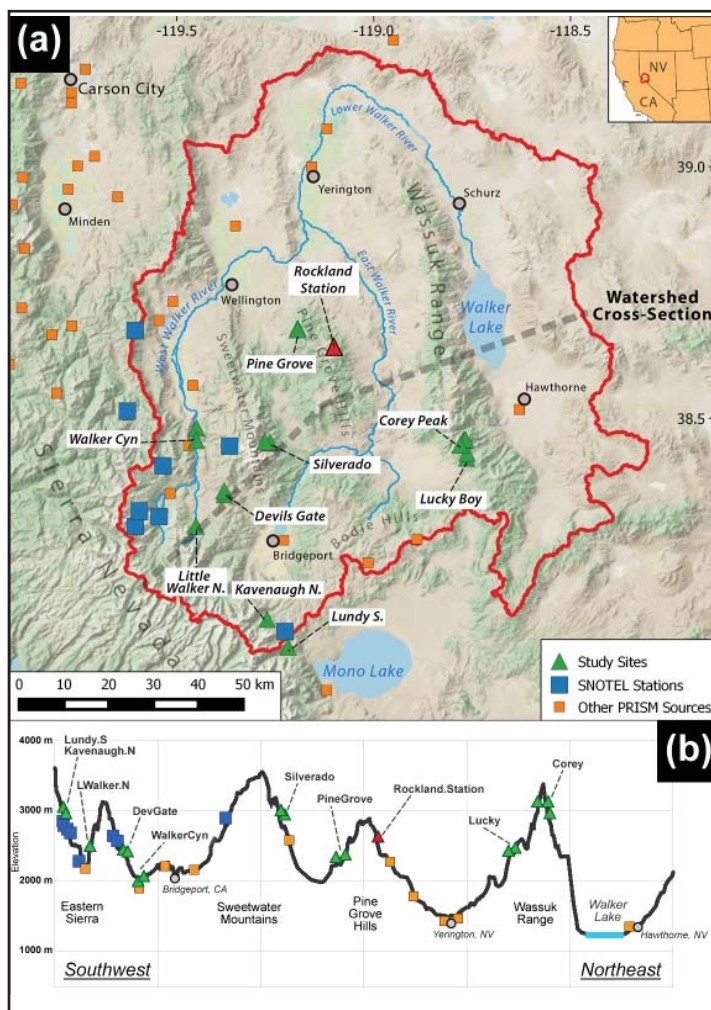


Figure 2. Study area map (1a) with elevation cross-section (1b). The distribution of paired study sites (green triangles) covered the major mountain ranges of the Walker Basin, starting with the Sierra front and progressing east. Stations providing source data for PRISM during the study period are shown (squares). A cross-section of the watershed elevations (denoted by dashed line in 1a) provides topographic context for stations and study sites, which are plotted in 1b even if they are located well away from the line itself. Most of the stations used by PRISM as source data are located in valley bottoms, with mid-elevation stations being primarily from the SNOw-TElemetry network (SNOTEL) and geographically skewed towards the western portion of the watershed.



Figure 3. Sensor deployment for this study involved placing temperature loggers on elevated, open woodland slopes. Gill-type radiation shields were used to replicate temperature observations across common source data networks for PRISM.

Site Characteristics					PRISM ₈₀₀ Error Statistics, Daily Values Oct 2013 – Sept 2015							
					T_{MAX} °C				T_{MIN} °C			
Site	Elev (m)	Slope (deg)	Aspect (deg)	DAH Index	Bias	MAE	SD	r^2 ($p < 0.0001$)	Bias	MAE	SD	r^2 ($p < 0.0001$)
Lucky.N	2480	21	325	-0.20	-1.37	1.83	1.78	0.97	-1.09	1.78	1.93	0.94
Lucky.S	2497	30	136	0.18	-3.45	3.49	1.54	0.97	-2.95	2.99	1.74	0.96
DevGate.N	2378	39	352	-0.52	0.70	1.15	1.30	0.98	-2.15	2.21	1.30	0.97
DevGate.S	2360	27	200	0.43	-3.47	3.49	1.31	0.97	-3.28	3.30	1.42	0.96
CoreyLow.N	2977	32	329	-0.31	0.78	1.68	1.96	0.96	-1.24	1.53	1.43	0.97
Corey.N	3104	34	307	-0.14	1.07	1.86	2.07	0.96	-0.27	1.22	1.49	0.97
Corey.S	3111	22	101	-0.07	0.95	1.42	1.46	0.97	-0.85	1.50	1.66	0.96
LWalker.N	2452	16	304	-0.04	-1.81	1.98	1.39	0.97	-0.91	1.14	1.30	0.96
Silverado.S	2897	26	157	0.30	-1.20	1.49	1.30	0.97	-2.67	2.80	1.83	0.94
Silverado.N	2937	31	270	0.20	-1.14	1.62	1.68	0.96	-1.99	2.13	1.69	0.94
PineGrove.N	2355	18	347	-0.24	-0.26	1.65	2.07	0.95	-2.58	2.65	1.68	0.95
PineGrove.S	2371	17	226	0.27	-3.19	3.32	1.86	0.96	-2.17	2.27	1.57	0.96
Kavanaugh.N	3000	37	310	-0.17	1.09	1.66	1.71	0.95	-1.29	2.07	2.17	0.91
Lundy.S	2911	33	212	0.51	-0.33	1.49	1.77	0.94	-1.27	1.86	2.00	0.92
WalkerCyn.N	2036	45	12	-0.67	1.69	1.82	1.68	0.97	-3.65	3.70	1.99	0.94
WalkerCyn.S	1967	38	188	0.57	-2.13	2.38	1.84	0.95	-2.88	2.93	1.72	0.95
Overall mean	2614	29	236	0.01	-0.75	2.02	1.67	0.96	-1.95	2.25	1.68	0.95

Table 1. Study site characteristics and PRISM error statistics.

These results simply brought more questions—classic field science, no kidding? Before drawing sweeping conclusions about the cause of the model departures from observations, we investigated both the observational method and the modeling scale for potential biases. We found none in the observational method, having tested the deployment design in parallel with a fixed high-end climate monitoring station in the same watershed. Because one of the concerns frequently (and rightly) aimed at gridded models is grid resolution relative to topographic complexity, we elected to experiment with three (3) additional scales of the PRISM model. We ran the same analysis with the often-used PRISM 2.5 arcmin (~4 km) dataset, a downscaled 3 arcsec (~80 m) model of the watershed, and a spatially-weighted point-interpolation. There was a noticeable improvement in error statistics by moving from the 4 km product to the 800 m resolution, but nothing beyond that (Fig. 4). This freed us to examine issues with PRISM's extrapolation of source data values across topography.

We calculated several relevant parameters of topographic position for each study site, and evaluated model departure statistics using a shameless extension of Prof. Bunn et al.'s (2011) application of Non-Metric Multidimensional Scaling (NMDS; Oksanen et al. 2015) ordination to topoclimatic problems (see original article for figures). In a nutshell, the reasons for doing this are tied to the NMDS accommodation of low-dimensional space, unknown distributions, rank-based correlation, and physiographically-related variables. We found that topographic variables of significance relative to model departures were not the same for $T_{\max}$ and $T_{\min}$ (Table 2), which points to near-surface meteorological mechanisms in play that PRISM did not properly extrapolate across the terrain. Daily Tmax model error on our slope sites is strongly associated with radiative aspect, whereas daily Tmin model error is instead correlated with elevation. At this point, it is important to quickly review the actual methods used by PRISM to perform the modeling procedure—something that is not a bad exercise for any of us who use PRISM data or models of this type (See Box 1).

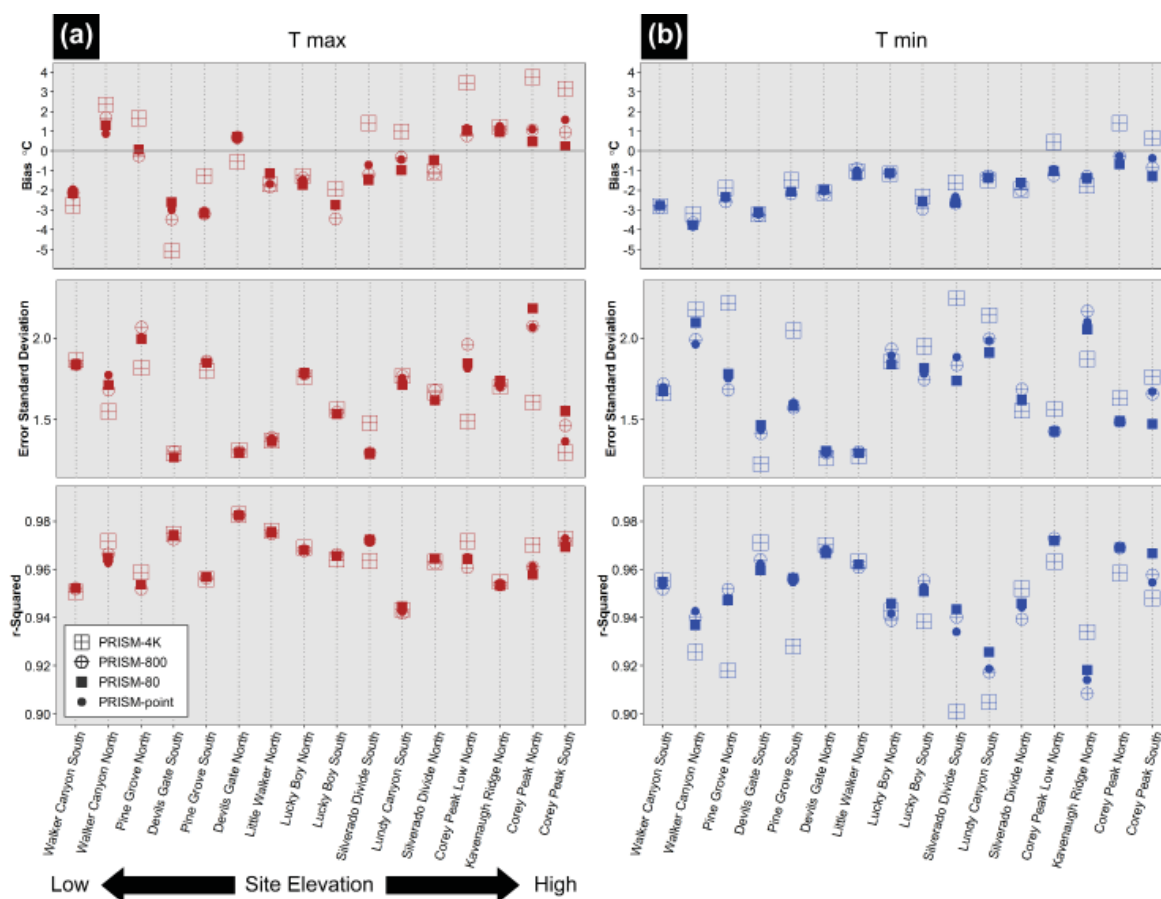


Figure 4. Model scaling test results of $T_{\max}$ (a) and $T_{\min}$ (b) over the entire 2-year study period. Tests of PRISM scale compared three error statistics (bias, standard deviation, and r^2) from the standard 4 km (square grid symbols) and 800 m (rounded grid symbols) grid products with point interpolations (solid dots) and downscaled 80 m grids (solid squares) across all 16 sites. The coarse-scale 4 km product has generally greater $T_{\max}$ (a; red) bias than the fine-scale products, but does not typically diverge from the other scales for $T_{\min}$ (b; blue) bias values. In most cases across all three error statistics, the finer scale products display similar behavior, whereas the 4 km product frequently diverges, usually in a direction that denotes less-accurate model performance.

Variable	Description	T_{MAX} Significance		T_{MIN} Significance		Reference
		r^2	p	r^2	p	
Elev	Elevation of 10 m DEM	0.170	0.294	0.872	0.001	
Slope	Slope steepness	0.401	0.042	0.121	0.452	
Asp	Aspect, degrees	0.026	0.837	0.283	0.107	
TPI	Topographic Position Index	0.535	0.002	0.106	0.490	[Guisan et al., 1999]
TRI	Terrain Ruggedness Index	0.418	0.034	0.119	0.433	[Riley et al., 1999]
DAH	Diurnal Anisotropic Heating Index	0.783	0.001	0.021	0.871	[Böhner and Selige, 2006; Böhner and Antonić, 2009]
StdH	Standardized Height	0.168	0.300	0.491	0.014	
SlopH	Slope Height	0.170	0.299	0.349	0.055	
NormH	Normalized Height	0.303	0.103	0.192	0.230	
MSP	Mid-Slope Position	0.333	0.074	0.280	0.114	
VllyD	Valley Depth	0.522	0.010	0.014	0.910	
TRASP	Topographic Radiation Index	0.818	0.001	0.039	0.754	[Roberts and Cooper, 1989]

Table 2. Topographic variables and relationships to PRISM error. Variables of primary (yellow) and secondary (green) significance are highlighted.

