

Filling the Data Gaps in Mountain Climate Observatories Through Advanced Technology, Refined Instrument Siting, and a Focus on Gradients

Authors: Strachan, Scotty, Kelsey, Eric P., Brown, Renée F., Dascalu, Sergiu, Harris, Fred, et al.

Source: Mountain Research and Development, 36(4) : 518-527

Published By: International Mountain Society

URL: <https://doi.org/10.1659/MRD-JOURNAL-D-16-00028.1>

BioOne Complete (complete.BioOne.org) is a full-text database of 200 subscribed and open-access titles in the biological, ecological, and environmental sciences published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Complete website, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/terms-of-use.

Usage of BioOne Complete content is strictly limited to personal, educational, and non - commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

Filling the Data Gaps in Mountain Climate Observatories Through Advanced Technology, Refined Instrument Siting, and a Focus on Gradients

Scotty Strachan^{1*}, Eric P. Kelsey^{2,3}, Renée F. Brown⁴, Sergiu Dascalu⁵, Fred Harris⁵, Graham Kent⁶, Bradley Lyles⁷, Gregory McCurdy⁸, David Slater⁶, and Kenneth Smith⁶

* Corresponding author: scotty@dayhike.net

¹ University of Nevada, Reno, Department of Geography, MS154, Reno, NV 89557, USA

² Mount Washington Observatory, 2779 White Mountain Highway, North Conway, NH 03860, USA

³ Plymouth State University, Department of Atmospheric Science and Chemistry, 17 High St. MSC48, Plymouth, NH 03264, USA

⁴ University of New Mexico, Department of Biology, MSC03 2020, Albuquerque, NM 87131, USA

⁵ University of Nevada, Reno, Department of Computer Science and Engineering, MS171, Reno, NV 89557, USA

⁶ University of Nevada, Reno, Nevada Seismological Laboratory, MS 174, Reno, NV 89557, USA

⁷ Desert Research Institute, Division of Hydrologic Sciences, 2215 Raggio Parkway, Reno, NV 89512, USA

⁸ Desert Research Institute, Western Regional Climate Center, 2215 Raggio Parkway, Reno, NV 89512, USA

© 2016 Strachan et al. This open access article is licensed under a Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>). Please credit the authors and the full source.

The mountain research community is still contending with the need to monitor ecosystems, both to improve local management practices and to address regional and global science questions related to the Future Earth themes of Dynamic Planet, Global Sustainable Development, and Transformations Towards Sustainability. How such efforts may be designed and coordinated remains an open question. Historical climate and ecological observatories and networks typically have not represented the scope or spatial and topographic distribution of near-surface processes in mountains, creating knowledge gaps. Grassroots, in situ investigations have revealed the existence of topoclimate that are not linearly related to general atmospheric conditions, and are also not adequately represented in gridded model products. In this paper, we describe how some of the disconnects between data, models, and applications in mountains can be addressed using a combination of gradient monitoring, uniform

observational siting and standards, and modern technology (cyberinfrastructure). Existing observational studies need to expand their topographic niches, and future observatories should be planned to span entire gradients. Use of cyberinfrastructure tools such as digital telemetry and Internet Protocol networks can reduce costs and data gaps while improving data quality control processes and widening audience outreach. Embracing this approach and working toward common sets of comparable measurements should be goals of emerging mountain observatories worldwide.

Keywords: Mountain observatories; ecohydrology; topographic gradients; instrumentation; siting standards; cyberinfrastructure; data networks; model testing.

Reviewed by Editorial Board: June 2016

Accepted: July 2016

Introduction

In this paper, we discuss examples of significant knowledge gaps that are emerging in modern ecohydrological observation in mountain environments, and we highlight opportunities to improve the quality and diversity of data collected as the mountain science community seeks to observe, quantify, and predict impacts of climate and human processes that will affect large proportions of Earth's population. As we will briefly demonstrate, 2 critical factors must be integrated as mountain system science moves forward: (1) comprehensive gradient monitoring and (2) modern

technologies for remote data acquisition and management.

Global perspectives of mountain ecosystems are currently undergoing a transformation, as communities and governments around the world recognize the critical role of upland regions for economies, food supplies, water resources, and biodiversity. While climate changes and disturbances in mountain systems have had impacts on lowland communities throughout human history, the ability to track and manage these impacts has emerged only in relatively recent times. Moreover, it is important to consider the sometimes-fragile nature of mountain social-ecological dynamics, which fall directly within

research themes described by the Future Earth (<http://www.futureearth.org/research-0>) science community. Specifically, anthropogenic resource use outside of the bounds of sustainable development has increased the vulnerability of these dynamic systems to changing climates, resulting in an emerging era of scientific and public interest. Accordingly, fine-scale monitoring of ecohydrological processes tied to mountain ecosystem services should be designed to inform and guide transformations toward sustainability (Kräuchi et al 2000; Diaz et al 2003; Viviroli and Weingartner 2004). Clearly, planning and managing for the future requires the best possible scientific data and multidisciplinary integration (Reid et al 2010); however, the research community as a whole is still grappling with exactly how to approach mountain ecosystems with these larger agendas in mind (Grabherr et al 2005; Knapp et al 2012; Williams 2014).

Technological advances have facilitated the acquisition of new environmental data in quantities not previously feasible (Hart and Martinez 2006; Krause et al 2015). Examples of these new modalities are visible at coordinated-funding scales (Schimel et al 2007; Chorover et al 2012; Collins and Childers 2014), as well as grassroots-level networking (Baldocchi et al 2001; Richardson et al 2007; Weathers et al 2013; Vanderbilt et al 2015). These recent improvements provide a window into the power of big data, but basic monitoring study design remains the crux in increasing our understanding of the breadth of potential mountain ecosystem services. Traditionally, monitoring objectives have been narrowly focused (eg to improve hazard management, forecast seasonal resources, or investigate specific ecosystem processes), but the same data are later leveraged for regional and global questions of scientific interest (eg elevation-dependent warming, biogeographic dynamics, and cryosphere mass balance), creating mismatches of study design and application that can cause unexpected or even undetected bias in scientific conclusions (eg Dai et al 2006; Daly 2006; Oyler et al 2015).

With these challenges in mind, we present a general approach to future monitoring of mountain systems that draws from specific examples of shortcomings in existing datasets and methodologies. These examples are largely drawn from mountains in North America, but the conceptual problems and their remedies do not recognize geographic borders. Indeed, similar themes were raised in a recent review of global thermal shifts at high elevations by the Mountain Research Initiative Elevation-Dependent Warming Working Group (2015).

