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

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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 topoclimates 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.*

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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

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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;

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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

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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 (Laternser and Schneebeli 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.

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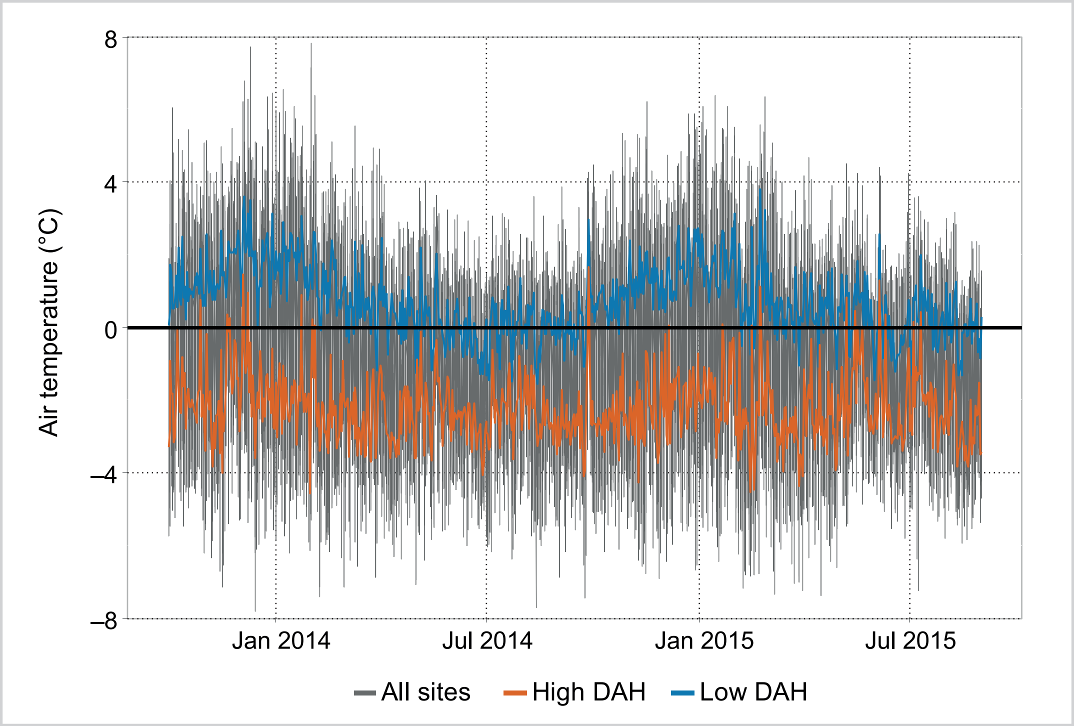
FIGURE 2 Cluster analysis of PRISM temperature model errors at each woodland study site revealed 2 distinct groups that were correlated to spatio-topographic variables. The most significant topographic variable ($r^2 = 0.8$, $p < 0.001$) for daily maximum temperature (T_{max}) error was the Diurnal Anisotropic 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

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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).

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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

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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.

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