Box 1. PRISM Methodology

Gridded mapping of daily T_{max} and T_{min} for the Walker Basin performed using the PRISM modeling system is summarized here from several previous publications (Daly et al. 1994, 2002, 2003, 2008). For each grid cell each day, PRISM calculated a local linear regression function between station temperature and a predictor grid (see below). Nearby stations entering the regression were assigned weights based primarily on the physiographic similarity of the station to the grid cell. In addition to distance and elevation differences between station and grid cell, physiographic factors accounted for included the level of the approximate wintertime inversion (if any) and a topographic index, which is measure of local topographic position (i.e., the station's elevation relative to the surrounding terrain). Detailed descriptions of the PRISM model algorithms, structure, input grids, and operation are given in Daly et al. (2002, 2008).

The PRISM AN81d (http://prism.oregonstate.edu/documents/PRISM_datasets.pdf) temperature time series was developed using Climatologically-Aided Interpolation (CAI). CAI uses an existing climate grid to improve the interpolation of another climate element for which data may be sparse or intermittent in time (Willmott and Robeson 1995, Funk et al. 2003, Hamlet and Lettenmaier 2005, Daly 2006, Daly et al. 2012, 2015). This method relies on the assumption that local spatial patterns of the climate element being interpolated closely resemble those of the existing climate grid (called the predictor grid). The use of CAI in mapping daily temperature for the AN81d dataset involved using existing PRISM 1981-2010 monthly T_{max} and T_{min} normals as the predictor grids (PRISM Climate Group, 2016). For example,

interpolating T_{max} for January 5, 2014 involved using the January 1981-2010 normal T_{max} grid as the independent variable in the local PRISM regression function for a grid cell, and nearby station values of January 5, 2014 T_{max} as the dependent variable. Details on normals mapping methods are available from Daly et al. (2008).

Station temperature data in and around the Walker River Basin used in the PRISM AN81d datasets (Fig. 1), came primarily from four main networks: (1) USDA Natural Resources Conservation Service SNOw TELemetry (SNOTEL; <http://www.wcc.nrcs.usda.gov/snow/>); National Weather Service (NWS) Cooperative Observer Program (COOP; <http://cdo.ncdc.noaa.gov/CDO/cdo/>) and Automated Surface Observing System (ASOS; <ftp://ftp.ncdc.noaa.gov/pub/data/noaa/>); and (3) USDA Forest Service and Bureau of Land Management Remote Automatic Weather Stations (RAWS; <http://www.raws.dri.edu>). Station data were screened for adherence to a “PRISM day” criterion. A PRISM day is defined as 1200 UTC-1200 UTC (e.g., 4 AM – 4 AM PST). Once-per-day observation times, such as those from NWS COOP stations, must fall within ± 4 hours of the PRISM day to be included in the AN81d T_{max} and T_{min} datasets. The dataset uses a day-ending naming convention, e.g., a day ending at 1200 UTC on 1 January is labeled 1 January. The PRISM day definition was established to match the “hydrologic day,” which is a standard in river modeling, and align with the observation times of most once-per-day observers (e.g., NWS COOP), which are in the morning.

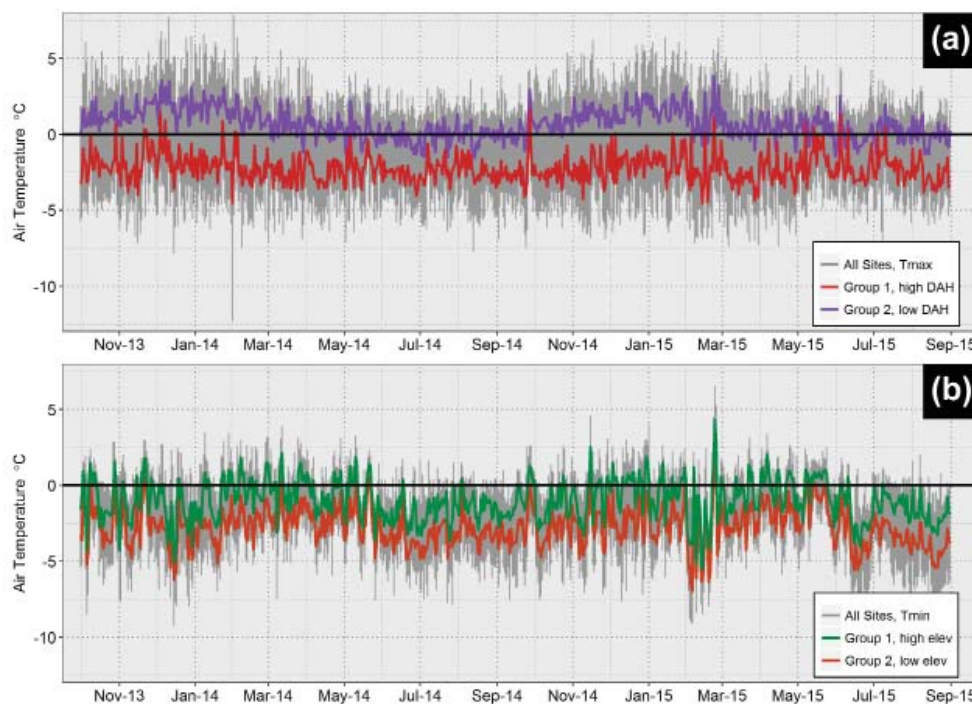


Figure 5. Error plots with cluster means. PRISM (800 m) daily errors (PRISM-Obs) are shown for all 16 sites (gray) with means for cluster groups (colored lines). Behaviour of these clusters is visually quite different in terms of absolute and seasonal bias. This result is strongly aligned with the association of radiative loading indices with $T_{\max}$ error (a; seasons with lower sun angle result in greater relative departure, including wintertime overestimation of $T_{\max}$ at sites with less incident radiation). Daily $T_{\min}$ error cluster groups (b) do not show terribly different behaviour, and are differentiated primarily by a mean bias offset. This result would agree with a spatial or elevational bias in the model given the locations and types of source data stations in the watershed.

Clearly, the challenges of historical and modern time-alignment, general siting of source data network stations, and changes in land cover and observation practice over time conspire to limit modeling accuracy at the daily scale. In fact, the most obvious source of bias to any mountain-focused field scientist is going to be the physiographic positioning of source data stations (most readers that got through Table 2 are probably screaming that now, or at least we hope you are!). It is indeed a classic case of the model only being as good as the source data, and the role of station siting in mountain temperature measurements should now become painfully evident as the crux of the matter. As a matter of fact, each of the source data networks in the Walker Basin have systematic siting specifications that are *not* designed to capture air temperature at mid-high elevation in open woodland slope topography!

This lack of topographic representation in the source data showed up in a cluster analysis of model error at each study site. Distinct cluster groups of sites emerged that were associated with the significant topographic categories highlighted by NMDS results. The mean errors of these groups are plotted along with error at all sites in Figure 5. Incident solar radiation and its effects on $T_{\max}$ on mountain slopes is nothing new, but it is

interesting to see the treatment in a gridded model that evolved in a forested environment (e.g., Daly et al. 2007). While PRISM station-weighting functions are designed to defeat significant bias effects of nighttime cool-air pooling to the lapse rate, the cold bias of $T_{\min}$ across the board indicates that a major lack of mid-slope representation in the Walker Basin. Scale, occurrence, and persistence of cold-air pooling are all determined by local and regional topoclimatology, and this remains a challenge for mountain climate modeling in general.

Another important source of error that readers should be aware of is hardware deployment practice within station networks. While general World Meteorological Organization standards for weather stations are well-known (WMO 2008), not all station networks adhere to these standards. In fact, some of these standards are downright impractical in mountain environments. For example, the positioning of the temperature sensor relative to shading, wind exposure, and ground (or snow) height is very difficult to control in mountain settings, and yet the difference in measured temperature at the 1 m height is often degrees away from the value at 10 m, depending on local turbulence. Measuring temperature accurately in all seasons and over time is not trivial, hence the triple-redundant fan-aspirated sensor design of the

US Climate Reference Network (CRN; <https://www.ncdc.noaa.gov/crn/>). Both the PRISM source data and the test observations in this study are subject to a certain amount of bias forced by hardware (primarily radiative shielding of the sensor) and sensor/station microsite characteristics (vegetative cover, snow presence/absence, and local surface albedo). While the test sensors were deployed in a uniform manner, the contributing network stations to PRISM consist of a wider variety of hardware and microsite factors. COOP stations in valley locations typically use the highly-effective passively-aspirated Stevenson screen sensor shelter (MacHattie 1965), whereas the RAWS and SNOTEL networks use Gill-type passively aspirated plate shields similar to the test installations. COOP and RAWS stations generally have the sensors located at approximately 2 m in height above ground level (as do the test observations), whereas SNOTEL sensors can be much higher (Figure 6). It may seem a bit geeky at first, but the applicability of temperature measurements made by any given network is directly impacted by the purpose and design of the network hardware deployment. Model users whose science questions revolve around single-digit °C differences in temperature across space (or change over time) need to be *very* cognizant of the origin and limitations of the source data in their region of interest.

Case in point: a primary source of mid-elevation data for PRISM in the western U.S. is the SNOTEL network, which, to remind the reader, is a series of sites maintained for seasonal streamflow prediction (not climate!) that also includes basic meteorological sensors (NRCS, 2015). The Walker Basin is no exception—there are eight SNOTEL stations within or near the watershed, and these dominate the local mid- and upper-elevation data contributions to the model. The topoclimatic siting characteristics of these stations therefore becomes an important factor in the performance of PRISM and other gridded models in the region. Because the SNOTEL network is designed to measure snow hydrology variables near the headwaters of major streams and rivers, the stations are frequently associated with upper-elevation montane forests. They are situated such that they are not thermally representative of woodland slopes, but rather flats or even sink zones. Accordingly, it is likely that the SNOTEL stations in and around the Walker Basin experience air conditions with canopy-influenced reduction of radiation and increased cooling as well as more stable, frequent flow of cool air during nighttime conditions (Fig. 6). These features make the SNOTEL sites a prime suspect in the PRISM departures in this study, due to local siting characteristics rather than systematic instrumental error.

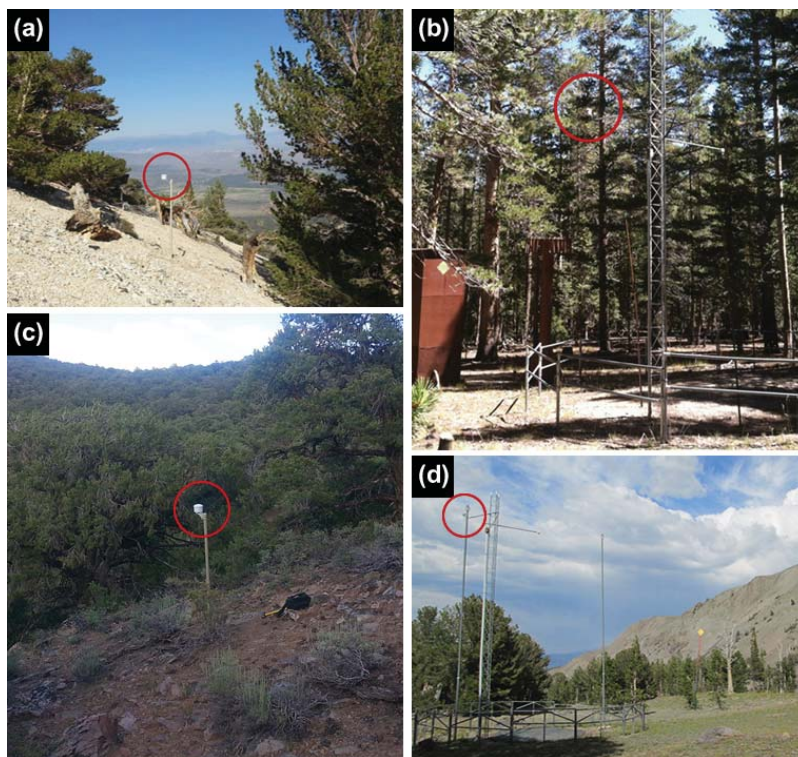


Figure 6. Examples of highly contrasting environments in both PRISM source data and test observations. Locations of temperature sensors are circled in red. The Silverado South study site (a) has sparse vegetation and high surface albedo. The Virginia Lakes Ridge SNOTEL station (b) is surrounded by tall vegetation. The Pine Grove North study site (c) is located in a medium-density woodland with neutral surface albedo. The Leavitt Lake SNOTEL station (d) is in a low-density woodland with surface albedo moderated by grasses. The height of the sensors above ground also differs, with SNOTEL sensors being located at times significantly higher than 2 m (b photo source: USDA NRCS, September 2014).