Knowledge gaps and their sources

Skewed spatial/topographic distribution of observation stations

Over recent decades, use of remote sensing and gridded model products for ecology, hydrology, and climate science has exploded, while at the same time there has

been a worldwide decline in the number of ground-based observation stations (Beniston et al 1997; Laternser and Schneebeli 2003; Mitchell and Jones 2005; Lawrimore et al 2011; Yatagai et al 2012). This is a serious problem, because in situ observations are the primary method to reliably verify the accuracy of remote sensing (from terrestrial, aerial, and satellite sources), as well as to calibrate and validate models of near-surface physical processes. The literature indicates that distribution of ground-based stations is highly biased toward lower elevations, providing inadequate representation of mountain geography resulting in increased model error (Hasenauer et al 2003; Pepin and Seidel 2005; Bales et al 2006; Stahl et al 2006). Given these facts, we suggest that funding agencies should aim to increase monitoring station density, especially in mountain ecosystems, rather than accept reductions.

There have been some recent efforts to address this issue, but not necessarily in ways that will help mountain science. In the United States, for example, significant investment has been made in the National Ecological Observatory Network (NEON), a continental-scale observation network with the goal of providing, among other deliverables, ground-based observations to constrain climate-ecological models (Schimel et al 2007). NEON was designed with a sparse distribution of core fixed long-term observation platforms supplemented by temporary, relocatable platforms. However, the spatial representation of ecoregions by the core sites is extremely poor in the US intermountain west (Keller et al 2008). As the mountain community advocates for additional ground-based observations, we need to make certain that the observational design addresses the needs of local populations, the priorities of regional-scale science, and crucial gaps in our understanding of mountain processes and their contributions to sustainable development.

Topoclimatic diversity: capturing processes

Climate impacts at the organism scale are not linear functions of elevational or regional trends, but are instead determined by interactions between topographic position, air mass exposure, vegetation cover, soil types, and a host of other abiotic factors (Kimball and Weihrauch 2000; Dobrowski 2011; Scherrer and Körner 2011; Graae et al 2012; Lenoir et al 2013; Millar et al 2014; Kelsey and Murray 2016). The resulting “topoclimates” and “microclimates” are real phenomena that drive species and community distributions across complex terrain in ways that are both responsive and resistant to climatic variability.

The discovery and description of these nonlinear relationships is relevant to the assessment of biological risk as well as seasonal hydrological processes (Weiss et al 1993; Wigmosta et al 1994; Diodato 2005; Lookingbill and Urban 2005; Van De Ven et al 2007; Daly et al 2010;

Krause et al 2015). Primary evidence of topographically driven decoupling of microclimate from regional trends has not come from established networks of climate stations or model predictions, but rather from in situ observations at finer scales. For example, a wireless sensor network deployed in central New Mexico, USA, monitored microclimate variations under native shrub canopies, which are important “islands of fertility” in arid environments, providing surprising implications for species abundance and diversity in desert ecosystems (Collins et al 2006). The microclimates associated with shrub canopy provided a buffer from heat and therefore delayed timing of aridity compared to canopy interspaces. Small-scale climatic decoupling is equally important at the other end of the elevation gradient, at the upper treeline (Körner 2012). Because a single monitoring point on a mountain landscape does not adequately capture variability across spatial and temporal scales, effective approaches will incorporate observations across gradients such as elevation, slope, prominence, vegetation, soil type, and radiative exposure.

Disconnects between data, models, and applications

To compound the problem, gridded climate products in mountainous regions often disagree with one another at ecologically and hydrologically relevant scales (Hijmans et al 2005; Yatagai et al 2005; Stahl et al 2006; Daly et al 2008; Minder et al 2010). Several key issues associated with source observations amplify methodological differences between gridded models.

Issue 1: Bias caused by siting disparity in ground observations is a recognized but generally unaddressed issue. National observation networks in the United States have traditionally been designed for a single purpose, usually by government agencies with a specific mission. Examples of these instrumented networks include the National Weather Service Cooperative Observer Program the U.S. Geological Survey National Streamflow Information Program, and the U.S. Natural Resources Conservation Service Snow Telemetry (NRCS 2015). Moreover, geographic location of sites within these networks is often determined by a combination of agency objectives and convenience. For example, weather service data were historically generated by observers in or near populated regions in order to assess daily to yearly conditions in places where people live and work. Snow Telemetry (SNOTEL) sites are specifically located to monitor snowpack conditions using logistically intense installations (Schaefer and Paetzold 2001), which means that stations are located in catchment zones accessible by vehicle during the summertime. These types of locations were not meant to represent the majority of mountain landscapes (Figure 1), can be poor estimators of primary climatic variables in complex terrain, and should not be treated as all-purpose monitors (Bales et al 2006; Lenoir et

al 2013). Trends measured on summits or within valleys do not necessarily represent what is happening on the slopes.

Issue 2: Lack of robust ground-truthing mechanisms for interpolated models and remote sensing remains a problem in mountain terrain. Historically, a lower density of ground stations in mountainous regions (Yatagai et al 2005; Daly 2006) means that gridded product accuracy cannot be independently verified across complex topography in a given region. In addition, ground station networks typically monitor limited variable sets and often do not have sensors installed to measure the same variable that models or remote sensing products are estimating. For example, remotely sensed land surface temperature is a skin temperature parameter that can vary tremendously by substrate and vegetation cover and thus can be difficult to reconcile with actual air temperature in mountains, even after trying to account for other sources of error (Wan 2008; Li Z et al 2013; Mutiibwa et al 2015). Indeed, error assessment of fine-scale gridded products in many topographic settings remains largely unexplored.

