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Mountain Observatories: Status and Prospects for Enhancing and Connecting a Global Community

Maria Shahgedanova[1]*, Carolina Adler[2], Aster Gebrekirstos[3], H. Ricardo Grau[4], Christian Huggel[5], Robert Marchant[6], Nicholas Pepin[7], Veerle Vanacker[8], Daniel Viviroli[5], and Mathias Vuille[9]

* *Corresponding author: m.shahgedanova@reading.ac.uk*

[1] *Department of Geography and Environmental Science, University of Reading, Whiteknights, PO Box 217, Reading, RG6 6AH, Berkshire, UK*
[2] *Mountain Research Initiative, c/o Centre for Development and Environment (CDE), University of Bern, Mittelstrasse 43, 3012 Bern, Switzerland*
[3] *World Agroforestry (ICRAF), United Nations Avenue, Gigiri, PO Box 30677, Nairobi, 00100, Kenya*
[4] *Instituto de Ecología Regional (CONICET–Universidad Nacional de Tucumán), Cc 34–4107, Yerba Buena, Tucumán, Argentina*
[5] *Department of Geography, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
[6] *York Institute for Tropical Ecosystems, Department of Environment and Geography, University of York, Heslington, York, YO10 5DD, UK*
[7] *School of the Environment, Geography and Geoscience, University of Portsmouth, Winston Churchill Avenue, Portsmouth, PO1 2UP, Hampshire, UK*
[8] *Earth and Life Institute, University of Louvain, 1348 Louvain-la-Neuve, Belgium*
[9] *Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, Albany, NY 12222, USA*

Mountainous regions are globally important, in part because they support large populations and are biodiverse. They are also characterized by enhanced vulnerability to anthropogenic pressures and sensitivity to climate change. This importance necessitates the development of a global reference network of long-term environmental and socioeconomic monitoring—mountain observatories. At present, monitoring is limited and unevenly distributed across mountain regions globally. Existing thematic networks do not fully support the generation of multidisciplinary knowledge required to inform decisions, enact drivers of sustainable development, and safeguard against losses. In this paper, the Mountain Observatories Working Group, established by the Mountain Research Initiative (MRI) Science Leadership Council, identifies geographical and thematic gaps as well as recent advances in monitoring of relevant biophysical and socioeconomic variables in the mountains. We propose principles and ways of connecting existing initiatives, supporting emerging areas, and developing new mountain observatory networks regionally and, eventually, globally. Particularly in the data-poor regions, we aspire to build a community of researchers and practitioners in collaboration with the Global Network on Observations and Information in Mountain Environments, Group on Earth Observations (GEO) Mountains, a GEO Work Programme Initiative.

Keywords: *mountains; long-term monitoring; elevation gradients; climate change; data networks; GEO Mountains; paleoenvironments; remote sensing.*

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Introduction

Mountains are among the world's most impressive landscapes and are vital to humanity. Depending on the criteria that are used for defining mountains, they occupy between 12% and 30% of the land surface (Kapos et al 2000; Meybeck et al 2001; Sayre et al 2018). They are home to between 0.9 and 1.2 billion people, accounting for 13% (FAO 2015a) of the global population. These global figures hide large regional variations. It is estimated that about 90% of the mountain population lives in developing and transitional countries. The average density of the mountain population in developing countries (40 inhabitants/km^2) is about 5 times higher than that in developed countries (8 inhabitants/km^2) (Huddleston et al 2003), and may even exceed 500 inhabitants/km^2 on the productive volcanic mountains of East Africa (Himeidan and Kweka 2012). Demographic trends in mountain regions are varied. There are areas where the population continues to increase, some areas with trends toward depopulation and abandonment, and areas where there is no major demographic change, but dramatic shifts in land cover from traditional land uses to new forms such as tourism and recreation are observed (FAO 2015a).

Mountains provide valuable environmental functions that underpin key ecosystem goods and services, a crucial supporting determinant for sustainable development potential. Mountain landscapes, characterized by diverse natural and managed systems (eg agricultural land), support biocultural diversity, food and energy security, tourism and recreation, and have spiritual and intrinsic values (Grêt-Regamey et al 2012; Mengist et al 2020). Mountain environments are directly linked to downstream regions through natural pathways (eg rivers and ecological corridors, which are themselves important habitats), as well as human infrastructure. Through these pathways, mountains provide the essential water, energy, food, and other resources and services, not only to the communities living in close proximity, but also to the downstream societies. They, therefore, play an important role in regional and global sustainable development. Most importantly, mountains act as water towers sustaining continuous flow of most of the world's major rivers (Viviroli et al 2007, 2020). At the same time, mountain environments are particularly threatened by the impacts of global environmental and climate change. Both the production and transmission of these environmental services occur in an environment characterized by prominent biophysical elevational gradients, as well as widespread natural hazards and threats in the form of extreme weather events, earthquakes, landslides, rock falls, avalanches, volcanic eruptions, wildfires, debris flows, and glacier lake outburst floods (GLOFs) (Glade 2013; Balthazar et al 2015; Haeberli et al 2015). Many of these hazards are modulated by highly variable weather conditions and, over the longer term, climatic change and its interactions with land cover and land use change.

Mountain environments are expected to experience particularly wide-ranging effects from current global climate change (Hock et al 2019). Rates of warming often depend on elevation (Pepin et al 2015). Although data availability and quality are lower (particularly at high elevations), changes in precipitation, cloud cover, wind, solar radiation, and other climatic variables are also likely to be strongly dependent on mountain elevation gradients (Lawrimore et al 2011; Viviroli et al 2011). In most mountain regions, snowpack and glaciers are receding (Hock et al 2019), leading to a positive feedback loop as surface albedo decreases and hydrological regimes downstream become less predictable (Huss et al 2017). The compression of ecological zones means that movements of species upslope can be rapid. Some species, typically found in the foothills and low montane zone, responding to drivers such as climate change by shifting upslope may benefit through increases in available area (Elsen and Tingley 2015). However, there is nowhere to go for the true cold-adapted species on high mountain summits (Nogues-Bravo et al 2007; Hagedorn et al 2019), and many may face local extinction (Elsen and Tingley 2015). It is not just impacts of climate change; continued fragmentation of habitats, caused by changes in land use, is another key factor leading to local or even global extinction of mountain species. The interaction among changes in land use, fragmentation, and changing climates is challenging the adaptative capacity of species and ecosystems.

As complex social–ecological systems, mountains exhibit emergent properties, nonlinearity, and dynamic feedback mechanisms (Klein et al 2019). Interacting pressures from changing climates, socioeconomic development, population growth, competing land uses, and national and international policies threaten the potential future sustainability and resilience of mountain systems across the world (Payne et al 2020; Thorn et al 2020). Nowhere are these pressures, and the need to understand the interactions between communities and environment, more acute than in the mountainous regions in developing countries. These regions face multiple and simultaneous threats spanning climatic, political, economic, institutional, and biophysical domains. Compelling evidence has accumulated that these interactions should be viewed as a globally interconnected, complex adaptive system in which heterogeneity, nonlinearity, and innovation play formative roles (Clark and Harley 2020; Payne et al 2020). However, there are also emerging opportunities to foster sustainability that take into account history and the complexity of social–ecological systems and use novel and inclusive participatory tools based on good-quality data and insight.