Instruments and topographic position being equal, the siting characteristics of SNOTEL sensors would, in general, result in cooler Tmax values than the test observations during times of low wind speed simply due to local shading and reduced local albedo. It has recently been pointed out that changes in SNOTEL temperature sensing hardware and calibration/processing practices are introducing biases into the network (Oyler et al. 2015). Reported shifts in temperature have been as much as ~1.1 °C, primarily on the warm side, but varying with temperature. At least some SNOTEL stations in the Walker were affected by this bias during the study period. We experimented with a preliminary correction using an empirically-derived 9th-order function developed in collaboration with the National Park Service in Alaska (Daly et al. unpublished data), but this did not make significant improvements to the model performance in our study (mean corrected Tmax bias = -0.58 °C compared to -0.75 °C uncorrected, mean corrected Tmin bias = -2.67 °C, compared to -1.95 °C uncorrected). Thus, corrections to the model to compensate for SNOTEL calibration bias are overshadowed by other bias sources to do with station micro-siting and hardware deployment practices.

So, readers who do not care about single-digit °C temperature inaccuracy may be asking (if they made it this far!), “at this point, what difference does it make?” That’s a great question, and in order to get an idea how model error at each study site could be propagated to other watershed-scale science questions, we tested a couple of applications: precipitation-as-snow and thermal-sum (growing degree-day) calculations. In short, precipitation-as-snow estimates using modeled temperatures were generally similar to those using observations at the 800

m and smaller model scales, while thermal sums were often significantly underestimated by PRISM (Figs. 7 & 8). If you are an ecologist or snowmelt modeler, you can probably draw your own conclusions as to impact on areal accuracy of derivative predictions in complex terrain.

To wrap this exercise up, our results indicate that PRISM temperature is reasonably representative of daily conditions on semi-arid mountain slopes (excellent r^2 values; Table 1), but that absolute bias caused by a combination of factors can be significant and should be taken into account when applying PRISM data in similar settings, including downscaling climate models over complex terrain. These findings further underline the importance of topoclimatic siting for near-surface observations in mountain science, and how data processing (e.g., SNOTEL calibration) or prediction experiments (e.g., warming) that shift regional temperatures by a degree or two can be completely overshadowed or negated within interpolation models by source data bias at locally-relevant scales.

Because we as a community rely on legacy station networks originally established for a variety of reasons, and not just climatology, source data for modeling remain compromised in one way or another. We feel that the need for expansion of sensory networks to better capture a range of climate variables across diverse topographies is made abundantly clear from this study. Model processes will also continue to evolve. Accurate adjustment for topographic position and land cover (a moving target in space and time) will remain tough challenges for gridded model development, as will local verification/validation efforts.

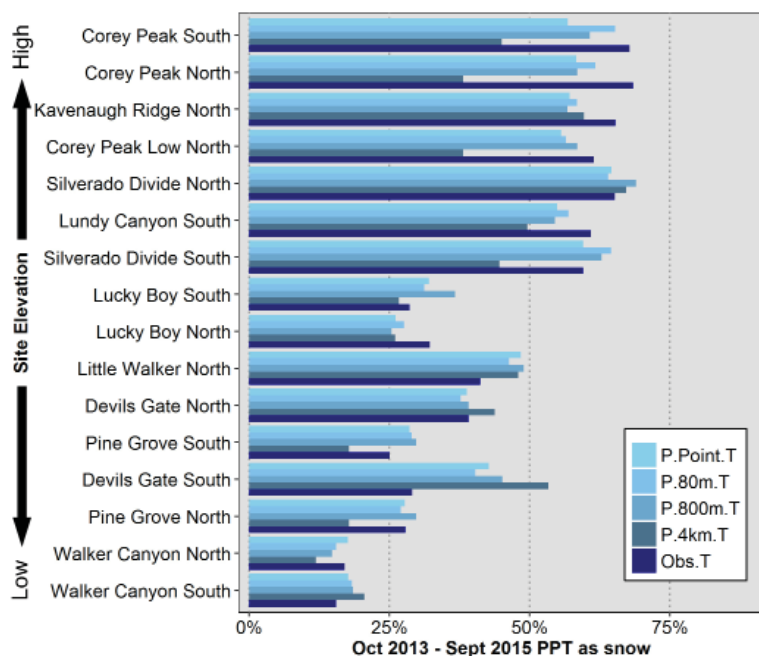


Figure 7. Estimated precipitation as snow. Four spatial scales of PRISM daily data are compared to observations when calculating percent of precipitation as snow during the two-year study period. Sites are sorted from low elevation (bottom) to high elevation (top). The PRISM temperature model performance in this test is generally excellent, with the exception of the 4 km product. It is evident that scale plays a role in application of modeled air temperature when estimating hydrometeorological parameters such as rain/snow boundaries. For example, the use of finer scale PRISM estimates are likely to produce more accurate results when downscaling climate projections to mountainous landscapes.

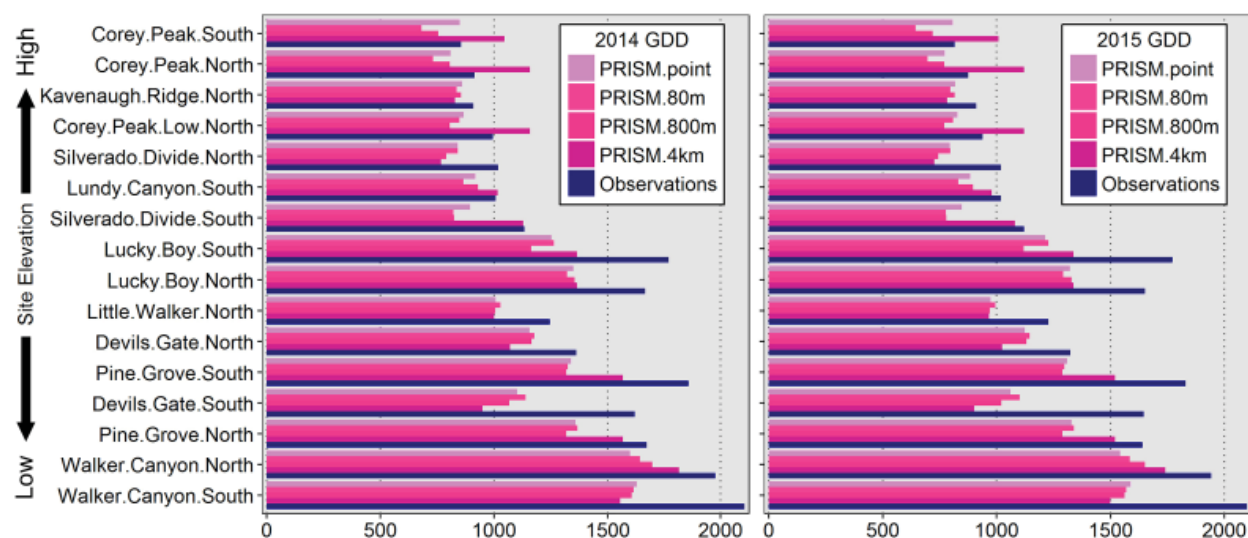


Figure 8. Growing Degree-Days. Four spatial scales of PRISM daily data as well as observations are used to estimate thermal sums on the study sites. In this case, growing degree-days (base = 5°C) are shown for Jan – Sept seasons in years 2014 and 2015. GDD5 or thermal sums of similar types are often incorporated in ecological prediction and snowmelt models tied to climate. Sites are sorted from low (bottom) to high (top) elevation. Finer scales of PRISM consistently underestimated GDD5 across the watershed, especially at lower and warmer elevations, while the 4 km product did not show the same consistency in bias.



Figure 9. Improving representative monitoring networks in mountainous environments remains a key challenge for the mountain science community. In-situ information is crucial for management, modeling, remote sensing verification, and studies of ecohydrological interaction.

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Shifts in Plant Species Elevational Range Limits and Abundances Observed Over Nearly Five Decades in Western North America Mountain Range

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Kopp, C. W. and Cleland, E. E. 2014. Shifts in plant species elevational range limits and abundances observed over nearly five decades in a western North America mountain range. *Journal of Vegetation Science* 25:135–146. <http://doi.org/10.1111/jvs.12072>

Background

North America's Great Basin, with its numerous isolated mountain ranges, provides an ideal natural laboratory in which to examine species responses to recent climatic change. It is projected that boreal habitats in this region may ascend at a rate as high as 167 m for every 1 °C increase in mean temperature, such that a 3 °C increase in temperature could result in a 66% to 90% loss of boreal range extent and a 20% to 50% loss of species (Murphy & Weiss 1992). This scenario could result in localized extinctions for alpine species, many of which are endemic, display strong soil affinities, and are confined to high mountain peaks (Van de Ven et al. 2007). In 2010, we documented shifts in plant species abundances along elevational transects on three distinct soil types in the White Mountains, California, USA (37° 30' N, 118° 10' W) first described in 1961 by Mooney et al. (1962).

Question and Hypothesis

Have there been shifts in abundance and distribution of alpine and sub-alpine plant species along an elevational gradient in an arid North American mountain range during the last half-century? We expected plant species ranges to shift upward such that species peak abundances would be observed higher in elevation in 2010 than in 1961.

Methods

Species abundance data were collected along line transects between elevations of 2900 m and 4000 m to evaluate the degree of plant community shift over time across this elevational range. To evaluate how each of the focal species varied in abundance across elevations and soil-types, z-scores were calculated for

individual species abundances averaged across transects at each elevation in 2010. A statistically significant change over time was defined as a species' abundance in 1961 that fell outside of two standard deviations ($z = \pm 2$) of the 2010 mean. Growing season climate data (June 1 through October 31) collected between 1961 and 2010 were analyzed to quantify the change in annual mean temperature and precipitation at this site.

Results

During the period between surveys (1961 to 2010) daily mean growing season temperatures at Barcroft Station (3800 m) increased 0.02 °C/yr and was largely driven by an increase in daily minimum temperatures (Fig. 1A). Yearly precipitation decreased 4.97 mm/yr between 1961 and 2010 (Figure 1B).

Artemisia rothrockii, experienced widespread increases in abundance over time on granite and quartzite substrates, where it is now the most abundant species below 3650 m in both the sub-alpine and alpine zones. Further, *A. rothrockii* was also the only species that appeared to increase its elevational range margin between surveys. It had upper range margins of 3500 m in 1961 on both granitic and dolomitic soils but the margin rose to 3650 m in 2010 on granitic soils. On quartzitic soils, a dark soil with a low albedo, *A. rothrockii* had an upper range margin at 3650 m, the upper bounds of this soil type in the White Mountains, in both 1961 and 2010 (Fig. 2A). Additional observations in 2012 provided strong evidence that *A. rothrockii* has advanced upwards in elevation (Fig. 3). Floristic accounts by (Lloyd & Mitchell 1973) indicate that this species was found at elevations as high as 3800 m in the 1960s. Flowering plants of *A. rothrockii* can now be observed as high as 3993 m and a second-year seedling of this species was observed at an elevation of 4102 m in 2012 on granitic substrates, 293 m higher than a herbarium specimen collected in 1964 by Mitchell and La Marche at 3809 m, a few kilometers to the north (data provided by the participants of the Consortium of California Herbaria, ucjeps.berkeley.edu/consortium/). This new elevation record far surpasses any previous observations for this species, suggesting that *A. rothrockii* is establishing a foothold in the high alpine areas of the White Mountains.