Issue 3: Comparability between ground-based datasets is a significant unsolved challenge for mountain climate monitoring. Specifically, the lack of convention in siting, sensor deployments, and post-processing hampers regional and global comparison of data. Although there are basic standards for weather station sensor deployments (WMO 2008), these are often seen as guidelines for individual network and application design and are most easily applied in open and flat terrain. Cooperative weather station networks (eg the National Weather Service Cooperative Observer Program), for example, can differ at some critical point, such as the precise time of daily observations, which complicates use of the data for comparative purposes (Karl et al 1986). Basic conventions are inherently difficult to apply in mountainous regions due to steep topographies and severe climatic conditions. Observations influenced by snow can be logistically difficult, such as maintaining uniform-height measurements during changing snowpack conditions. Measurement of precipitation in mountain environments remains especially challenging, particularly when snow or mixed-phase regimes dominate (Marks et al 1992; Peck 1997; Lundquist et al 2008; Rasmussen et al 2012; Marks et al 2013; Dai et al 2014). Mixed climate-ecological observation standards in mountains are even less developed, but emerging networks are developing highly standardized monitoring protocols, such as the international Global Observation Research Initiative in Alpine Environments (GLORIA) program, which measures alpine vegetation response to climate on mountain summits worldwide (Grabherr et al 2000). Methodological uniformity should also be extended to standards in data structure and format, which remains a universal problem in the biological and environmental

FIGURE 1 Only 1 Snow Telemetry station is present in Nevada's Snake mountain range (39°N 114°W; NRCS 2015), a zone containing the state's second-highest conifer diversity (Charlet 1996). This site (left) is located at 3060 m at the center of a heavily vegetated drainage. Atmospheric observations made here (such as daily maximum and minimum temperature) are unlikely to be representative of the vast majority of locations in the mountain range, which possesses numerous open woodland slopes and exposed topography both below and above the treeline (right). (Photos by Scotty Strachan)



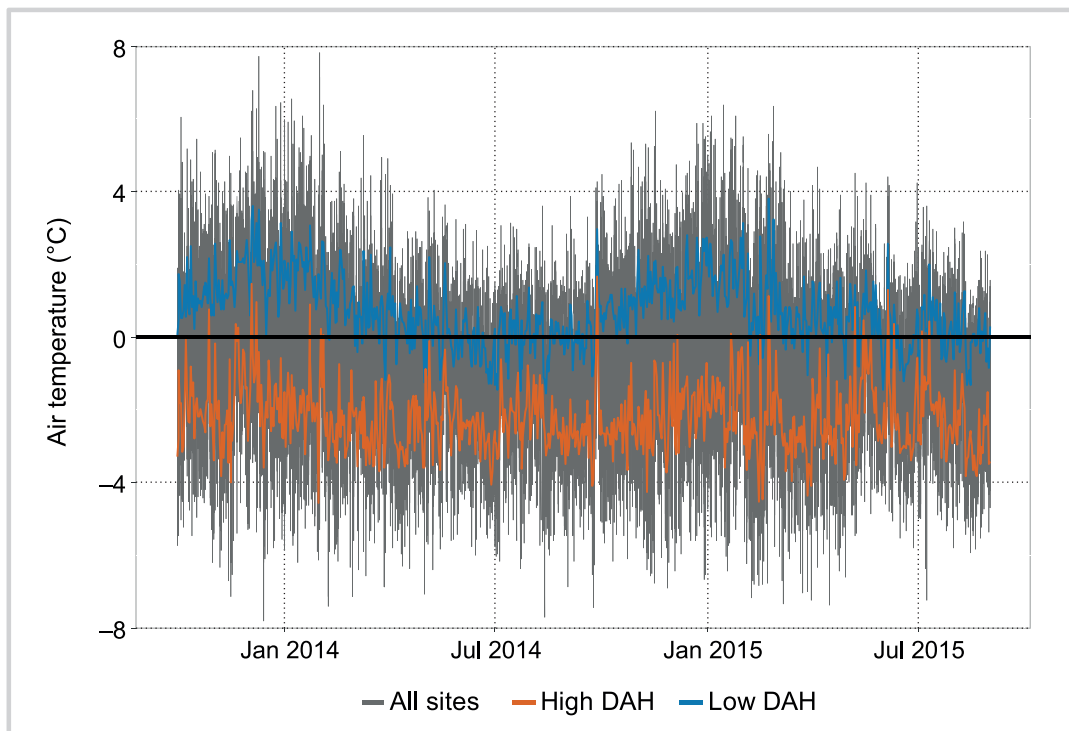
sciences (Tenopir et al 2011; Michener et al 2012; ESIP Envirosensing Cluster 2016).

Issue 4: Long-term ground-based climatic records are notorious for their large gaps and intermittent records, which can be difficult to fill if the spatial density of stations is low (Peck 1997; Jeffrey et al 2001; Mitchell and Jones 2005). While historic human-based observations struggle with continuity of person and place, automated platforms located in challenging environments often have major issues with missing data due to equipment failures and associated problems. Contributing factors include inadequate systems design, poor-quality installations, and lack of regular human access (ESIP Envirosensing Cluster 2016). Moreover, instrumented mountain observatories are frequently not provided a means of remote access via radio telemetry, meaning that issues with sensors and power systems are not recognized until a periodic site visit—or even worse, until post-processing and analysis of the data. Thus, records from mountain observatories are

much more likely to be incomplete or of poor quality, making scientific interpretation and meta-analysis challenging or even erroneous (Latenser and Schneebeil 2002; Stewart 2009).

These issues highlight key disconnects between actual observation methods and scientific application of data. There exist clear disparities between monitoring records and ground-truthing requirements. Because observation networks are typically mission-specific (and often grassroots) efforts, they are rarely set up with regional or global analysis in mind; yet they are often leveraged for this purpose, regardless of accuracy or representation issues. Refining our ecohydrological models of mountain ecosystems at both local and global scales is seen as a community priority, and the problems outlined above represent opportunities for improvement and direction. Fortunately, we can partially address these shortcomings by using technology to improve the representation of gradients.

FIGURE 2 Cluster analysis of PRISM temperature model errors at each woodland study site revealed 2 distinct groups that were correlated to spatio-topographic variables. The most significant topographic variable ($r^2 = 0.8$, $p < 0.001$) for daily maximum temperature (T_{max}) error was the Diurnal Anisotropic Heating (DAH) Index, as calculated using a 10 m digital elevation model in the software package SAGA-GIS (Böhner and Selige 2006). Groups were separated by low-DAH and high-DAH values, effectively northeastern and southwestern aspects, respectively. PRISM consistently underestimates T_{max} for high-DAH sites and overestimates at low-DAH sites during wintertime (Strachan et al 2015) as shown in this error plot (model - observations).



Opportunities

Stepping outside our topographic niche

Expanding study designs to include observations across a range of topographic, vegetation, and elevation gradients enables ground-truthing and improvement of distributed landscape process models (Lookingbill and Urban 2003; Anderson-Teixeira et al 2011; Li X et al 2013; Krofcheck et al 2014; Vitale 2015; Holden et al 2015). Moreover, gradient observations can provide more comprehensive data sets to address a wider range of science questions, as well as better inform socio-ecological considerations and management practices. Designing our studies to facilitate primary science inquiries as well as broader uses (eg in meta-analyses, management practices, and socio-ecological applications) will go a long way in making grassroots mountain science as multidisciplinary and crucial to Future Earth themes as possible.