Interactions among people, ecosystems, and environments within mountain systems, and between mountains and other systems, urgently require integrated observation. This can be used to quantify the signals of change in environmental characteristics, composition, structure, and distribution of ecosystems and should be delivered rapidly and ideally in near real time. Such monitoring strategies are key to understanding and supporting actions that aim to address development and livelihood challenges on a scientifically supported basis. Our potential to adequately observe, monitor, and report these changes and their complex interactions also offers the chance to identify opportunities for development and innovation. Despite recent advances, fully integrated, long-term observations of environmental and social systems have received little attention. This is due to difficulties in combining approaches and methods used in natural and social sciences and bias toward specialization within the limits of established academic disciplines. There are also various institutional, conceptual, and operational challenges to coordinating these efforts (Funnell and Price 2003), which are still relevant today.

The necessity and expectation of engaging human–environment relationships explicitly in knowledge generation are now growing from a policy standpoint (Gleeson et al 2016). Key global policy frameworks have emerged since 2015. These include, but are not limited to, the United Nations (UN) 2030 Agenda and its Sustainable Development Goals (SDGs), the Intergovernmental Platform on Biodiversity and Ecosystem Services, the UN Sendai Framework for Disaster Risk Reduction, the UN Framework Convention on Climate Change, and the Paris Agreement, as well as the current post-2020 process to establish a Global Framework on Biodiversity under the Convention on Biological Diversity (CBD). These global policy frameworks influence the utility of long-term and integrated monitoring campaigns, not least in the mountains. They also come with metrics (ie goals, targets, and/or indicators) that promulgate certain requirements on the types and formats of data to be collected for monitoring purposes. An additional consideration is that reporting and assessing against these metrics can pose some methodological challenges in mountain-specific contexts, such as disaggregated and sparse data at the relevant spatial and temporal scales (Kulonen et al 2019).

A Global Network of Mountain Observatories (GNOMO) was developed in the 2000s. It was spurred forward by multithematic, consistent, comparable, and reasonably uniform monitoring, with adequate precision and accuracy, in mountainous regions, providing data for scientific research, management, and policy requirements (Strachan et al 2016). The GNOMO initiative, originally grassroots, was supported and coordinated by the Mountain Research Initiative (MRI) network. In 2016, the Global Network for Observations and Information in Mountain Environments (now known as GEO Mountains), co-led by the MRI, was established as a Group on Earth Observations (GEO) initiative. It provided additional means to further institutionalize, support, and integrate GNOMO as part of this broader framework (Adler et al 2018). More recently, following an initiative from members of the MRI Science Leadership Council (SLC), the MRI established a Mountain Observatories Working Group (Adler, Balsiger, et al 2020).

This working group seeks to extend the work of GNOMO and support GEO Mountains on mountain observatories and observations through the Mountain Observatories initiative—an ongoing effort to coordinate multithematic data collection in the mountains. The Mountain Observatories initiative consists of several projects and tasks aimed at the crowd-sourcing of information on existing and emerging observatories, identifying gaps (both geographical and thematic) in data, and developing protocols for collection and processing of relevant data and information. It aims to build a community of researchers and practitioners as part of GEO Mountains.

The working group defines mountain observatories as sites, networks of sites, or data-rich regions where multidisciplinary, integrated observations of biophysical and human environments are conducted over a lengthy period of time in consistent ways, according to established protocols using both in situ and remote observations. The purpose of mountain observatories is to evaluate the current state of mountain systems and build up an understanding that captures past variations and charts future physical, biological, and social changes in mountain environments. Ideally, mountain observatories need to fulfill a function as supersites or hubs for comprehensive monitoring of mountain environments.

This paper: (1) provides a brief review of the current trends and challenges of socioenvironmental monitoring in the mountains, and available networks and products; (2) assesses challenges for implementing an integrative and holistic approach to monitoring socioenvironmental systems; and (3) proposes principles and ways of supporting the development and connection of mountain observatories. We stress that this paper is not a structured systematic review of the available literature, but a substantive piece by a group of experts and their relevant networks based on published literature and content presented at multiple workshops in the past.

Monitoring in the mountains: status quo

Evolving methods of monitoring mountain environments

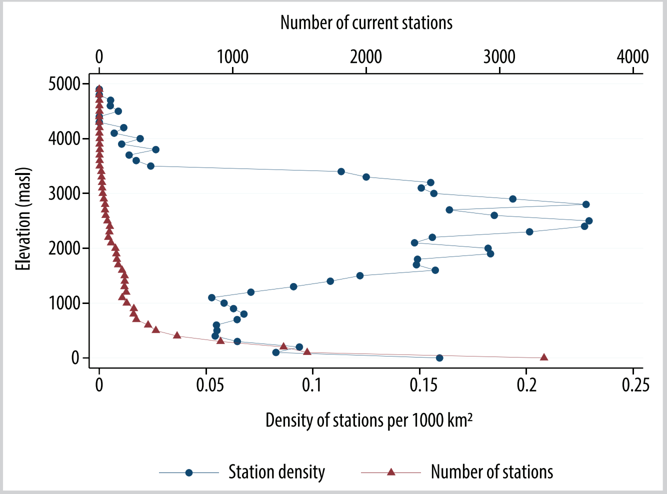
Systematic monitoring of mountain environments began in the European Alps in the 19th century by establishing meteorological, hydrological, and glaciological observations. Observations expanded in the 20th century, and continuous monitoring was initiated in many parts of the world during the first International Geophysical Year of 1957–1958 (Zemp et al 2009). At present, the World Meteorological Organization (WMO) runs the Polar and High Mountain Observations, Research and Services (PHORS) program, which coordinates standardized meteorological observations by nations and groups of nations. The World Glacier Monitoring Service (WGMS) coordinates activities on monitoring the state of glaciers, including long-term mass balance measurements (Zemp et al 2009). The Global Observation Research Initiative in Alpine Environments (GLORIA) (Grabherr et al 2000) focuses on monitoring changes in mountain-top vegetation. The global Critical Zone Exploration Network (CZEN; http://www.czen.org/) has a number of mountain sites where chemical, physical, geological, and biological processes that shape Earth's surface (Brantley et al 2017) are studied. A more recent campaign to highlight the need to support mountain-specific and relevant observation efforts was a topic of the WMO-hosted High Mountains Summit in 2019. The summit provided an opportunity to connect scientific and practitioner communities to take stock of recent developments and discuss prospects for monitoring to support climate services, thereby supporting efforts to safeguard mountain communities and ecosystems from the negative effects of climate change (Adler, Pomeroy, et al 2020).

Currently, there are 2 contrasting trends in environmental monitoring in mountainous regions. On the one hand, the density of in situ monitoring sites is declining, as they are costly and difficult to maintain in high-elevation environments. On the other hand, the availability of remote-sensing data with high spatial, temporal, and spectral resolution is increasing (Weiss and Walsh 2009). This complements and, in many instances, replaces in situ data, especially in the case of land use, land cover, and specific ecological data, such as plant productivity or phenology. Furthermore, the availability and use of proxy data based on paleoenvironmental reconstructions of past mountain environments are additional sources of information that have seen important developments lately. From a mountain observation perspective, paleoenvironmental data offer opportunities to better quantify the dynamics of environmental systems over longer periods of time. They also improve our understanding of environmental processes by putting the current and projected environmental changes in the mountains into a long-term perspective of natural ranges of variability (Marchant et al 2018).

In the following sections we delve into the trends behind in situ and remote-sensing monitoring methods and discuss the availability of mountain-related paleoenvironmental records in more detail.