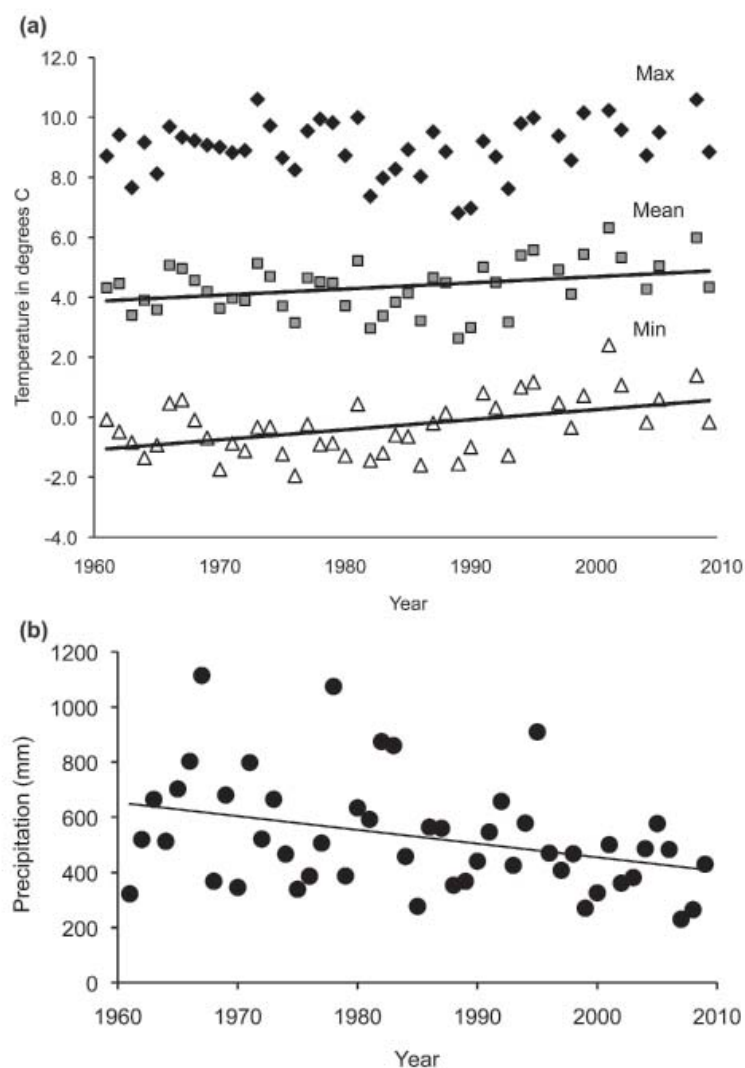


Figure 1. Daily mean 1 June through 31 October temperatures (A) at Barcroft Station (3800 m) increased 0.98 °C/yr between 1961 and 2010. Daily minimum temperatures were largely responsible for this increase as they rose 0.03 °C/yr while daily maximum temperatures increased only 0.008 °C/yr. Yearly precipitation at Barcroft Station (B) decreased 4.97 mm/yr between 1961 and 2010. From Kopp and Cleland 2014.

Three species, *Phlox condensata*, *Trifolium andersonii* and *Eriogonum ovalifolium* experienced decreased abundances on both granitic and quartzitic soils in 2010 compared to 1961. On quartzite, there were significant declines in abundance at elevations of peak 1961 abundance for these three species and as a result, abundances throughout their entire ranges in 2010 were minimal relative to 1961 abundances throughout their entire ranges in 2010. On granitic soils, where there is wider elevational distribution of these species, significant declines in abundance were observed in 2010 at the central portions of these species' ranges while low abundances were maintained at the lower portions of their ranges and peak abundances were maintained at the upper bounds of the survey. These declines in abundance at the central portions of cushion plant ranges in 2010

resulted in abundances similar to those observed at the lower portions of their ranges in 1961 (Figs. 2B,C,E). Additionally, one cushion plant, *Arenaria kingii*, showed no significant range or abundance shifts on either granitic or quartzitic soils and had only minor abundance shifts on dolomitic soils (Fig. 3G). Mooney et al. (1962) included data for *Poa glauca* and *Koeleria macrantha*, both perennial bunchgrasses. Due to identification problems in the field, we do not consider *P. glauca* here. However, *K. macrantha* had mostly minimal shifts in abundance on granitic and quartzitic soils and sporadic, largely insignificant, adjustments on dolomite (Fig. 2F). Finally, *Eriogonum gracilipes*, displayed more complex, but largely non-significant, shifts between 1961 and 2010 (Fig. 2D).

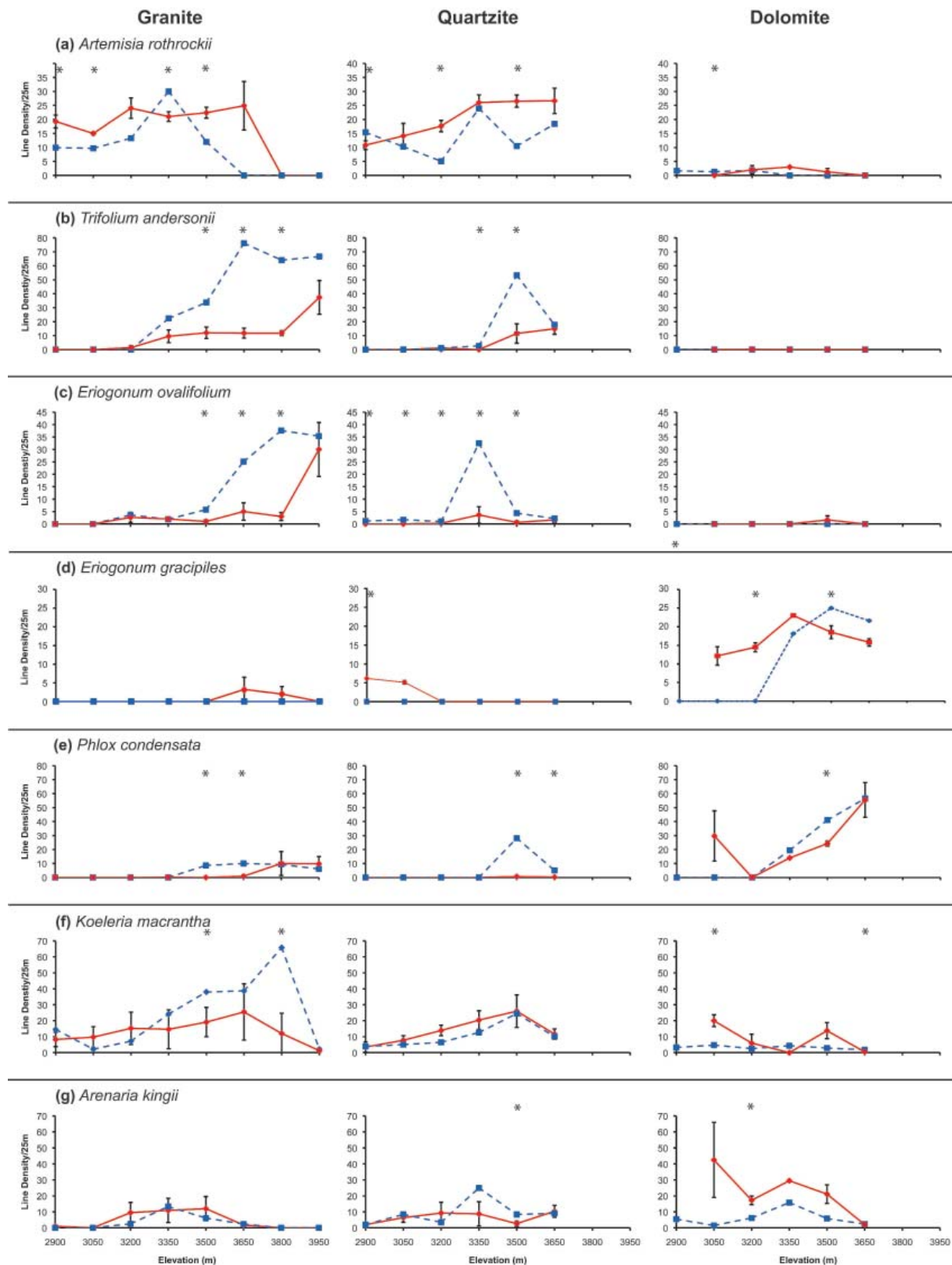


Figure 2. Distribution and abundance in 1961 (blue dashed) and 2010 (solid red) for seven species surveyed in the White Mountains in these years. Elevations with no data points were not surveyed. Significant differences in abundance between sampling years at specific elevations are denoted by *. From Kopp and Cleland 2014.

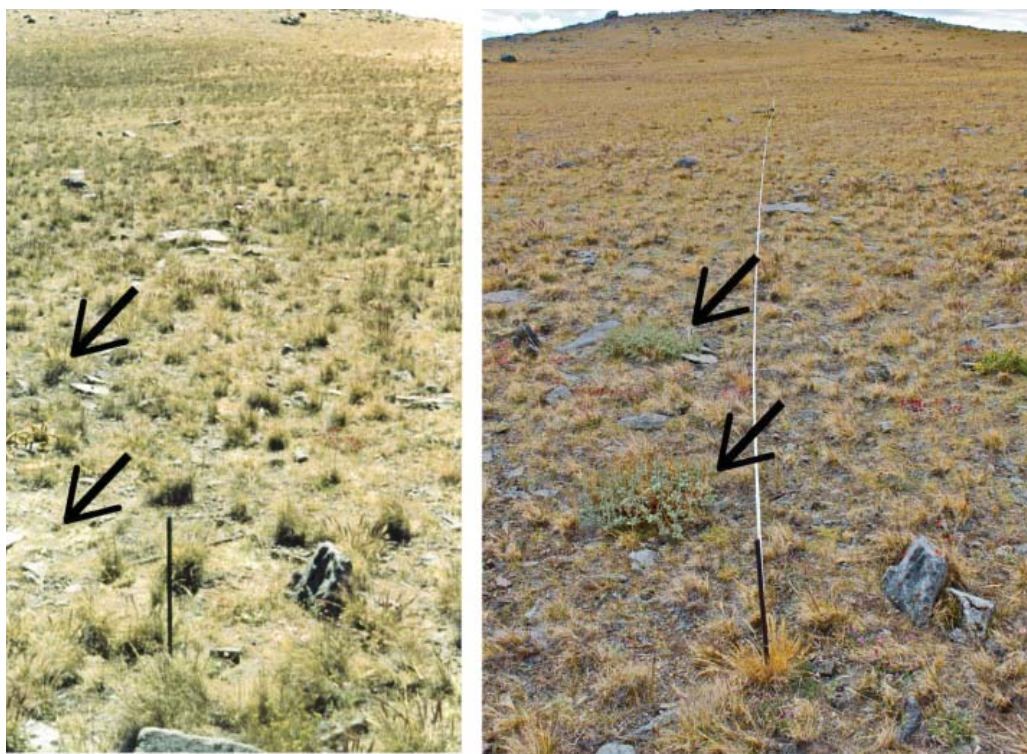
Conclusions and Future Directions

While our results are consistent with the expectation that plant species will have the largest responses to environmental change at the peripheries of their ranges (Sexton et al. 2009), there was large variation among species in how their abundances shifted over time. Only *A. rothrockii* displayed the expected increase in abundance in the upper portion of its elevational range, while three alpine cushion plants declined in the lower portions of their range, another alpine cushion plant appeared to have a downward elevational range shift, and a bunchgrass declined in the upper portions of its elevational range. The complex shifts we observed call attention to the need for future experimentation to identify the environmental and biotic mechanisms associated with shifting abundance and range distributions of unique species inhabiting this, and other, arid mountain ranges. Future studies should focus on the role of multiple drivers of environmental change, in addition to warming, in order to identify the mechanisms associated with declines of sensitive alpine species, as well as the potential role of biotic interactions with species such as sagebrush that are experiencing rapid range expansions.

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Figure 3. Comparisons of photos taken in the same location in 1993 (left) and 2012 (right) show that *Atrémisia rothrockii* is now present where it was not previously documented at an elevation of 3593 m. (From Kopp and Cleland 2014; 1993 photo by Steven Travers).



NEWS and EVENTS

MtnClim 2018 is scheduled for Mon Sept 17 to Fri Sept 21, 2018
at Rocky Mountain Biological Lab in Gothic, Colorado.
Please mark your calendars and stay tuned for more information.

Contact Andy Bunn or Scotty Strachan
andy.bunn@wwu.edu; scotty@dayhike.net



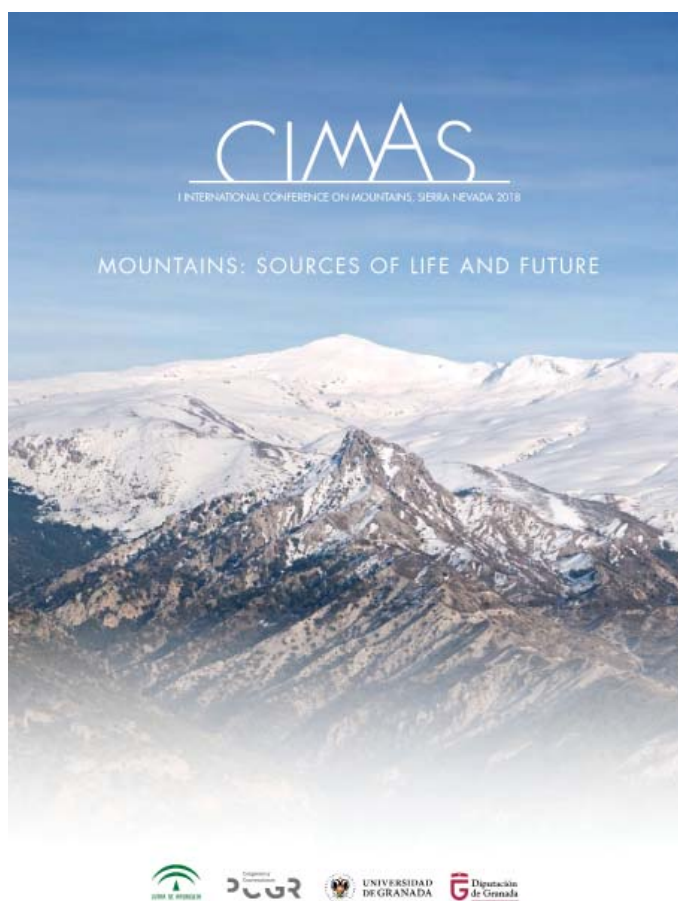
Rocky Mountain Biological Lab. Photo: Scotty Strachan

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VOICES IN THE WIND

In this section, I query members of the CIRMOUNT community for their perspective on a topic of current interest. — Editor

Question: First we have severe droughts in the West, then an epic snowpack winter of 2016-2017. In the systems and mountain regions where you work, did you observe any unusual or unexpected effects during the summer season that resulted from the heavy winter and/or the combined effect of prior drought and heavy winter(s)?