An example of a study design with multiple applications across topographic gradients is an ongoing effort in the Walker River watershed in the western Great Basin, USA (38°N; 119°W). Paleoclimatology records from tree rings are sampled from opposite-aspect slopes to investigate seasonal changes in climatic inputs over the last 1000 years (Strachan et al 2013). In order to calibrate gridded climate models used for reconstructions, temperature and snow presence microloggers were placed on 16 mountain woodland study sites, above cold-air pools and below ridgetops. Comparison of these temperature

data with the widely used Parameter-elevation Regression on Independent Slopes Model (PRISM) gridded temperature model (Daly et al 2008) indicates that specific topographic exposures are subject to different modes of error in the model (Figure 2). Thus, hydroclimate studies in the region that leverage PRISM or similar gridded products as inputs to water-balance models (eg Hatchett et al 2015) can be improved upon with this new information.

Uniformity and standards for siting

Regionally representative observations for different climate variables in mountains are ideally not all taken in the same geographic location. In order to monitor precipitation, for example, instruments need to be placed in zones with lower wind speeds and decreased wind shear so that rain and snow can fall more directly into gauge openings. Thus, gauges are typically located in topographically protected sites in forested valleys or depressions. However, air temperature, humidity, and wind can vary significantly between sheltered and exposed sites, rendering atmospheric data from protected sites unrepresentative of general conditions.

As an example, a 10–20 m high forest canopy shelters lower meteorological stations along the access road gradient up Mount Washington, New Hampshire, USA (44°N; 71°W), which can lead to a multiple-hour lag in air mass replacement after passage of a weather front, compared to the near-instantaneous air mass replacement

at fully exposed stations above the treeline. This lag can generate elevation-correlated temperature gradients that can be unrepresentative of much of the mountain (in some cases too stable, and in other cases unstable and even auto-convective). Similar outcomes are seen when large differences in local insolation occur (Dorfman et al 2016).

Ideally, siting conditions would be kept as uniform as possible across individual mountain gradients, in order to make comparative results robust. Future instrumentation and network design needs to be guided by specific, widely accepted protocols that account for differences in site environments that are not addressed by the World Meteorological Organization ideal. Slope, aspect, soil type, vegetation type and stature, and wind and sun exposure impact microclimate and must be considered when comparing multiple sites within and across networks. Montane environment instrumentation siting and data publishing standards and requirements should include a comprehensive list of metadata variables to facilitate researchers' understanding of the environmental complexities of each site when comparing multiple sites.

In addition, because the future of mountain systems science involves processes that are not necessarily captured by observations from conventional meteorological stations, it is crucial that other factors such as soil biogeochemical properties, temperature and moisture profiles, and other watershed catchment parameters, for example, are included in ways that are comparable across sites and regions. Development of a standardized mountain-specific set of near-surface observatory protocols is a crucial step for the community to take as a whole, and efforts in this direction are being undertaken within the grass-roots Global Network of Mountain Observatories (GNOMO).

Applying technology for efficacy

Technology is a key player in the transformation of mountain science. A plethora of electronic sensor applications that change the scale and number of observations can be made within a given study area. The range of costs per sensor deployment varies widely as well, and perhaps the most effective approach is to mix a few high-cost, high-quality automated measurements with a number of low-cost, distributable sensors (which was the case in the PRISM example above).

For very-long-term mountain observatory systems, the ability to set up real-time or near-real-time telemetry of data is crucial for maintaining data quality and minimizing gaps in the record. The most effective of these technologies utilize the standard bi-directional Transmission Control Protocol/Internet Protocol (TCP/IP). The reasons for this are many, notably that TCP/IP is inherently error correcting, eliminating data corruption during transmission. Moreover, the use of TCP/IP

technologies allows (1) efficient transfer of data offsite for redundancy, (2) immediate detection and remote troubleshooting of equipment-related failures, (3) remote device configuration and control, and (4) connection of any number of TCP/IP-enabled devices to a network (Gubbi et al 2013). In particular, the use of TCP/IP cameras is gaining traction not only to visually monitor climatic conditions, but also to track biodiversity (eg species occurrence and population size and vegetation phenology; Richardson et al 2007). Because TCP/IP networking is such a prolific technology, many options are available for extending this telemetry via satellite or 100+ km terrestrial wireless connections (ESIP Envirosensing Cluster 2016).

The long-term costs of maintaining remote observatory systems can be mitigated by the use of digital networking technologies. Because technician time and associated travel expenses are the most costly part of maintaining a field-based infrastructure, the ability to diagnose problems remotely and plan site visits accordingly is important from a budgetary perspective (ESIP Envirosensing Cluster 2016). Remote control of field devices such as cameras, heater units, relay panels, and dataloggers can allow scientists or technicians to manage equipment operation during adverse environmental conditions when physical access would be expensive. Furthermore, automated image capture from field-based TCP/IP cameras can assist in remote inspection and sensor data quality assurance and quality control (QA/QC), as in the systems part of the Nevada Climate-ecohydrological Assessment Network (NevCAN; Mensing et al 2013; Figure 3). Sensor and camera data captured in real-time within an IP environment are easily shared across database platforms and the Internet and thus possess the potential to “go viral” in the digital media sense, which would exponentially increase public awareness of the science.

Because of this, a significant byproduct of using technology and telemetry in mountain science is the potential for outreach and education. By allowing remote interaction and making real-time data accessible to the general public, researchers improve their ability to communicate science and attract support from unanticipated sources. For example, the Nevada Seismological Laboratory has built a TCP/IP “all hazards” data network around Lake Tahoe, California, USA (39°N; 120°W), which is currently feeding earthquake, wildfire, and weather data to scientists in Nevada and California as well as to public stakeholders and firefighting agencies. Live video (including near-infrared nighttime wildfire observations) as well as real-time weather data from various mountain observatory stations are transmitted via the Nevada Seismological Laboratory network. This effort is a sustainable model for diverse multihazard data sources, attracting support and buy-in from multiple agencies and institutions (Smith et al in press).

