GEO MOUNTAINS
Observing Mountain Environments

2022
International Year of
SUSTAINABLE
MOUNTAIN
DEVELOPMENT

POLICY BRIEF

MOUNTAIN OBSERVATIONS: MONITORING, DATA, AND INFORMATION FOR SCIENCE, POLICY, AND SOCIETY

Introduction

Observations play a key role in tracking mountain global change and its impacts, understanding the various processes and feedback mechanisms involved, and delivering more reliable projections of the future to society. This Policy Brief provides an overview of the current state of multi-disciplinary mountain observations. It represents a contribution of the Global Network on Observations and Information in Mountain Environments (GEO Mountains) to the observance of the International Year of Sustainable Mountain Development 2022.

Installation of mass balance stakes on Rikha Samba Glacier, Nepal (Photo: Jakob Steiner)

Cover images:
3D digital terrain representation. Rayshader. https://www.rayshader.com/

Snow depth at 500 m spatial resolution over the European Alps on 29 January 2018. Lievens et al. (2022). https://doi.org/10.5194/tc-16-159-2022

Daily mean streamflow in the Peyto Glacier Research Basin, Canada, over two historical periods. Pradhananga et al. (2021). https://doi.org/10.5194/essd-13-2875-202

Expansion of high-mountain vegetation in the Himalaya between 1993 and 2017. NASA Earth Observatory. https://earthobservatory.nasa.gov/images/149312/everest-area-plant-life-spreads

Projected gridded population count data for the year 2030 across the city of Santiago, Chile, and surrounding mountains. European Commission Joint Research Centre.
https://ghsl.jrc.ec.europa.eu/download.php?ds=pop

South Col automatic weather station (7,945 m), Everest. Khadka et al. (2021). https://doi.org/10.1002/wea.3931

Delineating Mountains and Characterising their Topography

- High elevations and rugged topography are, among others, two common defining features of mountain terrain, and affect most processes occurring in mountain social-ecological systems.
- The extent of mountain terrain is usually mapped by applying empirical criteria to digital terrain data.
- Three alternative spatial delineations, each representing different global mountain extents, have been generated [1] and can be downloaded from the Global Mountain Explorer [2].
- The resolution and accuracy of global digital terrain data have increased considerably; the latest products, such as the 30 m-resolution FABDEM [3], will likely benefit many mountain applications in the coming years.
- A hierarchical dataset of named mountain range polygons has also recently been released by the Global Mountain Biodiversity Assessment (GMBA) [4].

Installation of a precipitation gauge in the Mustang Valley, Nepal (Photo: Dawa Sherpa)

In Situ Observations

- In situ observations and measurements are crucial for tracking mountain climate and biodiversity change, downscaling and bias-correcting climate model outputs, calibrating remote sensing retrieval algorithms, and informing both process-based and data-driven climate impact models (e.g., cryospheric and hydrological models).
- The remoteness and inhospitality of many mountain settings frequently pose practical challenges to situ measurement activities. Also, certain key variables such as precipitation are difficult to measure accurately in mountains [5], and steep topographic gradients can limit measurements' spatial representativeness.
- Deficiencies in the global coverage of freely available in situ climatological time-series records from operational stations have been identified – including with respect to space (e.g., Fig. 1), time, elevation, as well in relation to other relevant factors – such as the hydrological importance of individual mountain ranges to humanity [6].

- Besides measurements made at operational sites by national and other authorities (e.g., the SNOTEL network in the United States [7]), extensive in situ monitoring in mountains is undertaken by the scientific community at sites established primarily for research purposes. For example, in the fields of ecology and biodiversity, research-focused network initiatives such as GLORIA [8] and MIREN [9] have established standard protocols which in turn have facilitated the collection and collation of datasets with research impact.
- In hydrology, meanwhile, observations are often focused on experimental catchments and are increasingly being openly published for reuse by others [e.g., 10].
- Given the multi-disciplinary and multi-institutional nature of in situ mountain monitoring, it has traditionally been difficult to obtain a clear overview of who is measuring what, where, when, how, and why across a given region.
- With this in mind, and in response to key founding objectives of the Mountain Research Initiative (MRI) [11], the GEO Mountains In Situ Inventory [12] was developed. The inventory collates data from many institutions and databases, including the World Meteorological Organization (WMO)'s OSCAR/Surface [13], DEIMS-SDR (eLTER/iLTER) [14], the Global Runoff Data Center (GRDC) [15], and the Global Historical Climatology Network-Daily inventory [16], amongst many others. Version 2.0 (released in October 2022) contains a total of over 51,000 records, some of which correspond to multiple monitoring sites (since local networks are often represented by a single entry).
- Where known, the inventory provides direct web links and/or contact information are provided to facilitate access to the corresponding data, and the research and practitioner communities are encouraged to add additional sites or improve the information available for existing sites.
- While specific metadata fields (e.g., variables measured, temporal coverage, instrumentation deployed, and protocols followed) must still be further populated, the considerable number of sites represented in the inventory challenges the common perception of mountains as sparsely observed regions to some extent (Fig. 2), although accessing the corresponding data from many sites often remains challenging.