Stu Weiss, Creekside Center for Earth Observation, Menlo Park, CA

Just south of Silicon Valley, thousands of acres of serpentine grasslands form “curves and slopes of inimitable beauty...colored and shaded with millions of flowers of every hue chiefly of purple and golden yellow” (J. Muir 1868) that support the mother lode of the threatened Bay checkerspot butterfly. In order to produce population estimates each year, my field crew and I spend sunny winter days systematically searching those curves and slopes in 10 person-minute intervals, staring into our shadows as we spot and tally black fuzzy larvae basking in the sun digesting tender young *Plantago* greens, both caterpillars and biologists enjoying idyllic California lifestyles. The population dynamics since 2012 (and indeed, since 1985 when I began), continue to reveal complex relationships between temperature, precipitation, topography, and phenological coupling between the butterfly and its annual hostplants. In 2012, a late start to the growing season and a wet March produced favorable phenology, leaving plenty of time for pre-diapause larvae to survive before hostplants senesced, especially on warm south-facing slopes; numbers increased 2-3 fold in 2013. In 2013 a truncated rainy season with a dry warm winter-spring led to poor phenological coupling, much lower pre-diapause survival, and a general 3-fold decline in 2014. However, heavy rainfall in Dec. 2012 led to the appearance of large stands of late-senescent purple owl’s clover at low elevations where populations locally increased. The driest year 2014, with a February start to the growing season, actually led to great phenology and populations boomed; in winter 2015 our thumbs were sore after tallying hundreds of larvae every few minutes in areas supporting 1-2+ larvae/m². 2015 was similar to 2013 but worse; the dry and record warm winter-spring produced 5-10-fold population crashes. The return of “average” precipitation in 2016 included two weeks of ill-timed rainfall in early March that caught much of the



population as vulnerable pupae or freshly emerged adults, and populations crashed again, hitting record lows across much of the habitat. There are no simple relationships between annual precipitation and population responses—timing of rainfall and warmth within a year and interactions with complex topoclimates make all the difference. The butterfly response to the record wet year of 2017 will only be known this winter, when we wander the curves and slopes in search of larvae and plug the results into our stratified sampling spreadsheets...

Mackenzie Jeffress, Nevada Department of Wildlife, Elko, NV

In northeastern Nevada, we did see great snowpacks in the winters of 2015/2016 and 2016/2017, but some areas saw more than others. One would imagine this would result in better habitat conditions, which some areas, like mountain brush communities to lower elevation Wyoming sagebrush sites, seemed to have responded positively, likely because the moisture was reaching those deep roots. These two years back to back also saw many seeps and springs that were previously dry begin to express water again. However, it hasn’t been enough to resolve several of the issues we’ve seen here. For example, many of our aspen stands were severely impacted by the drought, and even into this fall some of the trees continued to show signs of stress. This might be due in part to the fact that we have seen less summer and fall rains following these snowpacks. The reduction in moisture during these times also means limited or delayed fall green-up and less forage for some wildlife to build up winter reserves. Those drier conditions might have also contributed to wildland fires burning over 400,000 acres of western Elko County. A final observation this late spring was that most of the goshawk nests I was monitoring failed. This appeared to be from some late snows that



coincided with early hatching. These kinds of lower productive years can be expected on occasion but are still a disappointment when you want to see the birds succeed. In conclusion, there are definitely some positives to be seen from the great snowpacks but I expect it will take several years of normal to above normal conditions to help recover from the drought.

Sarah Stock, Resources Management and Science, Yosemite National Park, CA

On February 6, 2017, a law enforcement ranger knocked on the door of my home in Yosemite Valley with an evacuation notice and warnings of flooded roads, debris flows, and damaged sewers. Trepidation swept through me, as my thoughts immediately turned to the wild animals, and how they would need to work harder to gain access to sufficient food and shelter. As a wildlife ecologist, I wondered if this winter would take these animals beyond their thresholds for survival, or if they were resilient enough to make it through these relentless storms.



The bighorn sheep in the Cathedral Range defied expectations of gloom and doom: six ewes, including two yearlings born in the area, survived at over 11,000 feet elevation. Imagine the incredible fortitude and vitality needed to withstand back-to-back snow storms and regular gale force winds exceeding 50 miles per hour. Ironically, it was the high winds that blew away the deep snow that enabled the bighorns access to the scant forage available. While all Sierra herds made it through the winter, individual groups across the range declined by about 15-20%, in part due to heightened avalanche conditions and snow accumulation that challenged access to vegetation.

Birds surprised us too. Spotted owl nesting was the highest ever recorded in Yosemite's history—perhaps due to increased small mammal abundance triggered by wet conditions following the drought. Breeding birds in Poopenaut Valley were displaced from their usual willow habitat by inundation of Tuolumne River floodwaters. While the number of bird species present was lower than in previous years, there was a similar number of individuals, suggesting food resources were still adequate. The remaining bird species appeared to make the best of it, and nested in upland vegetation that would not have been a first choice in drier years (Michelle Desrosiers, *pers. obs.*). Farther up the watershed in

Tuolumne Meadows, meadow-nesting birds delayed nesting until the river receded in late July. Similarly, ground-nesting species like dark-eyed junco were later than past years and still had nestlings into August. In contrast, cavity nesting birds such as Williamson's sapsucker and mountain chickadee, and generalist species such as American robin and Steller's jay, were not impacted by the flooding and began nesting around their usual time in late June (Karen Amstutz, *pers. obs.*).

Butterflies were hard to miss this year. Yosemite's annual high-elevation butterfly count broke all previous records for the number of butterfly species (72) and individuals since the count began seven years prior. Not only were there more butterflies, but they were easier to find because many of the season's plants were in bloom at the same time, such as late shooting stars and early gentians (Karen Amstutz, *pers. obs.*). Anecdotally, we noticed an increased prevalence of black widows in Yosemite Valley (Caitlin Lee-Roney, *pers. obs.*) and a greater abundance and longer season for mushrooms, such as porcinis, in the higher elevations (Karen Amstutz, *pers. obs.*).

The next time I am evacuated from my house because of winter storms and flooding, I will not dwell on the hardships the animals are enduring, but rather will think about their resilience and remarkable ability to cope with what seem like impossible conditions.

Solomon Dobrowski, W.A. Franke College of Forestry and Conservation, University of Montana, Missoula, MT

It was an average day this past April as I rode the bus home from work. I struck up a conversation with the gentlemen across the aisle. The recent wet weather was the icebreaker. Missoula, Montana had just experienced an 'epic' winter as backcountry skiers described it (184% of normal precipitation). Winter was followed by an abnormally wet spring (113% of normal) which was the impetus for the grumbling and complaints I heard regularly on the bus those days. My brief conversation that afternoon followed a similar thread and then ended when the gentlemen said, "Well at least this summer should be a slow fire season". At the time, I nodded my head and thought to myself, "Does it actually mean that?"



It turns out that the summer of 2017 was quite a busy fire year in Montana and across the west. Nearly a million acres burned in Montana alone and, like many of the residents of Missoula, I spent much of August and September trying to escape the pervasive smoke that blanketed our town. How did we go from beautiful green vistas to smoke for a hundred miles in every direction?

Put simply, all it took was two hot and dry months. Missoula gets on average 14 inches of precipitation per year. This precipitation comes in a measured fashion, an inch a month except for the months of May and June, which receive two inches. By this annual measure, the 2017 water year was above average (16 inches or 114% of normal). June of 2017 was quite average with two inches recorded at our local weather station. Then came July which saw no measurable precipitation, and August which recorded a mere two tenths of an inch. If you combine this with the fact that the summer of 2017 was one of the hottest on record since 1948, you have all the ingredients needed to burn over a million acres in western Montana.

In a summer that saw record breaking rains in Houston, hurricanes that have leveled Puerto Rico's forests, and unimaginable firestorms in northern California, I am reminded that 'average' conditions are a useful construct but they rarely occur. Three inches of rain separate the driest July in Missoula (2017) from the wettest over the last 70 years. A dry July is not uncommon; the standard deviation for precipitation is almost as large as the average (0.8" vs. 0.99"). What is staggering is that

July temperatures have increased roughly 6° F since 1948 making the likelihood of a dry **and** hot summer increasingly likely.

As a scientist who studies climate and forests of the western U.S., I am well aware of the fallacy of the 'law of averages'. Yet, human nature looks for pattern and consistency by organizing today's outcome with respect to the past. As I began this writing assignment, the 2017 fire season in western Montana was admittedly a surprise to me. Now, as I reflect on what occurred, I've come to appreciate how unsurprising the outcome was.

C. Alina Cansler, USDA Forest Service, Rocky Mountain Research Station, Missoula, MT

The snow stayed on the ground late into spring here in Missoula, MT. Because of that, we were all expecting a mild, short fire season. In some parts of the country, like the southwest, heavy winter precipitation contributes to the growth of fine fuels, like grass, making the whole landscape more flammable the next summer. In contrast, in the mountains of the Northern Rockies, research has shown that big fire years typically occur when there is low winter snowpack and early snow melt.



Alina's daughter, Astrid, on playground with smoke from Montana fire in background

When snow melts early, there is more time for fuel to dry out, and for fires to ignite and burn during the summer.

The surprise, then, was that the heavy winter snowpack did not seem to matter at all. By mid-July fires surrounded us here in Missoula, and many nearby communities were evacuated. The smoke was incessant and oppressive, and in the nearby town of Seeley Lake was so persistently hazardous that officials recommended people evacuate because of the smoke. We broke local records for the number of days without rain – 46. By the end of the fire season there were over 70 large fires being managed across Montana, Idaho, Washington, Oregon, and Northern California, all areas that had above normal precipitation the previous winter and spring.

This year we learned that summer drought trumps winter and spring conditions. Climate variables are correlated: early snow melt likely occurs more often in years that also have more severe summer drought. As a scientist who has studied relationship between climate and fire severity, this summer warned me to be very careful about assigning causation among correlated climate variables.

The heavy snowpack did keep soil moisture high at high elevations, preventing or slowing burning along ridgetops during July. But by late-August the high-elevation areas began to burn more actively. One high-elevation area that burned in the nearby Lolo Peak fire was the Carlton Ridge Research Natural Area, designated for the > 400-year-old alpine larch and whitebark pine forests. I really want to know if the late snowpack and associated high soil moistures moderated fire behavior up there when it did finally burn. Since roads are closed in the burn and the snowpack is already getting deep on the ridgelines, I will have to wait until next summer to answer those questions.

Gordon Grant, USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR

The question posed is fundamentally addressing a deeper question: Do landscapes have inter-annual memory, and if so, how is this expressed? In other words, does a wet year following a dry year have a different effect on (fill in the blank) than two wet or dry years in a row or some other combination? This is a poorly-



understood topic, since it focuses on the issue of the *sequence* of events, rather than the events themselves. It has generally received little attention, in large part because it is difficult to achieve any kind of true replication with respect to the climate: every year is inevitably embedded in a sequence of other years, and so it's difficult to assemble a population of similar sequences of events within the limited (in most cases) data record. While there are many landscape attributes and processes that could fill the blank above, and the answer likely varies across landscapes, here I will focus primarily on streamflow response, as illuminated by some of our group's recent work in the Oregon Cascades.

By way of background, the Oregon Cascades are a long-lived (since the Oligocene) volcanic arc and an unparalleled natural laboratory for exploring the effects of geologically-mediated drainage efficiency on streamflow generation (discharge) under different climatic events or sequences. We define drainage efficiency as the timescale required for precipitation or snowmelt (recharge) to become discharge. The older, western part of the Oregon Cascades (known as the Western Cascades) is highly drainage efficient, and precipitation and snowmelt are rapidly delivered to streams as runoff, resulting in flashy peaks and little late summer streamflow. This is due to the steep topography, high drainage density, and very limited groundwater storage. In contrast, the neighboring geologic region immediately to the east is the High Cascades, a much younger (Plio-Pleistocene and younger) part of the volcanic arc, dominated by kilometer-thick stacks of highly porous lava flows, few streams, and relatively low relief. Here, high landscape permeability and gentle hydraulic gradients result in very low drainage efficiencies, muted streamflow peaks, and high, sustained baseflows.