FIGURE 3 Using a webcam as part of an environmental sensor deployment (top) allows the operator to capture images that assist data quality control. In this case, hourly images can show if precipitation is in solid form (middle), which is not usually captured properly by instruments such as a liquid tipping bucket gauge (bottom). (Photos by Scotty Strachan/NevCAN automated systems)



Integrating a cyberinfrastructure into observatory planning is essential, as expertise in digital data communications, management, and processing has become a crucial part of multidisciplinary science (Atkins 2003; McMahon et al 2011; Michener et al 2012). Cyberinfrastructure for field science requires individuals with technological skill sets that include datalogger programming, digital network management, wireless-microwave communications, database administration, application development, and data quality assurance and quality control. Ideally, the workflow for acquiring, managing, processing, and tracking environmental data

from a modern observatory should be a seamless integration of software and domain experts, but implementation of such a system in mountain observatories remains a challenge (Jones et al 2015; ESIP Envirosensing Cluster 2016). Demand is high in the global private sector for these fields of expertise, so recruiting and retaining talented cyberinfrastructure personnel is daunting. Developing environmental cyberinfrastructure training programs at universities and/or in collaboration with technology companies is one way to grow this labor force. Centralizing this effort within the mountain science community is a goal that should be considered, and there is a clear need for a dedicated technology and cyberinfrastructure support mechanism or institution that could act globally to assist researchers in implementing these tools.

Onward and upward

By moving forward with a consistent and reasonably uniform monitoring agenda for mountain ecosystems, the scientific community has the opportunity to address knowledge gaps by improving existing systems, extending existing networks, and/or establishing new ones. We should do so with gradients, uniformity in siting and standards, and long-lifetime technologies as central themes. Development of truly effective process models that address multiple societal needs and are relevant at multiple scales will occur through an evolutionary process of knowledge-based testing, evaluation, and improvement of interpolative techniques (Daly et al 2002; Hijmans et al 2005; Holden et al 2015), and these themes are an excellent basis from which to proceed.

Large-scale environmental observatory networks such as the Critical Zone Observatory (CZO), NEON, and the Long-Term Ecological Research (LTER) program include sites with significant topographic diversity, but do not necessarily monitor entire mountain gradients with socio-ecological objectives in mind. While it is true that data from these programs can be leveraged across temporal and spatial scales for local societal benefits and global-scale meta-analyses, issues of instrument siting and topographic representation are likely to persist because of network-specific and administrative objectives. Mountain observatories are being initialized that embrace a wider application scope, recognizing the need to monitor gradient processes for the benefit of both mountain communities and dependent lowland zones. Examples of these networks, such as the Innovative Urban Transitions and Aridregion Hydro-sustainability (iUTAH) project, the Nevada Climate-ecohydrological Assessment Network (NevCAN), and the Sevilleta Ecological Observatory Network (SEON), are doing so by leveraging digital technologies and cyberinfrastructure systems (Anderson-Teixeira et al 2011; McMahon et al 2011; Burt et al 2015; Jones et al 2015; Reale et al 2015; Sherson et al 2015; Dahm

et al 2015). Technological and logistical lessons learned in the course of these projects could be applied and expanded within emerging efforts such as GNOMO.

To pursue this agenda across a global network of mountain observatories, there is a need for close-knit research teams to expand study designs and create commonality among regional efforts. Data collection objectives within disciplines that incorporate gradients and topographic diversity should be outlined. Working groups (ideally in the form of well-funded and -organized teams) need to emerge to apply expert knowledge and continuity of methods and technologies to the task of adapting current ecohydrological sensory systems and

data practices to the major challenge of mountain environments. The mountain community should continue to make clear its major role within international research and sustainability movements (such as Future Earth), based on a united approach of comparable observations that drive and refine scientific hypotheses as well as contribute to immediate local management needs. By adding observations across gradients and diverse topographies (enabled and supported by digital data technologies), mountain researchers can combine efforts to improve our scientific impact at local, regional, and global scales.

ACKNOWLEDGMENTS

The authors are grateful for their home institutions' support of research in mountains, as well as collaborative workshops organized by the tireless Dr. Greg Greenwood at the Mountain Research Initiative (MRI) and Drs. Corinna Gries and Don Henshaw with the Federation of Earth Science Information Partners (ESIP) EnviroSensing Cluster. The support staffs of the Nevada Research Data Center, Nevada Seismological Laboratory, Mount Washington Observatory, Western Regional Climate Center, Sevilleita Long-Term Ecological Research Program, and the Nevada Climate-ecohydrological Assessment Network also deserve thanks for their continued efforts in making possible new directions in monitoring our mountains. We also thank Dr.

Constance Millar for reviewing an early draft of this paper and for her enthusiastic support and encouragement of all involved in the realm of mountain science. We also recognize the contributions of 2 anonymous reviewers and the MRD external editor who engaged our topic with enthusiasm and helped refine some of our points and objectives. This article was financially supported by the National Science Foundation through a Geography and Spatial Sciences grant (1230329) and the Nevada-National Science Foundation Experimental Program to Stimulate Competitive Research (grant IIA-131726), as well as the College of Science Dean's Office at the University of Nevada, Reno.