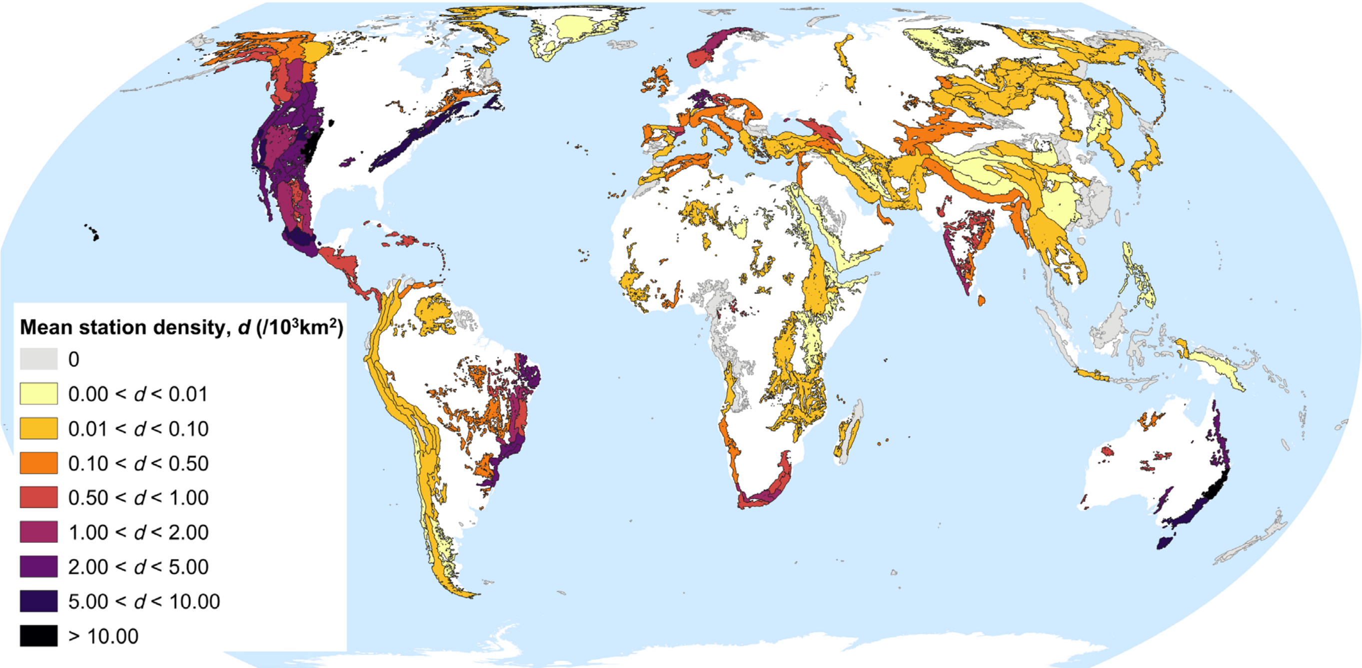

Figure 1. Mean spatial density of GHCNd stations in mountainous terrain providing daily precipitation data by GMBA mountain polygon, irrespective of record length. Source: Thornton et al. [6].