In situ observations: spatial limitations and technological opportunities: There is poor availability of long-term, homogeneous and comparable ground-based observations in most mountainous regions outside Western Europe and North America (Viviroli et al 2011). The density of high-elevation meteorological stations and hydrological gauging sites with long-term measurements (eg over 50 years) conducted manually has declined in many regions since the 1980s. This is particularly true in the post-Soviet countries, and also in Africa and in the tropical Andes (Beniston et al 1997; Zhou et al 2017; Shahgedanova et al 2018). However, the expansion of automated measurements alleviates this problem to some extent (Strachan et al 2016). The Global Historical Climatology Network dataset (GHCN Version 4) includes 27,467 meteorological stations, of which only 1328 (4.8%) are located above 2000 m above sea level (masl) and 211 (0.8%) are located above 3000 m. Importantly, these statistics refer to the stations that supplied data to GHCN for any period of time and not necessarily the stations with continuing, long-term observations. Our comparison of the elevational distribution of current meteorological stations (as of June 2020) with global hypsography of the land surface area shows that station density is relatively high between 2000 and 3000 masl when averaged globally (Figure 1). However, it still does not meet the WMO criterion of 4 stations per 1000 km^2 for measuring precipitation in mountainous areas (WMO 1994; Viviroli et al 2011). The

FIGURE 1 Global distribution of the GHCN stations with elevation. In this and other figures, stations were mapped by 100 m elevation bands.



geographical distribution of the high-elevation stations is uneven, with a higher density in North America and Europe (Figure 2A, B) but approximately 10 times lower density elsewhere, especially in Africa, Asia, and South America (Figure 2C, D). This is irrespective of whether all stations (Figure 2A, C) or currently operational stations (Figure 2B, D) are used. The density of meteorological stations declines sharply above 3000 masl, and the GHCN dataset does not feature a single station located above 5000 m (Menne et al 2018). In Africa and South America especially, there has been a dramatic decline in recent years in station coverage (Figure 2D), which is worrying, because there was already a much lower station density on these continents to begin with. Figure 3 further shows details of the geographical distribution and elevation coverage of all GHCN stations. It reveals that high elevations in the Northern Hemisphere are comparatively better covered, especially in parts of North America and Europe, whereas for Asia, more data from high and very high elevations would be highly desirable. In the Southern Hemisphere, as well as in low latitudes, data for high and very high elevations are generally much scarcer. High-elevation regions constitute a small proportion of the global surface area. However, the lack of stations in Africa, South America, and some parts of Asia, as well as the lack of ultrahigh-elevation stations everywhere, cannot be justified given the populations they support and enhanced rates of environmental change they experience (Pepin et al 2015).

Statistics from another global surface air temperature dataset, Climatic Research Unit Temperature (version 4) (CRUTEM4), are broadly similar (Jones et al 2012; Osborn and Jones 2014; Harris et al 2020). The Global Runoff Data Centre (GRDC) data show that runoff and precipitation measurements are underrepresented above 1500 masl (Viviroli et al 2011). The paucity of measurements is especially evident in Asia, where the density of rain gauges declines to 0.04 per 1000 km^2 above 2500 masl; that is about

FIGURE 2 Distribution of GHCN stations with elevation by continent: (A, C) all GHCN stations; (B, D) current GHCN stations as of June 2020.

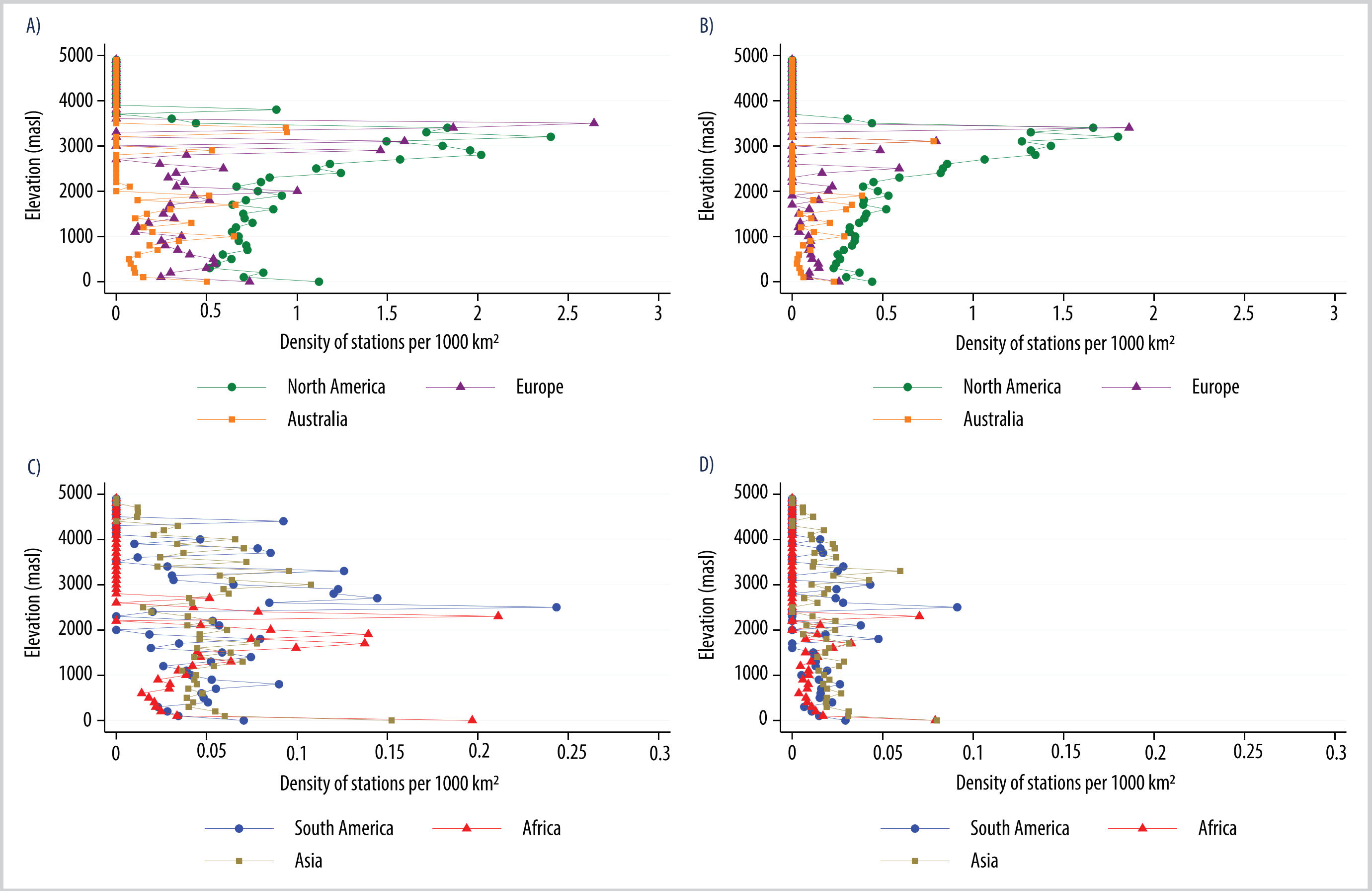
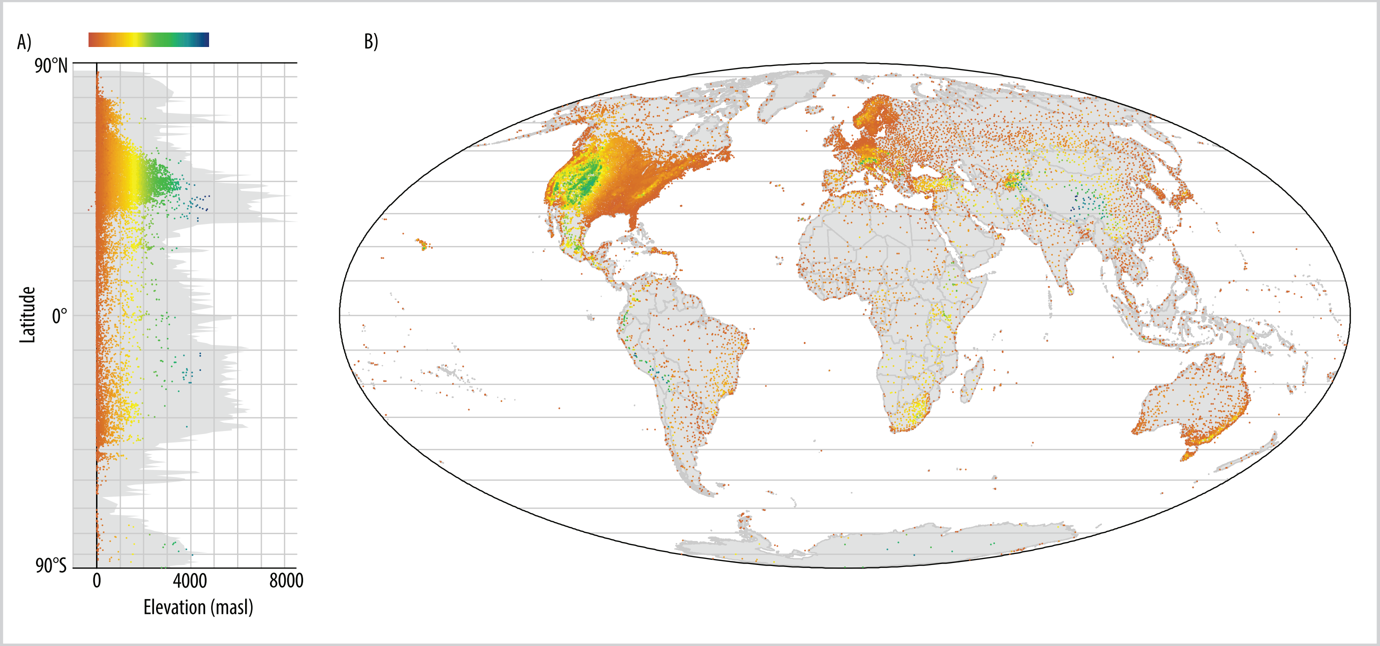