REFERENCES

- Anderson-Teixeira KJ, Delong JP, Fox AM, Brese DA, Litvak ME.** 2011. Differential responses of production and respiration to temperature and moisture drive the carbon balance across a climatic gradient in New Mexico. *Global Change Biology* 17(1):410–424.
- Atkins DE.** 2003. *Revolutionizing Science and Engineering Through Cyberinfrastructure: Report of the National Science Foundation Blue-Ribbon Advisory Panel on Cyberinfrastructure 2003-01.* <https://www.nsf.gov/cise/sci/reports/atkins.pdf>; accessed on 1 January 2016.
- Baldocchi D, Falge E, Gu L, Olson R, Hollinger D, Running S, Anthoni P, Bernhofer C, Davis K, Evans R, Fuentes J.** 2001. FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. *Bulletin of the American Meteorological Society* 82(11):2415–2434.
- Bales RC, Molotch NP, Painter TH, Dettinger MD, Rice R, Dozier J.** 2006. Mountain hydrology of the western United States. *Water Resources Research* 42(8):1–13.
- Beniston M, Diaz HF, Bradley RS.** 1997. Climatic change at high elevation sites: An overview. *Climatic Change* 36:233–251.
- Böhner J, Selige T.** 2006. Spatial prediction of soil attributes using terrain analysis and climate regionalisation. In: Böhner J, McCloy KR, Strobl J, editors. *SAGA—Analyses and Modelling Applications* (Göttinger Geographische Abhandlungen, Vol. 115). Göttingen, Germany: Verlag Erich Goltze, pp 13–28.
- Burt TP, Howden NJK, McDonnell JJ, Jones JA, Hancock GR.** 2015. Seeing the climate through the trees: Observing climate and forestry impacts on streamflow using a 60-year record. *Hydrological Processes* 29:473–480.
- Charlet DA.** 1996. *Atlas of Nevada Conifers: A Phytogeographic Reference.* Reno, NV: University of Nevada Press.
- Chorover J, Scatena FN, White T, Anderson S, Aufdenkampe AK, Bales RC, Brantley SL, Tucker G.** 2012. *Common Critical Zone Observatory (CZO) Infrastructure and Measurements.* A Guide Prepared by CZO Pls. https://criticalzone.org/images/national/associated-files/1National/CZO-specific_Infrastructure_Draft_V7_forWeb.pdf; accessed on 5 January 2016.
- Collins SL, Bettencourt LM, Hagberg A, Brown RF, Moore DI, Bonito G, Delin KA, Jackson SP, Johnson DW, Burleigh SC, Woodrow RR, McAuley JM.** 2006. New opportunities in ecological sensing using wireless sensor networks. *Frontiers in Ecology and the Environment* 4(8):402–407.
- Collins SL, Childers DL.** 2014. Long-term ecological research and network-level science. *Eos, Transactions of the American Geophysical Union* 95:293–294.
- Dahm CN, Candelaria-Ley RI, Reale CS, Reale JK, Van Horn DJ.** 2015. Extreme water quality degradation following a catastrophic forest fire. *Freshwater Biology* 60:2584–2599.
- Dai A, Karl TR, Sun BM, Trenberth KE.** 2006. Recent trends in cloudiness over the United States—A tale of monitoring inadequacies. *Bulletin of the American Meteorological Society* 87:597–606.
- Dai J, Manton MJ, Siems ST, Ebert EE.** 2014. Estimation of daily winter precipitation in the Snowy Mountains of southeastern Australia. *Journal of Hydrometeorology* 15:909–921.
- Daly C.** 2006. Guidelines for assessing the suitability of spatial climate data sets. *International Journal of Climatology* 26:707–721.
- Daly C, Conklin DR, Unsworth MH.** 2010. Local atmospheric decoupling in complex topography alters climate change impacts. *International Journal of Climatology* 30:1857–1864.
- Daly C, Gibson WP, Taylor GH, Johnson GL, Pasteris P.** 2002. A knowledge-based approach to the statistical mapping of climate. *Climate Research* 22:99–113.
- Daly C, Halbleib M, Smith JI, Gibson WP, Doggett MK, Taylor GH, Curtis J, Pasteris PP.** 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology* 28:2031–2064.
- Diaz HF, Grosjean M, Graumlich LJ.** 2003. Climate variability and change in high elevation regions: Past, present and future. *Climatic Change* 59:1–4.
- Diodato N.** 2005. The influence of topographic co-variables on the spatial variability of precipitation over small regions of complex terrain. *International Journal of Climatology* 25:351–363.
- Dobrowski SZ.** 2011. A climatic basis for microrefugia: The influence of terrain on climate. *Global Change Biology* 17:1022–1035.
- Dorfman M, O'Brian K, Kelsey E.** 2016. Procedures and advances in Mount Washington Observatory's mountainous mesonet sites. In: *Proceedings of the 96th American Meteorological Society Annual Meeting*, New Orleans, LA.
- ESIP [Earth Science Information Partners] EnviroSensing Cluster.** 2016. *Community Wiki Document on Best Practices for Sensor Networks and Sensor Data Management.* Federation of Earth Science Information Partners, USA. <http://wiki.esipfed.org/index.php/Introduction>; accessed on 5 January 2016.
- Graae BJ, De Frenne P, Kolb A, Brunet J, Chabrierie O, Verheyen K, Pepin N, Heinken T, Zobel M, Shevtsova A, Nijls I, Milbau A.** 2012. On the use of weather data in ecological studies along altitudinal and latitudinal gradients. *Oikos* 121:3–19.