We've been quite interested in how the streams draining these two contiguous but distinctly different landscapes respond to seasonal, annual, and inter-annual sequences of precipitation and recharge events, either as rain or snowmelt. Our working hypothesis has been that the low drainage efficiency landscape (High Cascades) will have much greater memory for year-to-year variations in the amount and timing of recharge, due to the slow response times, whereas the high drainage efficiency landscape (Western Cascades) will have little memory, since the response is rapid and there is little storage. In general the data support these hypotheses (i.e., Tague and Grant, 2009). However, we were quite surprised that the effect of the 2015 snow drought in Oregon did not result in record-breaking low flows in the High Cascades. Summer streamflows were among the lowest on record, but not as low as our models would have predicted. We now think this is the consequence of the extremely high volumes of water stored in the rock in this landscape—basically a single year of low snow input represents only a small fraction of the total stored water, so streamflows remain higher than expected.

Following the 2015 Water Year, both precipitation and snowpack were slightly above average in 2016, while summer streamflows were generally below average, a possible “memory” effect from the preceding year. By 2017, a year with slightly elevated snowpack but much higher rainfall, summer streamflows have generally recovered back to average levels.

An intriguing, though untested, idea that arises from this work is that there may be a landscape “sweet spot” in terms of inter-annual hydrologic memory. There appears to be little memory if groundwater storage is low (i.e., Western Cascades) or if the ratio of total active storage to annual precipitation is high (i.e., High Cascades). Between these two storage extremes it seems plausible that maximum inter-annual memory may be maximized. Obviously we need more research...!

Imtiaz Rangwala, Western Water Assessment, NOAA Earth System Research Laboratory, Boulder, CO

Working on a drought preparedness project for the tribes at the Wind River Indian Reservation (WRIR; surrounded by Wyoming’s Wind River Mountain Range on its west) since 2015, we have witnessed hydro-climate extremes related to too little or too much water—sometimes within a single season.

During the 2015 growing season, a very wet May (where precipitation came mostly as rain) was followed by a very dry September. Based on one measure, the Evaporative Demand Drought Index (EDDI), May had the lowest one-month EDDI (low evaporative stress) on the record going back to 1979 while September experienced the highest EDDI value. Overall, 2015 had near to slightly above precipitation but it experienced significant drought impacts later in the growing season driven by factors related to a warming climate and ineffective water management.

Fast forwarding to 2017, there were wide-spread flooding in WRIR and its vicinity because of above average snowpack and a rapid melt-out. Although to a lesser extent, such spring flooding has become more frequent in the region in recent years. Our stakeholders at WRIR now want to integrate the ongoing drought planning efforts with flood planning. Accurate and comprehensive observations on the patterns of precipitation (rain



vs. snow) and snowpack in these mountain regions are scarce, if not completely absent. Nonetheless our analysis points to the “expectedly” changing nature of the hydroclimate in this region of the Intermountain West where a warmer, moister and thirstier atmosphere is enhancing the “rate” of hydrologic processes thereby facilitating extremes related to both too little and too much water leading to measurable emerging impacts for humans and ecosystems.

Catie Bishop, GLORIA Great Basin (Global Observation Research Initiative in Alpine Environments), Oroville, CA

The last several years of severe drought have had me pondering: Is this the new normal?... a disconcerting thought. However, California has experienced droughts of over 100 years duration in its past, lowering natural lake levels an astonishing amount. Now we have had a very welcome wet winter. I live in the blue oak woodland, and I look to them to tell me how things are. They are so tough that I feel when they look bad, times must be bad. They look bad right now, even after the almost-record winter rains. Their normal blue-green canopy has been brown for months. That tells me that even an exceptionally wet year doesn’t make up for several dry ones, the subsurface water bank is still overdrawn.



One thing I am discovering though is their resilience. During this last wet spring many native plants put on greater than average growth. With variable success, they struggle now to maintain that extra mass, losing pieces of themselves big and small. But the blue oaks kept to their “slow and steady wins the race” strategy. They are survivors, and as dry and brown as they look now, I know they have survived worse than this. They will drop those brown leaves, and green up nicely next spring. That is comforting to know. And so, while I wonder if drought is the new normal, the blue oaks abide. Good rain years come and go, boom and bust for most plants, but blue oaks have a way of enduring with a patience I can only envy. That is their normal.

Greg Pederson, U.S. Geological Survey, Northern Rocky Mountain Science Center, Bozeman, MT

After a winter and spring of high snowpack and relatively cool temperatures across the Northern Rockies, we were prepared for a classic green and relatively smoke-free summer. Unfortunately, as people across the West already know, what happened stands in stark contrast to expectations. First the good news. Snowpack in the mountains accumulated to relatively high levels in most basins, and melted out with relatively “normal” timing, at least normal relative to recent decades (e.g. 1981-2010). This kept water managers across the Missouri River Basin quite happy through the summer demand season since they were able to top off reservoirs early, and in certain basins, like the Bighorn, spill



massive amounts of water during spring runoff. Then, in a similar fashion to 1910, the tap shutoff (i.e. precipitation stopped), and warm and windy conditions dried soils and forests in a matter of weeks. Forest fires kicked off early across the Northern Rockies and Pacific Northwest, resulting in evacuation of communities and the loss of property, and, most unfortunately, several lives. Air quality was as bad as I have ever experienced across broad regions, and it lasted months until we received substantial rainfall by mid-September. I had all but forgotten about the high winter snowpack and good water year flows, until we returned to a field site above 10,000' in the Beartooth Mountains to collect ancient whitebark pine material that has been melting out of ice patches. The 5,300 yr. old wood did not emerge from the snow this year, which is a rare event anymore, and served as the only reminder I had of the high 2017 snowpack.



Danny Stahle sampling whitebark pine in 2016



Sampling area, September 2017 (green outline)

FIELD NOTES

The Great Northwest DendroExpedition

Charlie Truettner

Department of Geography, University of Nevada, Reno, Nevada

“Whoa! The tree core just shot out of the borer!” I laughed without realizing what followed... the sticky sap came spewing out all over me. Luckily, the increment borer was half way out of the Douglas fir before the sap attack happened. Unluckily, the Dougie that I was coring was over 130 cm DBH and wasn’t giving the borer up. By the time we were able to remove the increment borer, Dr. Emanuele Ziaco, Nick Miley, and I were covered in sap. Good thing we had a surplus of the contemporary dendroecologist’s best friend... 100% ethanol did the trick for our hands and arms! Our field clothes will stay field clothes forever.

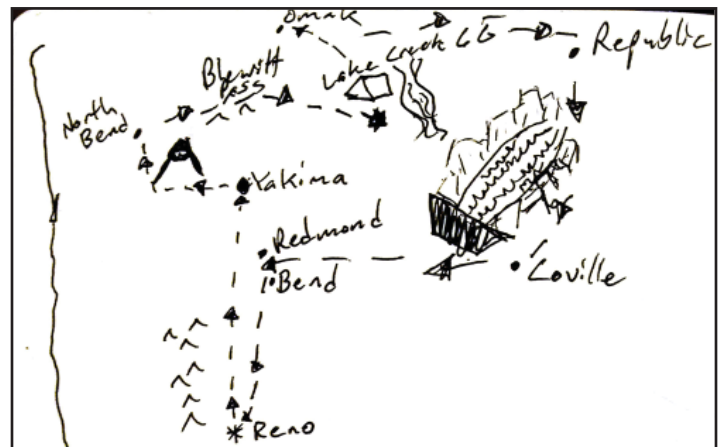
I’ve been coring trees in the semiarid mountains of the Southwest as a dendroecologist for more than six field seasons and have never experienced a tree core exit an increment borer on its own. These were the lessons I wasn’t prepared to learn as Team DendroLab from University of Nevada, Reno embarked on its two-week expedition up the Cascade Mountain Range and into the depths of interior Washington. Our objective was to relocate at least ten International Tree-Ring Data Bank chronology sites and core the largest, oldest ponderosa pine and Douglas firs at those locations.



Charlie coring a large ponderosa pine

The thick haze from a wildfire surrounded us as we drove north to Yakima from Reno. It was the end of August, and the wildfire season was in full swing. We were lucky to reach our first sites near Mt. Rainier before the southern areas of Mt. Baker-Snoqualamie National Forest were closed to the public due to the wildfires. A few ridges near the top of Mt. Rainier were the only parts of the iconic mountain that we could see as we drove through the smoky Mt. Rainer National Park to our next potential sites near Cayuse Pass. That night we found a primitive campground along a Forest Service road on the west side of the Cascades, excited to relocate our next sites. In the morning, we drove up a ridgeline to relocate our sites, when Mt. Rainer in all its beauty was sitting behind the top of the pass, while the sea-faring fog was rising from the west.

You could just imagine the enigmatic Sasquatch cruising through the humid, productive ecosystems full of enormous trees. We joked around about its possible sightings, as all visitors of the temperate Northwest rainforests have the chance to do. Then we were off to the drier eastside of the Cascades near new and old Blewitt Pass. There, after scoping out both passes, we settled on coring a nice stand of Pondos (ponderosa pines), agreeing that we didn’t “blow it.”



Great Northwest DendroExpedition map

Lake Creek Campground in Wenatchee National Forest was a nice treat after some fully-packed double site coring days. The following day we climbed up a high relief, steep mountain side to a ponderosa pine grove under some cliff bands that seemed like the best bet to core old trees. To our surprise, we had a difficult time finding some old Pondos in what appeared to be a recovering forest. We drove away from the site frustrated.

A few tacos from a food truck in Chelan made us feel better as we turned our attention east towards the small town of Republic. We finished our trip coring some stunning ponderosa pine and Douglas-fir stands where we found remnant coring holes in some of the trees, presumably from the dendrochronologists who first discovered the sites decades before.

The smoke was rolling down from British Columbia as our Great Northwest DendroExpedition was coming to an end. We had succeeded in relocating 11 ITRDB sites, and rewarded ourselves with a good dinner and a few locally brewed beers at Republic Brewing Company. A pleasant stay at a motel in town that night, followed by a lazy morning, was a good way to recharge for the journey back.

The drive through eastern Washington was astounding, especially driving by the colossus Colville Dam. I had mixed feelings about the incredible engineering project. On one hand, it stopped the natural flow of a keystone river. But with all the ash and other aerosols we had encountered on our field trip, I had to also consider the clean energy it produced and the community that was enhanced with the building of the dam. These difficult environmental and ecological conundrums will be in the forefront of management and policy strategies in our threatened national forests.

Our last night was spent in Redmond after crossing the Oregon border where we fell asleep watching old “The Simpsons” reruns.. exhausted. The next morning we had a pleasant breakfast with Nick’s father and drove back to Reno. It’s not only exploring forests in new mountain ecosystems that reminds me of why I chose to study forests, but also the companionship you form with the people you are with. In modern times of constantly battling over memory space between ArcGIS and R, it’s a tranquil pleasure to walk through iconic forests driven by the passion to save them.



Team DendroLab

DID YOU SEE IT?

Branch Drop, Take II: The Mystery Widens

Connie Millar

USDA Forest Service, Pacific Southwest Research Station
Albany, California

In the spring 2017 issue of *Mountain Views Chronicle* (<https://www.fs.fed.us/psw/cirmount/publications/mtnviews>; pgs 67-68) I wrote about a singular event observed in late March, 2017 by eastern Sierra Nevada travelers along the margins of US 395 north of Mammoth Lakes, California. What they saw, as the epic winter morphed into spring, were piles of short, green (live) branchettes lying on top of the deep snowpack and directly under the crowns of Jeffrey and lodgepole pines (*Pinus jeffreyi*; *P. contorta*) near the highway. This effect was visible along the forested 10-mile stretch between Deadman Summit (2453 m) and Smokey Bear Flat. Without conviction, I concluded that the cause resulted from some pre-conditioning weather/ice event(s), and likely ultimately related to wind blasting from the snow-removal trucks that were in frequent use during the extremely heavy periods of snowfall.

In late May, as I began my annual field season in the Sierra Nevada around the greater Mono Basin, I had not forgotten about that mysterious event. I was not expecting, however, to find

what I did: pervasive branchette drop under conifers scattered across high elevation slopes of the central Sierra Nevada. This phenomenon occurred far from paved highways, dirt roads, or trails, and on slopes of diverse aspects and steepness. When I started my season, the snowpack still lay deep, more than 2 m at elevations ~2800 m and above. As I plodded over the snow to my work sites, I was astonished to find tidy packages of branchettes bearing green needles, describing neat circles on the snow below the trees from which they fell (Fig. 1).