FIGURE 3 Distribution of GHCN stations with data for any period of time. (A) Longitudinal profile with station elevations (colored dots) and maximum elevation of the land mass (gray area); (B) geographical distribution in a Mollweide equal-area projected map, with station elevations shown in colors similar to panel (A).



1% of the WMO-recommended density for mountainous regions (WMO 1994).

The lack of spatiotemporal data coverage in the mountains results in crucial knowledge gaps and hampers our ability to validate remote-sensing data and models and address practical challenges. The usefulness of the available global and regional datasets for practical applications (ie watershed management, infrastructure development, implementation of adaptation options) is limited because solutions depend on topographic categories (eg slope, aspect), and these attributes are not represented. The lack of data from high elevations means that it is all too common for data from lowland sites to be used to evaluate processes in high mountains, resulting in uncertainties and poor characterization and modeling of high-elevation environments. Meteorological stations in the mountains tend to be located in valleys and in urban areas because of accessibility, which has inadvertently created bias in the data. For example, valley stations throughout the world often show strong microclimate effects, such as cold air ponding, urban heat islands, and rain shadows, which can make upslope extrapolation unreliable (Lundquist et al 2008). The Chinese Meteorological Administration currently operates 87 stations across the Tibetan Plateau, but many of these are located in the incised valleys in the south and east of the plateau, and often in towns. Their data cannot be reliably used for detecting signals of climate change at higher elevations, and cross-referencing these data with remotely sensed data is required to understand temperature trends above the highest station (4780 m) (Pepin et al 2019). Similarly, in Central Asia, streamflow data from gauging sites located in the foothills are often used to characterize impacts of glacier change on water availability. Positioning runoff gauges at basin outlets was originally designed to integrate information about runoff from the entire basin, including higher elevations. However, water abstraction and channel modifications often make these data unsuitable for attribution of the observed changes and modeling impacts (Shahgedanova et al 2018). Information on subsurface hydrology, which is an important component in mountain hydrological services to lowlands, is scarce and does not adequately support both research and water management applications (Somers and McKenzie 2020).

In situ observations often focus on the aboveground properties of mountain ecosystems, while long-term monitoring of soil properties in mountain environments is rare. Soils deliver various provisioning and regulating ecosystem services (eg carbon sequestration and storage, water storage and regulation, provision of food). The capacity of soils to deliver these services depends on soil functions and properties. Soil management and policies supporting it require accurate and spatially explicit soil information to meet present-day and near-future demands for food provisioning and regulation of climate and water cycles (Poesen 2018). The GlobalSoilMap.net consortium aimed to produce standardized soil information at an increasingly fine resolution, including mountainous regions. The African Soil Information Service created an online portal for soil information mapped out across the African continent (http://africasoils.net/services/data/). This has been useful for many different stakeholder groups, from national and regional policy development to farm-level land management, that require soil and landscape information. However, despite these efforts, soil information from the mountainous regions is often limited to local case studies and is fragmented in space and time (FAO 2015b). An integrated landscape approach is crucial in the management of mountain soils, given the variety of land use and soil management systems and the types of soils that can be found in mountain areas. Mountains are important stores of carbon, and montane rivers export sediment and organic carbon downstream and to the world ocean (Wohl et al 2012). Climate change, combined with the naturally high rates of erosion and chemical weathering that characterize montane environments, unsustainable management, and increasing frequency of disturbances such as wildfires, floods, and landslides intensify carbon exchanges in the mountains. A full carbon budget has been quantified in very few montane locations, and expansion of carbon monitoring is required to assess carbon stores and budgets, and the processes affecting their dynamics (Hilton and West 2020).

A positive development, and indeed an efficient way forward, is the increasing density of automated in situ measurements (Strachan et al 2016). The automated approach is particularly common in hydro-meteorological and, more recently, glaciological and ecological monitoring and is used by long-term monitoring programs such as, for example, Glaciers and Observatory of the Climate (GLACIOCLIM) (Shea et al 2015), Stations at High Altitude for Research on the Environment (SHARE) (Bonasoni et al 2008), and the Nevada Climate-Ecohydrological Assessment Network (NevCan) (Strachan et al 2016). Some of the automated sites (eg GLACIOCLIM) archive the collected data. Others (eg NevCan) make data publicly available in real time. Despite these advances, however, the very high-elevation weather stations (>4000 m) are again rare (Viviroli et al 2011). The longest records on mountains such as Kilimanjaro (∼5800 masl) or Quelccaya (∼5700 masl) only extend back some 15–20 years (Yarleque et al 2018), and this hampers our understanding of longer-term climate variability and change. A preliminary global assessment of the spatial distribution of known high-elevation automated meteorological observations suggests a distinct concentration of networks in the midlatitudes of the Northern Hemisphere, but also some sites in Africa and South America. However, at present, there is no global collation of such observations. The recent proposal by the MRI to develop a coordinated database of observations from the automated sites and their transects across elevational gradients (the Unified High-elevation Observation Platform or UHOP) is a welcome example, but it is in its infancy (Adler et al 2018). This makes it almost impossible to know how the number of high-elevation weather stations changes over time, and where spatial coverage is particularly poor and the ensuing need is most acute.