- Grabherr G, Gottfried M, Pauli H.** 2000. GLORIA: A global observation research initiative in alpine environments. *Mountain Research and Development* 20:190–191.
- Grabherr G, Gurung AB, Dedieu J, Haeberli W, Lotter AF, Nagy L, Pauli H, Psenner R.** 2005. Long-term environmental observations in mountain biosphere reserves: Recommendations from the EU GLOCHAMORE project. *Mountain Research and Development* 25:376–382.
- Gubbi J, Buyya R, Marusic S, Palaniswami M.** 2013. Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems* 29:1645–1660.
- Hart JK, Martinez K.** 2006. Environmental sensor networks: A revolution in the earth system science? *Earth-Science Reviews* 78:177–191.
- Hasenauer H, Merganicova K, Petritsch R, Pietsch SA, Thornton PE.** 2003. Validating daily climate interpolations over complex terrain in Austria. *Agricultural and Forest Meteorology* 119:87–107.
- Hatchett BJ, Boyle DP, Putnam AE, Bassett SD.** 2015. Placing the 2012–2015 California-Nevada drought into a paleoclimatic context: Insights from Walker Lake, California-Nevada, USA. *Geophysical Research Letters* 42:8632–8640.
- Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A.** 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25:1965–1978.
- Holden ZA, Swanson A, Klene AE, Abatzoglou JT, Dobrowski SZ, Cushman SA, Squires J, Moisen GG, Oyster JW.** 2015. Development of high-resolution (250 m) historical daily gridded air temperature data using reanalysis and distributed sensor networks for the US Northern Rocky Mountains. *International Journal of Climatology*, Early View, 5 January 2016. <http://dx.doi.org/10.1002/joc.4580>.
- Jeffrey SJ, Carter JO, Moodie KB, Beswick AR.** 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling and Software* 16:309–330.
- Jones AS, Horsburgh JS, Reeder SL, Ramirez M, Caraballo J.** 2015. A data management and publication workflow for a large-scale, heterogeneous sensor network. *Environmental Monitoring and Assessment* 187:348–367.
- Karl TR, Williams CN Jr, Young PJ, Wendland WM.** 1986. A model to estimate the time of observation bias associated with monthly mean maximum, minimum and mean temperatures for the United States. *Journal of Climate and Applied Meteorology* 25:145–160.
- Keller M, Schimel DS, Hargrove WW, Hoffman FM.** 2008. A continental strategy for the National Ecological Observatory Network. *Frontiers in Ecology and the Environment* 6:282–284.
- Kelsey EP, Murray G.** 2016. Boundary layer exposure and a control on elevation dependent warming. Paper presented at the American Meteorological Society Annual Meeting, New Orleans, LA, 11–14 January.
- Kimball, KD, Weihrauch DM.** 2000. Alpine vegetation communities and the alpine-treeline ecotone boundary in New England as biomonitors for climate change. *USDA Forest Service Proceedings* 3(5):93–101.
- Knapp AK, Smith MD, Hobbie SE, Collins SL, Fahey TJ, Hansen GJA, Landis DA, La Pierre KJ, Melillo JM, Seastedt TR, Shaver GR, Webster JR.** 2012. Past, present, and future roles of long-term experiments in the LTER network. *BioScience* 62(4):377–389.
- Körner C.** 2012. *Alpine Treelines: Functional Ecology of the Global High Elevation Tree Limits*. Basel, Switzerland: Springer.
- Kräuchi N, Brang P, Schönenberger W.** 2000. Forests of mountainous regions: Gaps in knowledge and research needs. *Forest Ecology and Management* 132:73–82.
- Krause S, Lewandowski J, Dahm CN, Tockner K.** 2015. Frontiers in real-time ecohydrology—A paradigm shift in understanding complex environmental systems. *Ecohydrology* 8:529–537.
- Krofcheck DJ, Eitel JUH, Vierling LA, Schulthess U, Hilton TM, Dettweiler-Robinson E, Pendleton R, Litvak ME.** 2014. Detecting mortality induced structural and functional changes in a piñon-juniper woodland using Landsat and RapidEye time series. *Remote Sensing of Environment* 151:102–113.
- Latenser M, Schneebeli M.** 2002. Temporal trend and spatial distribution of avalanche activity during the last 50 years in Switzerland. *Natural Hazards* 27:201–230.
- Latenser M, Schneebeli M.** 2003. Long-term snow climate trends of the Swiss Alps (1931–99). *International Journal of Climatology* 23:733–750.
- Lawrimore JH, Menne MJ, Gleason BE, Williams CN, Wuertz DB, Vose RS, Rennie J.** 2011. An overview of the Global Historical Climatology Network monthly mean temperature data set, version 3. *Journal of Geophysical Research: Atmospheres* 116:1–18.
- Lenoir J, Graae BJ, Aarrestad PA, Alsos IG, Armbruster WS, Austrheim G, Bergendorff C, Birks HJB, Bräthen KA, Brunet J, Bruun HH, Dahlberg CJ, Decocq G, Diekmann M, Dynesius M, et al.** 2013. Local temperatures inferred from plant communities suggest strong spatial buffering of climate warming across Northern Europe. *Global Change Biology* 19:1470–1481.
- Li X, Cheng G, Liu S, Xiao Q, Ma M, Jin R, Che T, Liu Q, Wang W, Qi Y, Wen J, Li H, Zhu G, Guo J, Ran Y et al.** 2013. Heihe Watershed Allied Telemetry Experimental Research (HiWATER): Scientific objectives and experimental design. *Bulletin of the American Meteorological Society* 94:1145–1160.
- Li Z, Tang B, Wu H, Ren H, Yan G, Wan Z, Trigo IF, Sobrino JA.** 2013. Satellite-derived land surface temperature: Current status and perspectives. *Remote Sensing of Environment* 131:14–37.
- Lookingbill TR, Urban DL.** 2003. Spatial estimation of air temperature differences for landscape-scale studies in montane environments. *Agricultural and Forest Meteorology* 114:141–151.
- Lookingbill TR, Urban DL.** 2005. Gradient analysis, the next generation: Towards more plant-relevant explanatory variables. *Canadian Journal of Forest Research* 35:1744–1753.
- Lundquist JD, Neiman PJ, Martner B, White AB, Gottas DJ, Ralph FM.** 2008. Rain versus snow in the Sierra Nevada, California: Comparing Doppler profiling radar and surface observations of melting level. *Journal of Hydrometeorology* 9:194–211.
- Marks D, Dozier J, Davis RE.** 1992. Climate and energy exchange at the snow surface in the alpine region of the Sierra Nevada, 1. Meteorological measurements and monitoring. *Water Resources Research* 28:3029–3042.
- Marks D, Winstral A, Reba M, Pomeroy J, Kumar M.** 2013. An evaluation of methods for determining during-storm precipitation phase and the rain/snow transition elevation at the surface in a mountain basin. *Advances in Water Resources* 55:98–110.
- McMahon MJ, Dascalu SM, Harris FC, Strachan S, Biondi F.** 2011. Architecting climate change data infrastructure for Nevada. *Lecture Notes in Business Information Processing* 83:354–365.
- Mensing S, Strachan S, Arnone J, Fenstermaker L, Biondi F, Devitt D, Johnson B, Bird B, Fritzinger E.** 2013. A network for observing Great Basin climate change. *Eos, Transactions of the American Geophysical Union* 94:105–106.
- Michener WK, Allard S, Budden A, Cook RB, Douglass K, Frame M, Kelling S, Koskela R, Tenopir C, Vieglais DA.** 2012. Participatory design of DataONE-enabling cyberinfrastructure for the biological and environmental sciences. *Ecological Informatics* 11:5–15.
- Millar CI, Westfall RD, Delany DL.** 2014. Thermal regimes and snowpack relations of periglacial talus slopes, Sierra Nevada, California, USA. *Arctic, Antarctic, and Alpine Research* 46:483–504.
- Minder JR, Mote PW, Lundquist JD.** 2010. Surface temperature lapse rates over complex terrain: Lessons from the cascade mountains. *Journal of Geophysical Research: Atmospheres* 115:1–13.
- Mitchell TD, Jones PD.** 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology* 25:693–712.
- Mountain Research Initiative Elevation-Dependent Warming Working Group.** 2015. Elevation-dependent warming in mountain regions of the world. *Nature Climate Change* 5:424–430.
- Mutibwa D, Strachan S, Albright T.** 2015. Land surface temperature and surface air temperature in complex terrain. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 8:4762–4774.
- NRCS [Natural Resources Conservation Service].** 2015. SNOTEL Sites. U.S.D.A. Natural Resources Conservation Service. <http://www.wcc.nrcs.usda.gov/snow/>; accessed on 5 January 2016.
- Oyster JW, Dobrowski SZ, Ballantyne AP, Klene AE, Running SW.** 2015. Artificial amplification of warming trends across the mountains of the western United States. *Geophysical Research Letters* 42:153–161.
- Peck EL.** 1997. Quality of hydrometeorological data in cold regions. *Journal of the American Water Resources Association* 33:125–134.
- Pepin NC, Seidel DJ.** 2005. A global comparison of surface and free-air temperatures at high elevations. *Journal of Geophysical Research D: Atmospheres* 110:1–15.
- Rasmussen R, Baker B, Kochendorfer J, Meyers T, Landolt S, Fischer AP, Black J, Thériault JM, Kucera P, Gochis D, Smith C, Nitu R, Hall M, Ikeda K, Gutmann E.** 2012. How well are we measuring snow: The NOAA/FAA/NCAR winter precipitation test bed. *Bulletin of the American Meteorological Society* 93:811–829.
- Reale JK, Van Horn DJ, Condon KE, Dahm CN.** 2015. The effects of catastrophic wildfire on water quality along a river continuum. *Freshwater Science* 34:1426–1442.
- Reid WV, Chen D, Goldfarb L, Hackmann H, Lee YT, Mokhele K, Ostrom E, Raivio K, Rockström J, Schellnhuber HJ, Whyte A.** 2010. Earth system science for global sustainability: Grand challenges. *Science* 330:916–917.
- Richardson AD, Jenkins JP, Braswell BH, Hollinger DY, Ollinger SV, Smith ML.** 2007. Use of digital webcam images to track spring green-up in a deciduous broadleaf forest. *Oecologia* 152:323–334.
- Schaefer G, Paetzold R.** 2001. SNOTEL (SNOWpack TElemetry) and SCAN (Soil Climate Analysis Network). *International Workshop on Automated Weather Stations for Applications in Agriculture and Water Resources Management*