Describing the Event

Characteristics of the branchette drop event included the following:

- * Branchettes were short (most 5-15 cm), and almost exclusively first-year growth, especially in the pines (Fig. 2);
- * Branchettes lay on top of the snowpack (early season) in piles directly below the crowns of trees, tending to the downslope sides



Figure 1. Whitebark pine with green needles lie on top of the snowpack in June 2017 under Mt. Dunderberg



Figure 2. Branchettes that dropped were primarily first-year branches



Figure 3. Branchettes accumulated in circular piles concentrated close under stems, Kavanaugh Crest

(where there was slope) and concentrated under the crowns—not extending more than 2–3 m from the trunk (Fig. 3);

* Needles were green (live) while they rested on top of the snowpack, and turned brown (dead) when the snow melted and they rested on dry ground (Fig. 4);

* Cones were not common in the debris, and needles remained attached to the branchette stems;

* The ends of the branchettes were broken off, not chewed (as by rodents) nor did they display the common pattern of branch-cut by Clark's Nutcracker (*Nucifraga columbiana*), which would be restricted to whitebark pine (*Pinus albicaulis*);

* Branchlette drop occurred under trees that were taller than ~3 m; mature trees were affected where branches occurred at ~3–5 m height along the stem;

* Although I couldn't readily discern the broken branch ends on the trees, where I could they appeared to be at about 2.5–4 m height. At this same height-zone on live trees, I also observed, but not as commonly, dead needles on branches, whereas needles above and below this height were not affected (Fig. 5);

* Affected trees were mostly above 2850 m and extended to treeline at approximately 3200 m; krummholz (shrubby) conifers and solitary upright trees above treeline were not affected;



Figure 4. Dead needles on branchettes in late season once snow had melted, Saddlebag Lake



Figure 5. Dead needles remaining on branches at 2–4 m height in trees, H.M. Hall Research Natural Area



Figure 6. Branchettes of white fir had the same pattern as other species, west of Sonora Pass



Figure 8. Stems of whitebark pine broken at 2—3 m height, Virginia Canyon

* Affected trees were in diverse environmental contexts with no obvious pattern to slope, aspect, exposure, or forest type;

* Species affected included whitebark pine, lodgepole pine, western white pine (*Pinus monticola*), mountain hemlock (*Tsuga mertensiana*), red fir (*Abies magnifica*), white fir (*A. concolor*, Fig. 6) and Sierra juniper (*Juniperus grandis*; Fig. 7);

* In some especially exposed areas, I observed stems of mature trees broken at about 2—4 m height; in other areas below steep cirque slopes, avalanche debris was common, again with stems appearing to have broken at this height from the ground (Fig. 8);

* I observed this phenomenon patchily distributed in the central eastern Sierra Nevada extending from Mono Pass (Mono County,

south of Tioga Pass) to the Silver King region (Alpine County) north of Sonora Pass (2680 m), a distance of about 50 miles; in the one time I was on the western slope, below Sonora Pass, I observed the effect as low as 2425 m;

* I did not observe the effect in ranges directly to the east of the Sierra Nevada (Sweetwater Mtns, Bodie Mtns, Glass Mtns, White Mtns) nor in any of the many high central Nevada ranges that I visited. Nate Stephenson (USGS) reports not seeing branchlette drop in the southern Sierra, either in the region of Sequoia-Kings Canyon National Parks or on a backpack trip that extended as far north as Bishop Pass.



Figure 7. A. Branchettes of Sierra juniper, Silver King watershed. **B.** Ends of branchettes showing broken tip

Explaining the Event

Of this I am certain: snow-removal equipment was not involved! With high confidence I also rule out rodent chewing by Douglas tree squirrels (*Tamiasciurus douglasii*) or clipping by Clark's Nutcrackers. Beyond that the explanation gets speculative.

Assuming weather must be involved, I inspected the daily output from relevant SNOTEL sites and other stations that report high-elevation weather conditions for the months from March 2016 to October 2017. Nothing spectacular jumped out, although there were distinct and unseasonal freeze-thaw periods, as well as deep-winter thaw days (i.e., no temps $> 0^{\circ}\text{C}$).

I was getting desperate to explain the event, having made the decision to include a report for this issue of *Mountain Views Chronicle*, when I was forwarded on November 17, 2017 a draft proposal for a new record California wind gust (California Extremes Committee 2017). The Extremes Committee described a remarkable wind event that occurred the evening of February 20, 2017, and was recorded in the northern Sierra Nevada at the Alpine Ski Resort west of Lake Tahoe, CA. On Ward Peak (2634 m), a gust of 199 mph was recorded at 11 pm; at nearby Squaw Peak (2650 m) a gust of 193 mph was recorded at a similar time. Investigating historic records, the Extremes Committee proposes that the February 20, 2017 event is likely the strongest measured surface wind in California. The Committee further described that

this event occurred during a powerful atmospheric river storm, wherein winds passing the California Central Valley focused high onto the Sierra crest, with rapid acceleration over ridges that concentrated wind at 2440—2740 m elevation.

Maybe I'm grasping, but this dramatic wind event, which produced record maximum gusts at high elevations, must be involved with the branchlette drop I observed in summer 2017. But how was it involved? Branches of high-elevation conifers are adapted to severe winter weather, especially in winter when they are in hardened off condition. Further, is there evidence for unusually extreme high winds in locations where I observed the branchlette drop? Ward Peak is 57 miles north of the northernmost location where I observed the effect. I didn't survey areas farther north so I don't know if it occurred in the northern Sierra Nevada.

Using SNOTEL records, I focused on historic data from the Virginia Ridge station, which is near the northern edge of the Mono Basin, at 2879 m (February 2017 daily data; Fig. 9). By February 1, snow depth was already 188 cm. A series of snowstorms dropped a cumulative 61 more cm between Feb. 2 and Feb. 10. Most of this occurred during freeze-thaw days, that is, where maximum daily temperatures were $> 0^{\circ}\text{C}$ and minimum daily temperatures were $< 0^{\circ}\text{C}$. On Feb. 8—9, however, a short thaw period occurred, where both minimum and maximum

Station (846) MONTH=2017-02-01 (Daily) NRCS National Water and Climate Center - Provisional Data - subject to revision
Tue Nov 07 11:48:59 GMT-08:00 2017

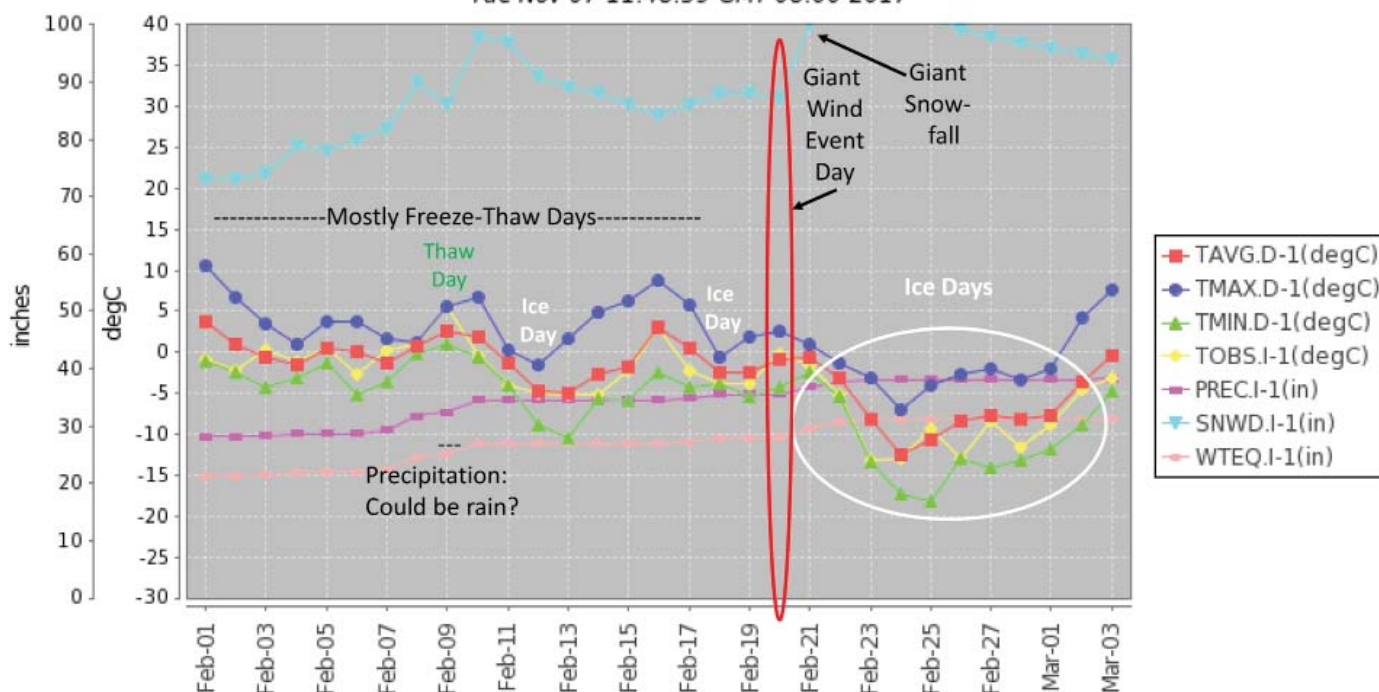


Figure 9. Virginia Ridge SNOTEL station (2879 m), daily data for February 2017

temperatures were $> 0^{\circ}\text{C}$. At the same time, precipitation fell (purple line, Fig. 9), but snow depth declined, suggesting rain not snow. This is confirmed by temperature and precipitation records from the Mammoth Mountain Ski Area station (Ski Patrol Records, Winter 2017). Several periods of ice days (minimum and maximum temperatures $< 0^{\circ}\text{C}$) occurred after this and before the Feb. 20 wind event (marked as a red vertical circle, Fig. 9). With this sequence of events, it is possible that the rain that fell on Feb. 8–9 subsequently froze into ice casings on high-elevation conifer branches. This would create a ballast-like weight on the otherwise highly flexible conifer branch ends. The ice would likely be thickest on the areas where needles occur (ends of branches), coating the needle area like a cylinder. Such ice-encrusted branches would be more susceptible to break if/when a big wind occurred.

A big wind would be very unlikely to kill needles on branches before they broke, nor would ice formation kill winter foliage. Further, snow depth was about the right height around Feb. 20 to account for my summer observations. The big wind might also have had a shearing-scouring impact at the top of the snowpack, which could have led to dead needles that I observed remaining on conifers at 2–5 m height in the crowns, and also patterns of broken mature trees and avalanching. Although the Virginia Ridge SNOTEL record suggests that a large amount of snow fell starting on Feb 21 (thus, after the wind event), the Mammoth Mountain Ski Area station reports that 86 cm of snow fell on Feb 19 and 20. If the wind event occurred while snow was falling, this would help to explain why the branchettes remained directly below the tree crowns rather than being scattered far off by wind.

Of the many remaining questions that remain, one is whether the concentrated, high-elevation, extreme winds reported in the Tahoe Sierra actually occurred in the region of the observed branchette drop. For stations in the Mono Sierra that report wind information, I find no evidence for unusually high wind speeds, either sustained or gusting, on February 20 or 21, 2017 (Table 1). To the contrary, the stations reported wind gusts no higher than 42 mph, a rather average day for this part of the Great Basin. Apparent restriction of the unusual winds on the evening of Feb 20 to high elevations, however, suggests that lower elevation stations, such as these in the Sierra Nevada, would not report the effect, a pattern not unsurprising given the atmospheric conditions (Eric Kurth, National Weather Service, Sacramento, pers. comm. Nov 27, 2017). So, the only evidence for extreme winds, circular as it is, remains the branch-drop effect, along with broken stems at the depth of the snowpack in late February, as well as apparent avalanching at the time.

Two high-elevation weather stations are available in the general latitudinal band of the Mono Sierra but in the White Mountains, east of the Sierra Nevada: Barcroft and Crooked Creek. Those stations reported somewhat higher wind velocities than the lower Sierran stations, but in the same order of magnitude, and nothing extraordinary (Table 1). That these high elevation locations, in the elevation zone of the reported record wind gusts, did not receive extreme winds suggests that the unusual atmospheric event producing extreme winds in the Sierra did not reach the White Mountains. The lack of extraordinary winds in the White Mountains is concordant with my observations of no branch drop effect in that range.

Table 1. Maximum wind speeds recorded at stations in the central eastern Sierra Nevada on February 20, 2017. From MesoWest and WRRRC records. All stations are in California unless noted.