The automated measurements are often funded and operated by individual or national-scale organizations and are associated with short-term research and development projects. They often provide narrowly focused, short time series, which do not necessarily adhere to standard protocols of sensor deployment and data collection. Problems surrounding the deployment of automatic stations, including their siting, continuity of measurements, and data transmission, were comprehensively reviewed by Strachan et al (2016). Here, we note that within the setting of mountain observatories, uniform observational techniques can be introduced, and procedures for operating and maintaining automatic stations can be taught. For example, protocols for uniform observations and data quality control have been introduced within the GLORIA network (Pauli et al 2015).

Many research or development initiatives measure (automatically or manually) the same variables but use different metrics and standards, resulting in datasets that are not directly comparable. While standards for weather station deployment and meteorological data collection (WMO 2008) and guidelines for soil description and classification (FAO 2006) have long existed, standardization of measurements is less common in other areas. Other examples where significant advances toward methodological uniformity have been made include the WGMS (Zemp et al 2009) and the GLORIA (Grabherr et al 2000) networks, concerned with glacier mass balance measurements and ecological monitoring, respectively. However, despite the global sharing of observational protocols, GLORIA sites tend to be concentrated in Europe, the tropical Andes (CONDESAN regional network; Saravia and Bièvre 2013), and western North America (CIRMOUNT regional network; Millar 2004), with limited monitoring elsewhere.

Increasing role of remote sensing in addressing limitations: Remote sensing in general, and remote sensing from space in particular, helps to alleviate logistical challenges of high-elevation monitoring. It helps to provide multiscale and multithematic information obtained in a consistent way over large areas. It is frequently presented as a solution to the problem of declining in situ observations. Depending on the type of sensors used and questions to be addressed, spaceborne—most often satellite—imagery is available at a wide range of scales: from high/fine (<15 m), to medium/moderate (15–500 m), and low/coarse (>500 m) pixel resolution. Spatial resolution is generally traded off against temporal resolution both in terms of frequency of repeat measurements and the temporal extent of the time series.

The monitoring of mountain environments using remote sensing has expanded significantly since the 1980s, when aerial photography was superseded by spaceborne remote sensing (Weiss and Walsh 2009). Currently, however, airborne measurements from unmanned aerial vehicles (UAVs) are expanding in monitoring mountain environments (eg Piras et al 2017). There has been a growth of products, accessibility to data, and number of tools with which to analyze and visualize satellite and other spaceborne datasets that has led to its more widespread application. Remote-sensing products, particularly the repeated imagery from Moderate Resolution Imaging Spectrometer (MODIS), Landsat, ASTER, and Sentinel, have helped to fill a significant data void, especially in developing countries and in remote regions.

Remote sensing, however, has several important limitations when used on its own (Pfeifer et al 2012). First, remote-sensing products are inherently limited in their temporal coverage and are too short to provide a comprehensive long-term monitoring perspective—the world did not start in the 1970s! Second, despite recent advances, some environmental characteristics still cannot be monitored from space or even from UAV. For example, remote sensing captures spatial and temporal changes in vegetation, aboveground plant biomass, phenology, and productivity well, but not soils, or animal and plant biodiversity. Progress is being made, however, in using spaceborne data for plant biodiversity monitoring (Skidmore et al 2015). Third, there are challenges specific to mountain environments. These range from spatial resolution, which is still too low for many applications, and technical problems, associated with complex mountainous topography and their radiative properties, to lack of quality ground-control data (Weiss and Walsh 2009; Balthazar et al 2015).

For example, global precipitation datasets such as Tropical Rainfall Measuring Mission (TRMM) (Huffman et al

2007) and Global Precipitation Measurement (GPM) (Skofronick-Jackson et al 2017) datasets have spatial resolution of 0.25° and 0.1–0.5°. They are available from 1997 and 2000, respectively, and are widely used in environmental analyses. However, data derived from TRMM and GPM are less helpful in characterization of elevation-dependent precipitation trends controlled by topography slope, aspect, and exposure in the mountains. These and other precipitation datasets derived from satellite observations have difficulties in estimating orographic precipitation, particularly in southeastern Asia, in the Himalayas and in the Western Ghats (Sun et al 2018). Soil moisture datasets include the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) (Kerr et al 2012), and the National Aeronautic and Space Administration (NASA) Soil Moisture Active Passive (SMAP) datasets (Entekhabi et al 2010). They have spatial resolutions of 30–50 km and 9 km (downscaled to 3 km), respectively, which is problematic in mountain regions. Efforts are being made to increase the spatial resolution and utility of such datasets. For example, soil moisture data at a scale of meters became available recently from several satellites, albeit at the cost of reduced temporal resolution (Mohanty et al 2017). Another example is TAMSAT (Tropical Applications of Meteorology using SATellite data and ground-based observations), which provides daily rainfall estimates for all of Africa at 4 km resolution (Maidment et al 2014, 2017; Tarnavsky et al 2014). The global Land Surface Temperature (LST) dataset available from 2010, compiled by ESA, is available at 5 km resolution. However, many processes in the mountains (eg cold air drainage, which is critical for ecological responses) are controlled by even smaller-scale topography (Lundquist et al 2008; Morelli et al 2016). In addition, a lack of high-elevation ground-truth data hampers the validation of remote-sensing products in many mountain regions. For example, several sites used for the validation of the LST data are positioned above 1000 m, but none is in complex terrain (Martin et al 2019).

The high-resolution digital elevation models (DEMs) are derived from spaceborne data. They enable mountain topography to be assessed and are extensively used in environmental analyses and models. This is particularly important for natural hazard assessments, predictive species distribution models (Platts et al 2008), and assessing glacier change (Marzeion et al 2017). Elevation data were obtained by the Shuttle Radar Topography Mission (SRTM) in 2000 for the region bound by 60°N and 54°S latitudes. These data were used to generate the 30-m horizontal resolution SRTM30 DEM, representing 80% of Earth's surface with a vertical accuracy of at least 16 m at a 90% confidence level (Rodríguez et al 2006). The DEM captures general topographic gradients but not the finer-scale topographic variations that affect a range of processes—from ecological to glacier change—in regions with high topographic complexity (Marzeion et al 2017). Another example is a multitemporal global land surface altimetry product (GLA14) generated from the Geoscience Laser Altimeter System instrument on the Ice, Cloud and Land Elevation Satellite (ICESat). This is designed to measure changes in ice-sheet elevation with 60 m to 70 m resolution (Schutz et al 2005). The geolocation accuracy of GLA14 is below 1 m and can be a valuable supplement to other DEMs. The recent sub-meter-resolution optical satellites such as GeoEye, Quickbird, WorldView, and Pléiades provide higher-resolution spaceborne DEMs on a scale of mountain systems, for example, the High Mountain Asia 8 m DEM (Shean 2017), and for smaller mountain areas worldwide (eg Berthier et al 2014).

Many practical problems in the routine use of remote sensing in environmental applications that were common a decade ago have been overcome, and spaceborne remote sensing has become a predominant method of monitoring in many disciplines. Most assessments of changes in glacier area are conducted using satellite remote sensing, and comprehensive regional and global datasets characterizing the observed glacier change have been developed (Kargel et al 2014; Pfeffer et al 2014). Monitoring seasonal snow cover is another example. This includes both its spatial extent (eg Gafurov et al 2016) and snow depth using airborne laser altimetry (Deems et al 2013) and satellite data (Marti et al 2016; Lievens et al 2019). However, obtaining data about snow water equivalent, required in many hydrological applications, remains problematic. Similarly, evaluation of many glacier characteristics, such as ice thickness, the main constraint on simulating future glacier evolution and assessment of water resources (Vuille et al 2018; Shahgedanova et al 2020), requires ground-based measurements or airborne remote sensing with ground support (Gärtner-Roer et al 2014) combined with glacier modeling (Linsbauer et al 2012; Farinotti et al 2019). The evolution of mountain lakes, either glacier (eg Gardelle et al 2011) or other (eg Casagranda et al 2019), can be easily measured using satellite imagery. By contrast, data on lake bathymetry require field surveys, which limits data availability to a few regional datasets worldwide (eg Cook and Quincey 2015; Kapitsa et al 2017; Muñoz et al 2020).