Proceedings, Lincoln, NE. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.177.966&rep=rep1&type=pdf>; accessed on 1 March 2016.

Scherer D, Körner C. 2011. Topographically controlled thermal-habitat differentiation buffers alpine plant diversity against climate warming. *Journal of Biogeography* 38:406–416.

Schimel D, Hargrove W, Hoffman F, MacMahon J. 2007. NEON: A hierarchically designed national ecological network. *Frontiers in Ecology and the Environment* 5:59–59.

Sherson LR, Van Horn DJ, Gomez-Velez JD, Crossey LJ, Dahm CN. 2015. Nutrient dynamics in an alpine headwater stream: Use of continuous water quality sensors to examine responses to wildfire and precipitation events. *Hydrological Processes* 29:3193–3207.

Smith K, Kent G, Slater D, Plank G, Williams M, McCarthy MI, Vernon F, Braun HW, Driscoll N. In press. Integrated multi-hazard regional networks: Earthquake warning/response, wildfire detection/response, and extreme weather tracking. Applied Geology in California: Association of Engineering Geologists Special Publication. Available from corresponding author of this article.

Stahl K, Moore RD, Floyer JA, Asplin MG, McKendry IG. 2006. Comparison of approaches for spatial interpolation of daily air temperature in a large region with complex topography and highly variable station density. *Agricultural and Forest Meteorology* 139:224–236.

Stewart IT. 2009. Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes* 23:78–94.

Strachan S, Biondi F, Millar CI, Charlet DA. 2013. Watershed-scale topoclimatic dendrochronology: Combining tree-ring records, in-situ instrumentation, and baseline ecology in the Walker River Basin, California-Nevada. Paper presented at the *Second American Dendrochronology Conference*, Tucson, AZ. Available from corresponding author of this article.

Strachan S, Daly C, Millar CI. 2015. Testing the PRISM temperature model in a semi-arid mountainous watershed. Unpublished paper presented at the *American Geophysical Union 2015 Annual Meeting*, San Francisco, CA, 14–18 December. Available from corresponding author of this article.

Tenopir C, Allard S, Douglass K, Aydinoglu AU, Wu L, Read E, Manoff M, Frame M. 2011. Data sharing by scientists: Practices and perceptions. *PLoS ONE* 6:1–11.

Vanderbilt KL, Lin C-C, Lu S-S, Kassim AR, He H, Guo X, Gil IS, Blankman D, Porter JH. 2015. Fostering ecological data sharing: Collaborations in the International Long Term Ecological Research Network. *Ecosphere* 6(10):1–18.

Van de Ven CM, Weiss SB, Ernst WG. 2007. Plant species distributions under present conditions and forecasted for warmer climates in an arid mountain range. *Earth Interactions* 11:1–33.

Vitale AP. 2015. *Near-Surface Air Temperature in Complex Terrain: Daily Predictions of Fine-Scale (30 m) Temperature in the Snake Range, Nevada, USA* [MS Thesis]. Reno, NV: University of Nevada Reno.

Viviroli D, Weingartner R. 2004. The hydrological significance of mountains: From regional to global scale. *Hydrology and Earth System Sciences* 8:1017–1030.

Wan Z. 2008. New refinements and validation of the MODIS Land-Surface Temperature/Emissivity products. *Remote Sensing of Environment* 112:59–74.

Weathers KC, Hanson PC, Arzberger P, Brentrup J, Brookes J, Carey CC, Gaiser E, Hamilton DP, Hong GS, Ibelings B, Istvanovics V, Jennings E, Kim B, Kratz T, Lin F-P, et al. 2013. The Global Lake Ecological Observatory Network (GLEON): The evolution of grassroots network science. *Limnology and Oceanography Bulletin* 22:71–73.

Weiss SB, Murphy DD, Ehrlich PR, Metzler CF. 1993. Adult emergence phenology in checkerspot butterflies: The effects of macroclimate, topoclimate, and population history. *Oecologia* 96:261–270.

Wigmosta MS, Vail LW, Lettenmaier DP. 1994. A distributed hydrology-vegetation model for complex terrain. *Water Resources Research* 30:1665–1679.

Williams MW. 2014. What a long strange trip it's been: Lessons learned from NASA EOS, LTER, NEON, CZO and on to the future with sustainable research networks. In: *AGU Fall Meeting Abstracts*, Vol. 1. San Francisco, CA: American Geophysical Union, p 10.

WMO [World Meteorological Organization]. 2008. *Guide to Meteorological Instruments and Methods of Observation*. Geneva, Switzerland: WMO.

Yatagai A, Kamiguchi K, Arakawa O, Hamada A, Yasutomi N, Kito A. 2012. Aphrodite constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *Bulletin of the American Meteorological Society* 93:1401–1415.

Yatagai A, Xie P, Kito A. 2005. Utilization of a new gauge-based daily precipitation dataset over monsoon Asia for validation of the daily precipitation climatology simulated by the MRI/JMA 20-km-mesh AGCM. *Sola* 1:193–196.