Station	Station Elev (m)	Max Wind Gust (mph)	Time of Max Wind (hrs)	Ave Wind Direction (degrees)
<i>Stations near Mono Sierra</i>				
Valentine Reserve, UCNRS	2160	42	2000	161
Mammoth Airport	2171	35	1900	180
Crestview Fire Stn	2316	28	1400	184
Bridgeport Valley	1980	45	1800	174
<i>Stations distant from Mono Sierra</i>				
Crooked Creek, White Mtns	3094	34	2400	123
Barcroft Stn, White Mtns	3783	50	1900	240
Carson Valley, NV	1426	43	2200	247
Hope Valley, SR 88	2107	43	2300	329

So, I come back to the tenuous conclusion that an extreme wind event occurred in the Mono Sierra on the same day the Tahoe Sierra stations reported it, but that there are no meteorological measurements of it, and that extreme winds did not occur in elevations below 2350 m or in mountain ranges east of the Sierra Nevada. Accepting that, however, and also allowing freeze-thaw and freezing rain as pre-conditioning factors, does not explain why broken stems were only first-year branches, rather than longer branches including older stem nodes. Pre-conditioning by the long California drought (2012-2015) seems unlikely as drought stress would more likely affect older needles than current-year ones. That effect was observed in giant sequoia (*Sequoiadendron giganteum*) where branch death and senescence occurred in 2014 in the oldest foliage (Stephenson et al. 2017).

Green fall foliage can be damaged, as any gardener knows, by hard early frosts. Serendipitously two periods of extended frosts occurred in the central eastern Sierra in late summer (September) and early autumn (October), 2017. Less than one week after the first event, I started to observe needle death of first year branchettes on high-elevation lodgepole and whitebark pines (Fig. 10). This lead me to think that late summer/early autumn frosts not severe enough to kill foliage might weaken first year branchettes as they proceed into winter, making them vulnerable to subsequent storm events. Indeed the September and October 2016 Virginia Ridge SNOTEL records do show freezing events, although not lasting more than one day. These multiple pre-conditioning events, if indeed they were involved, suggest the complexity of an ultimate event, such as an unusual branch drop.

One last question leads full-circle back to the lower elevation branchette drop along US 395 that I wrote about in the spring 2017 issue of *Mountain Views Chronicle*. I can only conclude that similar pre-conditioning events might have affected those pines, and that in place of a high-elevation extreme natural wind event, the artificially induced wind from snow-blower equipment had the same effect.

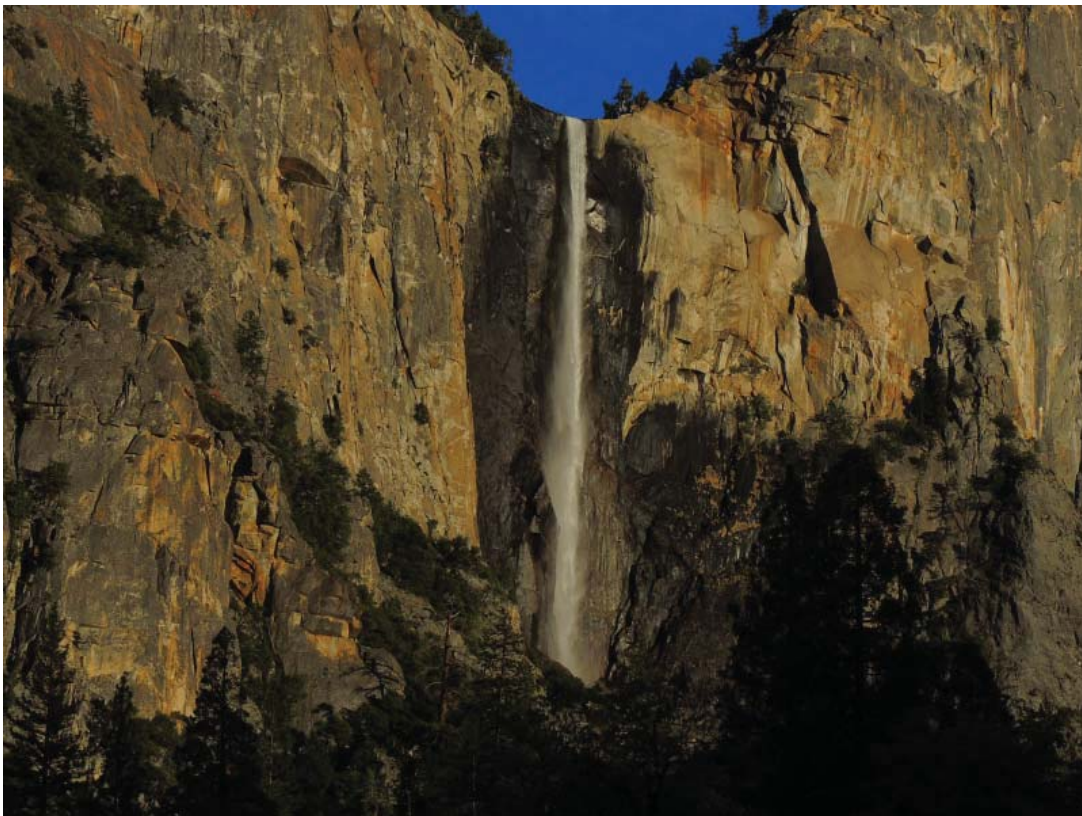
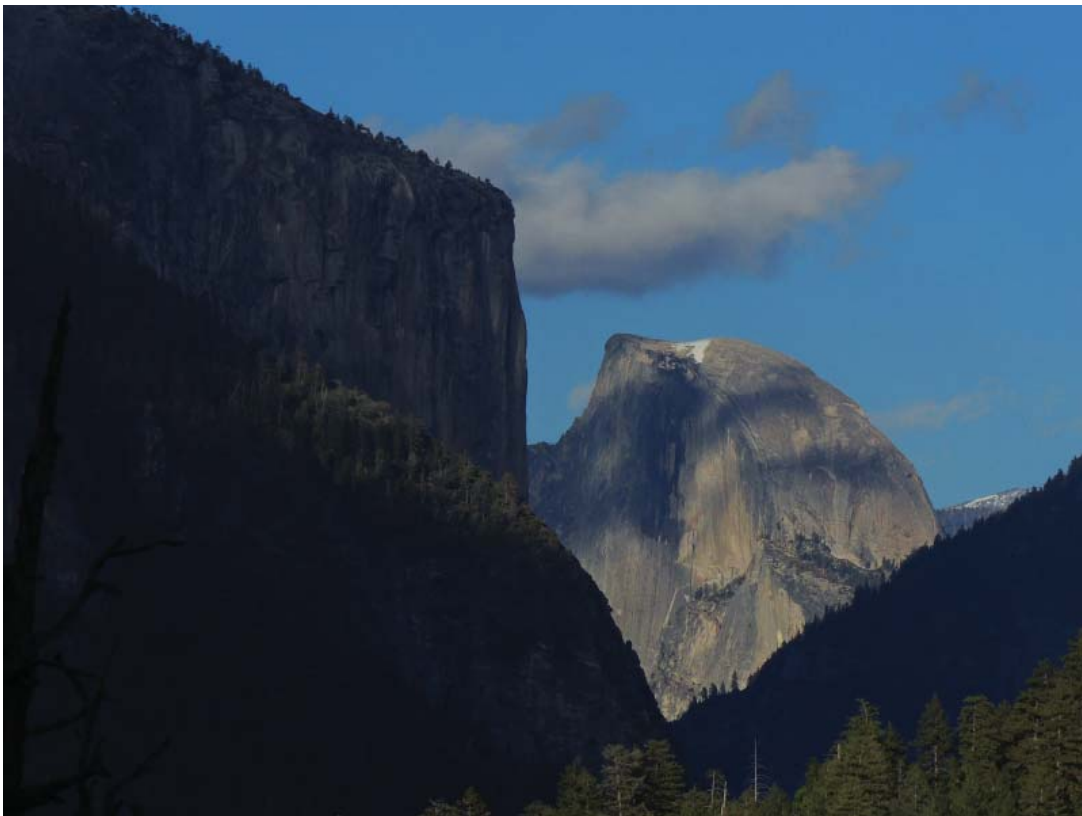
The jury is out, and many of you will have far more meteorological insights and perhaps ecological experience to explain or modify what I propose. I welcome your comments and suggestions!

References

- California Extremes Committee (M. Anderson, A. Blair, K. Gleason, E. Kurth, D. McEvoy, C. Shoemaker). 2017. Draft Proposed California Record Wind Gust. 14 pages. Available from E. Kurth, NWS, Sacramento.
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Figure 10. Needle death on first year branches of lodgepole pine one week after a hard frost in mid-September 2017



Half Dome. and Yosemite Falls
Kelly Redmond

CONTRIBUTING ARTISTS

Bob Coats is a research hydrologist and Principal of Hydroikos Ltd. in Berkeley, CA. Bob has been studying climatic, hydrologic, and ecological processes in the Lake Tahoe Basin—and writing poetry—for more than 40 years. His poems have appeared in *Orion*, *Zone 3*, *Windfall*, *The Acorn*, and the *Pudding House* anthology, *Fresh Water: Poems from the Rivers, Lakes and Streams*, *Harsh Green World*. He has generously shared his works previously with the CIRMOUNT community in *Mountain Views Chronicle*. Bob wrote "Cloud Watching" (in *Harsh Green World*, Sugartown Publishing) in 2011; the cloud-watching day with his geologist father dates to the summer of 1960 in the Bull Run Mountains of northern Nevada.

John King is founder and director of Lone Pine Research (LPR), Bozeman, MT, which he established in 2000 to provide expertise in dendrochronology (tree-ring research). LPR's primary mission is to provide clients with scientific information to support decisions in forest and ecosystem science and resource management. John has 20 years of experience as a dendrochronologist, including five years at the legendary Laboratory of Tree-Ring Research at the University of Arizona

in Tucson. As an expert craftsman as well, John often finds unusual—sometimes comic—patterns in the wood he prepares. Find more about John's work at: www.ringwidth.com.

Harriet Smith has a Ph.D. in experimental ecology, which led first to her work as a primatologist, studying vocal communication in squirrel monkeys at the National Institutes of Health, and subsequently to a career in clinical psychology, where her experience in primate behavior and ecology gave her a unique perspective. Harriet raised and bred cottontop tamarins in her home for 30 years; in the early years these were the most endangered primate in South America. She contributed over 50 juveniles to cottontop breeding conservation programs. With her vertebrate biologist and pioneering pika ecologist husband, Andrew Smith (University of Arizona), she has traveled mountains of North America and Asia. Retired now, they both spend more time at their cabin of 50 years at June Lake in the Sierra Nevada, CA, where Harriet finds inspiration for her mosaics. Find more pictures on Instagram at "monkeyharriet"; her work will be on sale at the Mono Lake Committee Bookstore starting in spring, 2018.



America pika under Mt Dunderberg

Harriet Smith

MOUNTAIN VISIONS

Cloud Watching

We head up Beaver Creek,
my father with worn rucksack,
aerial photos, rock hammer,
I with knapsack, lunch and canteen.

The trail steepens, slants
through pungent sagebrush,
thickets of mountain mahogany
scree slopes and crags of rhyolite.

At the head of a draw,
sun blaring down
we find a cattle-battered aspen grove,
and settle in the shade

to watch cumulus bloom,
unfolding white petals
toward the sun, promising relief,
only to wilt and vanish.

Lying back in the grass,
we discuss the clouds' progress:
Will this one make it? Look,
it's darker than the others.

Finally a shadow reaches us.
We sip water, shoulder packs,
soon top the ridge,
then down a dry gulch

to Wildhorse Crossing,
tangy sweet smells of alder,
of cottonwood. Find the Jeep
parked in dark willows.

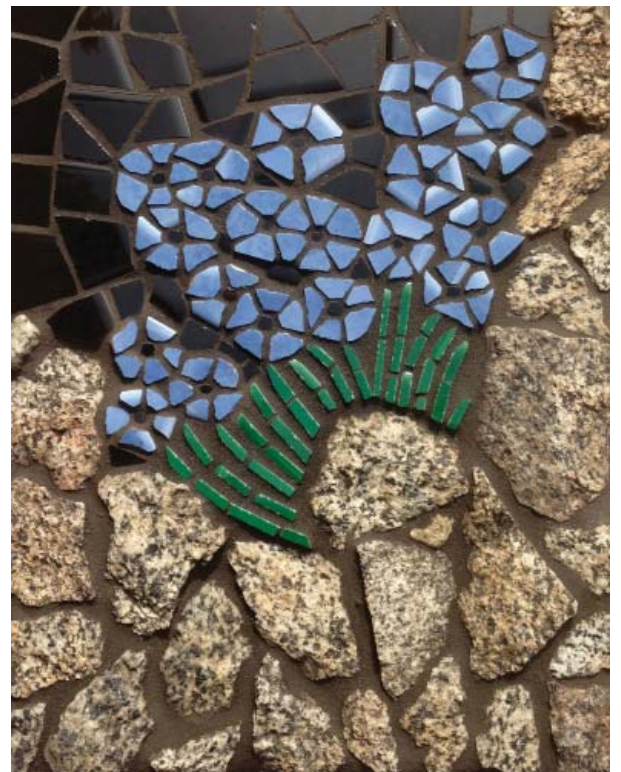
— Robert Coats



Devils Postpile



Lahontan cutthroat trout



Sky pilot in bloom

Mosaics by Harriet Smith



Lundy Canyon Bighorn Sheep
Harriet Smith