A good example of combining the in situ and satellite measurements in a complementary way is the Pléiades Glacier Observatory established by the WGMS in collaboration with the French Space Agency. It provides very high-resolution stereo images (0.5 m), enabling assessment of glacier thickness change in the WGMS benchmark glaciers (Berthier et al 2014; Kutuzov et al 2019; Kapitsa et al 2020). This approach enables expansion of mass balance monitoring from individual glaciers to regional scale through the application of high-resolution satellite DEM validated with ground-control data. Another example is the Virtual Alpine Observatory (VAO), operating under the Alpine Convention (http://www.alpconv.org) as a network of 16 high-elevation research stations based in 6 Alpine and 4 associated countries. The mountain observation sites, which form the backbone of VAO, are linked to several high-performing computing centers. These enable efficient access to and visualization of in situ data generated by VAO, and relevant remote-sensing and modeling data for the member institutions, wider research community, and stakeholders through the Alpine Environmental Data Analysis Centre (Virtual Alpine Observatory 2017).

Some key challenges to using remotely sensed data, such as the fragmentation of products from different agencies and the range of specialized analytical tools, have been overcome by the Google Earth Engine (Gorelick et al 2017). This combines a wide catalogue of satellite imagery and geospatial datasets with inbuilt modeling tools to map trends and quantify landscape changes and the drivers behind these changes (eg Kumar and Mutanga 2018; Kennedy et al 2018; Bian et al 2020).

Use of proxy data and paleoreconstructions: Understanding how terrestrial ecosystems change at global scales is a fundamental challenge that demands datasets with extensive temporal depth and wide spatial coverage. There is growing interest in harnessing networks of long-term records that extend past the instrumental records. This would allow researchers to explore, contextualize, and predict the responses to abrupt and gradual environmental change, investigate the interplay of abiotic and biotic interactions, understand rates and direction of change (Bi et al 2015; Nolan et al 2018), and characterize mechanisms that promote resilience (Rayback et al 2020). All of these fundamentally require an understanding of response over time. Indeed, placing recent global warming and environmental change in the context of natural climate variability requires the long-term perspective that can be provided only by paleoenvironmental proxy records (Carilla et al 2013; Bi et al 2016; Kaufman et al 2020). This is particularly important in regions where the availability and quality of long-term environmental and climate data are limited.

Paleoclimatic, paleoecological, and paleoenvironmental proxy data are extensively used to reconstruct past changes over a range of different timescales and to examine the changing relationships between people and the environment. Paleoenvironmental research is focused on basins where sediments accumulate over time, archiving signals of their surrounding environment, or it uses data records extracted from ice cores, glacial deposits (moraines), lake cores, tree rings, speleothems, and lichens. Many of these records are obtained in the mountains where lakes, bogs, mires, glaciers, and thermally or hydrologically limited biological growth are common features. As a result, there are numerous paleoreconstructions focusing on individual sites or regions (eg Carilla et al 2013; Wirth et al 2013; Solomina et al 2016; Mokria et al 2017; Fan et al 2019, to name but a few). While the value of these records is in describing change, like any observation, the value diminishes with distance from the observation. This is particularly true in the mountains, where environmental conditions change strongly over small distances. Although there are numerous archives collating paleoenvironmental data, a comprehensive database of paleoclimate records that focuses on mountains is lacking. As for the datasets compiled for the Arctic (Linderholm et al 2018), such a database could be invaluable to place single records into the longer-term and wider spatial context.

A recent global compilation of quality-controlled temperature-sensitive proxy records extends back 12,000 years through the Holocene from 679 sites, many of these from mountain settings (Babst et al 2017). Centralized databases are playing an increasingly important role, for example, National Oceanic and Atmospheric Administration (NOAA) National Centre for Environmental Information and datasets therein (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets), Neotoma (Williams et al 2018), Forest Inventory and Analysis (US Department of Agriculture Forest Service; https://www.fia.fs.fed.us/tools-data/), TRY Plant Trait Database (www.try-db.org), and the International Tree Ring Data Bank (ITRDB; https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring) (Grissino-Mayer and Fritts 1997). The ITRDB holds data from 238 tree species obtained at more than 4000 sites in 6 continents (Sullivan and Csank 2016) used to quantify and evaluate the long-term environmental and ecological changes across large regions and environmental gradients (Gebrekirstos et al 2014; Babst et al 2017; Zhao et al 2019). The long-term data with annual resolution collected by the Dendro-Ecological Network (DEN; https://www.uvm.edu/femc/dendro) enable scientists to detect and assess slower ecological processes as well as the rare events and link current environmental change with past human agency and other biological data (Holz et al 2017; Williams et al 2018; Stephens et al 2019; Correa-Díaz et al 2020). There is a recent move to combine these single proxy databases that is galvanizing the community. For example, the multiproxy Neotoma database now holds over 4 million observations of micro- and macrofossil distributions from 31,000 datasets and 15,000 sites. Importantly, these new multiproxy databases include analytical and display functionality to improve access and use: Neotoma data via Neotoma Explorer, Google-Datasets-discoverable landing pages, NOAA/NCEI-Paleoclimatology, Flyover Country, and the Global Pollen Project (Williams et al 2019).

The prospect for stimulating a compilation of relevant paleoscience and paleodata and information sources in a mountain context has long been an aim of the MRI. The MRI SLC led activities for the 2020–2021 period (Adler, Balsiger, et al 2020). These were coupled with renewed efforts, via GEO Mountains, to incorporate paleodata and information for mountains to address current gaps.

Thematic foci and emerging examples of holistic approaches

Multiple assessments of environmental change within mountain regions are usually conducted by networks and programs within subdisciplines. Examples include WGMS's (Zemp et al 2009) and GLORIA's (Grabherr et al 2000) monitoring of glaciers and vegetation, respectively. More recently, other thematic regional and global networks have been established with a focus on the cryosphere, ecology, or biodiversity, such as the Climate and Cryosphere (CliC) project (http://www.climate-cryosphere.org) supported by the World Climate Research Programme (WRCP). The World Overview of Conservation Approaches and Technologies (WOCAT) has regional initiatives that include mountain regions (eg in Ethiopia, Bhutan, Nepal, Uganda). It has launched efforts to systematize information on sustainable land management (eg Liniger and van Lynden 2005). There are many examples of successful regional thematic monitoring programs, such as the Andean Forest Network, which monitors changes in structure and diversity of montane forests in this vast region (Malizia et al 2020).

Although thematically and locally focused networks make an important contribution to our understanding of environmental change in the mountains, the data they provide are fragmented. There are ongoing efforts to integrate meteorological, glaciological, hydrological, and natural hazard monitoring at high elevations. These are coordinated by the WMO Global Atmospheric Watch (GAW) program. Alternatively, they may be pursued by regional networks, such as GLACIOCLIM (Shea et al 2015) and SHARE (Bonasoni et al 2008), originally established in the Hindu Kush Himalaya region, but now expanding to Africa, Europe, and South America. In particular, SHARE and the Global Change in Mountain Regions (GLOCHAMORE) (Grabherr et al 2005) projects have succeeded in overcoming thematic boundaries, integrating objectives of natural and social sciences, long-term observations, and modeling.

There are examples of integrated multithematic observations operating on regional and local scales. The VAO, operating in the European Alps, Scandinavia, and southern Caucasus and supported by governmental funding, provides an example of how systematic and consistent observations are enhancing our understanding of the interactions among regional development, economy, and environment in the mountains. The International Long-term Ecological Research (LTER) network, which operates globally, adopts an integrated approach to monitoring and research of ecosystem, critical zone, and socioeconomic aspects of landscape evolution (Rogora et al 2018; Angelstam et al 2019). Another example is the long-term environmental and social–ecological monitoring in transboundary landscapes in the Hindu Kush Himalaya region (Chettri et al 2015). An example of an emerging network is Monitoring High Andean Ecosystems of Colombia (EMA), which is building on the existing glaciological, hydrological, biosphere, and land cover and land use monitoring facilities and network with the aim to build an integrated system of transdisciplinary socioenvironmental monitoring in the Andes (Llambí et al 2019). A smaller regional network, NevCAN, established by the University of Nevada and the Desert Research Institute, operates in the southwestern United States monitoring climatic conditions, snow depth, surface hydrology, soil conditions, ecology, and biodiversity (Strachan et al 2016), while the Mountain Social Ecological Observatory Network (MntSEON) focuses on the vulnerabilities of mountain systems and the human communities they support in the United States (Alessa et al 2018). There is a much smaller KiLi Observatory established under the Ecosystems under Global Change project and confined to the limits of Mount Kilimanjaro. KiLi supports research on impacts of climate change, land use change, and a range of human activities on tropical mountain biota, and the resilience and adaptive capacity of natural and modified ecosystems to climate change along elevation gradients (Albrecht et al 2018).

Although working at different geographical scales and within different funding frameworks, these are all too infrequent, but successful, examples of integrated multithematic observations focusing on socioeconomic as well as biophysical monitoring.

Thematic gaps and suitability of the available datasets

In this paper, we briefly reviewed, in the context of mountain environments, typical observations and relevant datasets (regional and global, obtained in situ or using remote sensing) available to and widely used by the academic and stakeholder communities. Three important points emerge from this analysis. First, many datasets (eg TRMM, GPM, SMOS, SMAP, CRUTEM4) are not mountain-specific and are not designed to address a concept of large change (eg in temperature, precipitation, species, etc) over a fine spatial scale. Second, while some datasets are easily accessible (eg via Randolph Glacier Inventory [RGI] and WGMS), many regional datasets, both historical and contemporary, remain within institutions and are not shared. Better knowledge about existing datasets, data access, and data rescue is required. Third, most of the above discussion concerns monitoring of the physical environment. Very few observatories and networks combine monitoring of the natural environment with the assessment of socioeconomic and cultural impacts and associated indicators, even though this is important to develop future scenarios of environmental and socioeconomic change (Thorn et al 2020). There are, however, examples of successful integration of biophysical and socioeconomic monitoring by such mountain-specific networks, such as VAO, NevCan, MntSEON, and KiLi, while the EMA (Llambí et al 2019) and other networks explicitly focus on interdisciplinarity in their development plan. In particular, LTER has developed a social–ecological research platform to enhance the links between biophysical and socioeconomic monitoring and research (Angelstam et al 2019). Social, political, and cultural observations are scattered and often based on individual case studies or contexts. This largely reflects a very specific epistemic perspective and set of research questions, methods, and design that may not be amenable to, nor necessarily intended to, align or be integrated with observational data for biophysical variables.

The topography of mountains implies that upstream and downstream regions are connected in terms of impacts, most notably by gravity-driven water and mass flows. Examples include downstream water supply impacted by high-elevation precipitation and snowfall patterns (Viviroli et al 2020) and glacier changes (Huss and Hock 2018), or GLOFs and debris flows produced by upstream geomorphological processes (Haeberli et al 2015). While glacier lakes are often reasonably well monitored, potential or actual impacts of related hazards are often monitored poorly in the absence of socioeconomic data and trends other than national census data.

Efforts to provide a robust basis for systematic, comparable, and coordinated observation frameworks incorporating social dimensions need to capture the unique sociocultural place-based conditions while allowing for cross-comparisons within and across locations and scales. Integrating observations in complex social–ecological systems and contexts is an emerging area that addresses a complex and fundamental methodological challenge. Examples from a few multithematic and mountain-specific initiatives offer promising prospects for their scaling and development. Typologies and frameworks for capturing relevant social data and information are an important basis for designing monitoring systems and networks that are fit-for-purpose and facilitate and respond to these integrated observation needs in mountain social–ecological systems (eg Collins et al 2011; Altaweel et al 2015).

Finally, as highlighted in Hock et al (2019), citing Dickerson-Lange et al (2016) and Wikstrom Jones et al (2018), citizen science can also contribute to generating and integrating diverse observation data, complementing instrumental and modeling efforts. Furthermore, lessons learned from community-based observation methods in the Arctic offer transferable application prospects for the mountains (Griffith et al 2018). These can enhance the value and integration of human dimensions in observation campaigns, as do observations based on indigenous and local knowledge (Abram et al 2019).

BOX 1: Aims of the Mountain Observatories initiative

1. Crowdsource information, including metadata, on existing or emerging observatories.
2. Specify or provide guidance for relevant protocols to help mountain observatories in operationalizing mountain-relevant data and information for multiple applications.
3. Build capacity through concrete activities in mountain monitoring and sustainable development, including provision of on-site courses and training exercises with a particular focus on developing countries with fragile mountainous ecosystems.
4. Facilitate links between the Mountain Observatories initiative and the GEO Mountains program.

BOX 2: Remits of the mountain observatories

Atmosphere and climate

Cryosphere

Hydrology, hydrochemistry, and water quality

Soils and biogeochemical cycles

Vegetation and biodiversity

Land cover and land use

Hazards and disasters

Quantitative demographic, livelihood, and household information

Qualitative sociocultural information, including governance and land tenure systems

Overall and despite many recent efforts, there is still a lack of datasets for many regions. Where such datasets exist, they still have a disciplinary focus, and their fragmentation and often a lack of accessibility are major challenges (Thornton et al 2021). The question, therefore, remains whether existing datasets from high-elevation regions serve the purpose of a holistic approach to understanding environmental change in mountains and assessment of impacts and vulnerabilities.

Mountain observatories: quo vadis?

The Mountain Observatories initiative, coordinated by the MRI Mountain Observatory Working Group, is expected to build on and go beyond the remits of traditional, highly specialized monitoring programs operating in mountainous regions. It aims to deliver a highly visible and valuable output (Box 1). This will stimulate the development of a comprehensive partnership of key stakeholders and trigger actions leading to realization of the goals stipulated in global frameworks such as the Paris Agreement or the SDGs. It will also support regional and local policymaking and communities in the management and governance of common resources in mountains.

The remits of the mountain observatories are illustrated by Box 2. This list is not exclusive nor exhaustive and intentionally embraces a wide thematic and spatial scope. While it may not be possible or indeed necessary to monitor such a system in its entirety, monitoring at mountain observatories should fulfill several criteria, creating commonality between diverse observational programs. First, observational programs should be multi- and interdisciplinary and include components that can be monitored in a consistent way across the globe (eg climate), as well as those specific to the region (eg glaciers). Second, integrated monitoring of environmental and social processes should be achieved. Third, mountain observatories should aim to effectively integrate in situ measurements, remote sensing, modeling, and other forms of data and information sourced from community-based approaches. Fourth, they should link mountains and downstream regions with regard to both processes and impacts. Recognizing the need to monitor gradient processes for the benefit of both mountain communities and dependent lowland zones is important, as previously emphasized by Pepin et al (2015), Strachan et al (2016), and the recent proposal by the MRI on UHOP development (Adler et al 2018).

Although the reviewed initiatives operate at different scales, their success rests on the same pillars. All are designed and maintained as long-term programs supported by shorter-term projects. The former enables continuity and consistency; the latter brings in new expertise, improves instrumentation and communication, and ensures production and publication of relevant scientific results in a timely fashion. All rely on technology and provide efficient data access. All operate according to the established protocols, collecting and storing data in a consistent and comparable way. All work toward building digital and data infrastructure because generated datasets are too large for manual processing, and automation and workflow architectures are necessary. An important feature is the collaborative approach and sharing of knowledge and resources between countries, institutions, academics, and practitioners. Institutionalization of observational networks or strong links with public and private stakeholders can help to secure long-term monitoring.

The MRI Mountain Observatories Working Group, working closely with GEO Mountains, will support the development of regional and eventually global networks of mountain observatories by focusing on 3 tasks.

While the overall concept of mountain observatories has been developed, problems and mechanisms of delivery vary between regions. The first task, therefore, is the formulation of problems at regional network level, enabling network participants to express their opinion on the agenda of the Mountain Observatories initiative and adjust it to their needs. At this stage, a program of multithematic data collection along mountain gradients in different mountain regions will be created, including, but not limited to:

- Understanding elevation-dependent warming (Pepin et al 2015) and its broader conception of elevation-dependent climate change. This can be further evidenced through analysis of meteorological and associated data, information on soil characteristics, vegetation, and their response patterns obtained systematically along a variety of elevational gradients.

- Identifying the changing capacity of mountain regions to store water in its frozen form (snow, glacier ice, ground ice, and permafrost) and supply it to the lowlands (eg Huss et al 2017).
- Characterizing changes in individual components of the water balance and combined influence of hydrological changes and anthropogenic activities on water availability and quality (Viviroli et al 2011, 2020).
- Using global and regional climate models to characterize the changing climate of mountainous regions (eg Urrutia and Vuille 2009; Palazzi et al 2013; Platts et al 2014; Kotlarski et al 2015).
- Assessing the level of adaptation and vulnerability of human mountain communities and relevant resilience traits to climate change and other socioenvironmental changes (Lopez et al 2017; Klein et al 2019).
- Recording elevation- and topography-dependent changes in human–climate–ecosystem interactions and particularly monitoring changes that are likely to result in nonlinear and potentially abrupt impacts on human and environmental systems (eg changes in mudflows and GLOFs, avalanche occurrence, etc).
- Identifying key changes that impact mountain biodiversity and ecosystems, including the capacity to support ecosystem services, and interactions between climate change and land use at the relevant spatial and temporal scales (UNEP et al 2020).
- Recognizing changes in human demography, livelihoods, cultural practices, and governance arrangements, and their interactions with land use, ecosystems, climate change, and topography.

Many of these thematic areas individually comprise major scientific communities and long-standing research and monitoring efforts, some of which are institutionalized in international programs. It is therefore vital to recognize and build on these networks and standards and collaborate with the respective scientific communities. Other thematic areas mentioned above, especially the more interdisciplinary (eg adaptation) one, have emerged more recently but likewise require connections to rapidly growing scientific communities and networks.

The second task is to continue the development of metrics and indicators to be monitored by mountain observatories to ensure consistency and comparability of data in collaboration with GEO Mountains and Global Climate Observing System (GCOS) programs and thematic networks. A set of Essential Climate Variables (ECVs) specific to mountain environments is being developed as an activity of GEO Mountains, with the inputs of the relevant MRI Working Groups (Thornton et al 2021). Mountain-specific ECVs are defined with respect to different mountain processes such as cryospheric change, ecological change, and the hydrological cycle, building on and complementing the existing ECVs as defined by GCOS. Protocols for how these are to be measured using in situ observations and remote sensing, and in models, are being developed in close collaboration with experts in the different thematic areas of existing ECVs (Thornton et al 2021). Principles for the best practice for informatics focused on essential biodiversity variables (EBVs) were compiled recently to support the emerging EBV operational framework (Hardisty et al 2019). Work is ongoing to develop a set of EBVs characterizing biodiversity specifically in the mountains (Kulonen et al 2020).

The third task is that of facilitation. Efforts of the MRI Mountain Observatories Working Group will focus on provision of information about mountain observatories via interactive websites to give access to metadata and, in some cases, navigate users to individual observatories and networks (MRI n.d.). Importantly, the MRI, led by the Mountain Observatories Working Group, will foster and facilitate the development of regional networks of mountain observatories through bringing together regional researchers, practitioners, and international experts experienced in running successful mountain observatories in a series of regional workshops. The following regions will be initially targeted: Central Asia and the Caucasus, East Africa, the Hindu Kush Himalaya region, and the tropical/subtropical Andes. Workshops and targeted campaigns in other regions such as North America and Europe will be pursued with partners in parallel. These workshops will focus on the identification of network-level research issues and foster multidisciplinary observational programs relevant to both regional needs and research issues of global relevance. When possible, regional workshops would be complemented with in situ courses and summer schools or equivalent to promote the use of the data, recruit human resources, and facilitate the development of innovative and transdisciplinary research.

Conclusions

This paper provides a brief review of the current state and challenges of socioenvironmental monitoring in the mountains, available networks, and products. Two opposing trends were identified: reduction in high-elevation in situ observations and increase in the coverage and sophistication of remote sensing. The expansion of automated measurements partly alleviates the lack of in situ observations, but the datasets they generate are often short-lived and inconsistent in time and methods, and there is no database that would compile at least metadata for these measurements. There is no mountain-specific paleodatabase, although many paleo-datasets are obtained from the mountains. Spatial resolution remains a problem: Regional and global datasets are designed to capture large-scale spatial variability and do not resolve smaller-scale processes and sharp gradients characterizing mountain environments. Another major limitation is a lack of integration of biophysical and socioeconomic data and transdisciplinary research collaborations. We identified a number of emerging successful multithematic observatories and networks, acting at different spatial scales and in different financial frameworks. However, most observations retain thematic foci, and integrated, holistic observations are still a rarity in the mountainous regions. This fragmentation hampers our ability to characterize and quantify the observed and projected climate and environmental change, their impacts on high-elevation regions, and their consequences for downstream locations relying on ecosystem services to facilitate sustainable development. The MRI Mountain Observatories Working Group, working in close collaboration with GEO Mountains, as well as researchers and practitioners from various mountain regions in Asia, Africa, and the tropical Andes, aims to facilitate the development of multithematic mountain observatories by identifying mountain-specific essential biophysical and socioeconomic indicators to be monitored, thereby contributing to the development of monitoring protocols and provision of information about mountain observatories, and, importantly, helping to build regional mountain observatories network communities that can inform our understanding of mountain social–ecological and environmental processes and meet future management challenges.

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OPEN PEER REVIEW

This article was reviewed by João Azevedo and Scotty Strachan. The peer review process for all MountainAgenda articles is open. In shaping target knowledge, values are explicitly at stake. The open review process offers authors and reviewers the opportunity to engage in a discussion about these values.

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