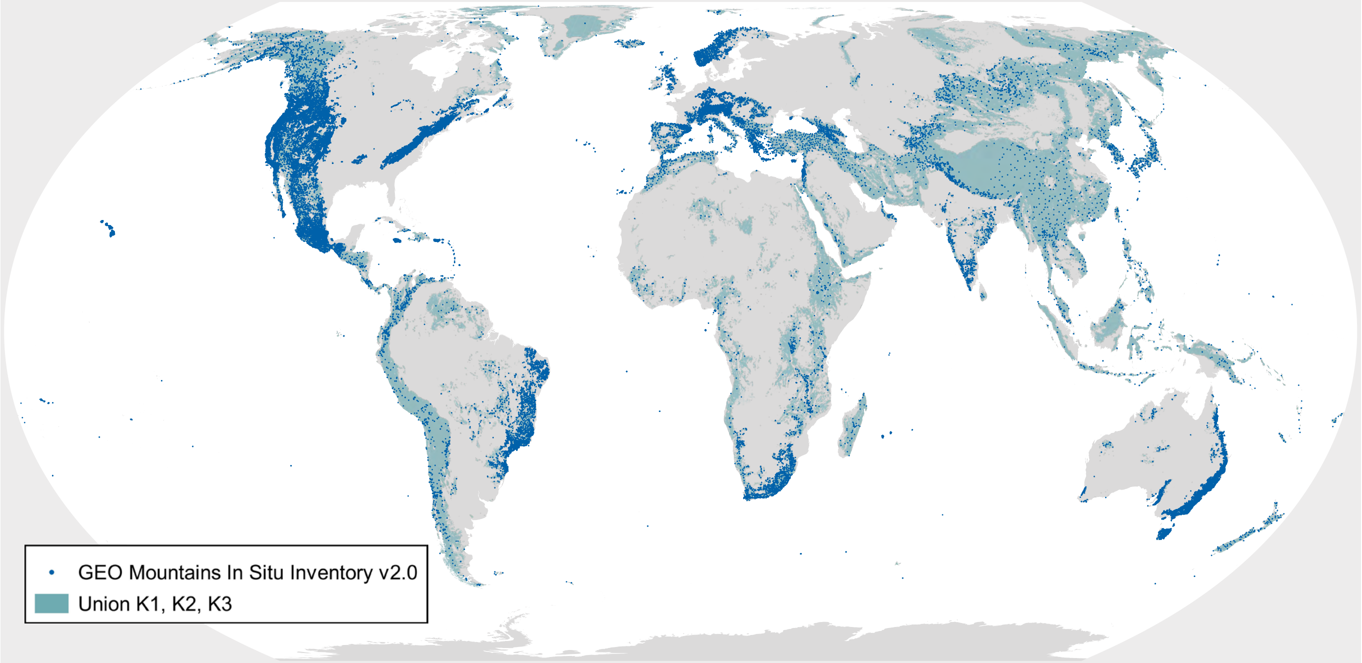

Figure 2. Locations of sites represented in the GEO Mountains In Situ Inventory, v2.0 [12].

Remote Sensing

- The quantity and quality of satellite remote sensing data available over mountainous terrain have risen dramatically over recent years and decades, with the MODIS and Landsat missions now providing lengthy records that have been heavily exploited for applications like snow cover mapping and trend analysis (e.g. [17,18]).
- Increasingly, to reduce the technical and computational burden on users, remotely sensed data are provided in pre-processed or even "analysis ready" formats, including via data cubes (e.g., the Swiss Data Cube; [19]).
- However, the application of remotely sensed data can be difficult in mountains; for example, optical methods are affected by clouds and shadows, and weather radar measurements are affected by topographic blocking and reflection [20].
- Additionally, some important variables cannot currently be derived remotely, including Snow Water Equivalent (SWE) estimates [21], high-resolution soil moisture patterns, and vertical ground temperature profiles.
- Unmanned Aerial Vehicles UAVs (commonly known as drones) and satellite constellations operated by private companies [e.g., 22] can provide higher resolution and/or frequency data than other sources, although data acquisition may be costly.

BOX 1: "MOUNTAIN OBSERVATORIES"

Recognising the need to characterise mountain social-ecological systems in a holistic or integrated manner, the Mountain Research Initiative's Mountain Observatories Working Group [48] proposed the development of a global network of long-term environmental and socio-economic monitoring sites, which they referred to as "Mountain Observatories" (MOs). More specifically, these prospective MOs are defined "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" [49]. Currently, with the help of GEO Mountains Inventories' [12,45], work is underway to identify sites that already meet these criteria (e.g., Sonnblick Observatory [50]), or else have the potential to. Thereafter, these sites will initially be grouped into a series of regional networks, the first of which is proposed to be the Central Asian Mountain Observatory Network (CAMON).

Gridded Climate Datasets, Reanalyses, and Models

- Gridded climate datasets [e.g., 23,24], which are typically available for several variables, are generated by interpolating in situ measurements using sophisticated techniques. Therefore, they are spatially and temporally complete over a given domain, although the coverage of the underlying stations strongly influences their uncertainty.
- Climate reanalysis products are generated by running physics-based, coupled climate models into which in situ and remote sensing observations are continually fed (using data assimilation techniques). As such, reanalysis products also provide multi-variate historical data that are spatially and temporally complete over a given domain. The ERA5 product [25] resolves the atmosphere in 137 vertical levels and provides hourly data on a 30 kilometre grid, while ERA5-Land [26] provides hourly data for land surface variables from 1950 to present on a nine kilometre grid.

A TOMST TMS4 in situ sensor in the tundra vegetation near Abisko, northern Sweden, part of a SoilTemp long-term microclimate monitoring network (Photo: Jonas Lembrechts)

- These products often need to be downscaled and/or bias-corrected prior to use in mountain applications, and inconsistencies between different products can be considerable [e.g. 27].
- Global Climate Models (GCMs, e.g., CMIP6 [28]) and Regional Climate Models (RCMs, e.g., CORDEX [29]) provide future projections under various plausible greenhouse gas emission and land use change scenarios, in addition to historical reconstructions (typically from 1850 to present). Climate models also enable the mechanisms involved to be explored and disentangled, and attribution studies (which seek to quantify the respective contributions of natural and anthropogenic forcing to observed trends) to be conducted.
- However, due to their coarse resolutions, GCMs require empirical "compensations" (parameterisations) to represent important smaller-scale processes such as convection and surface snow processes, and their representation of topography is heavily smoothed [30]. These factors contribute to uncertainties and biases in GCM simulations, especially in mountains.
- Even RCMs provide data at far coarser spatial resolutions than the characteristic scales of key mountain processes and change impacts; often requiring additional downscaling / bias correction [31].
- Moreover, for specific mountain ranges, it is currently unclear to what extent climate model ensemble members should be considered equally plausible, or whether some should be favoured over others (cf. [32]).

BOX 2: INTEGRATING COMPLEMENTARY DATA SOURCES FOR CLIMATE IMPACT PROJECTIONS

Both process-based and data-driven (e.g., Machine Learning) algorithms offer excellent possibilities to combine in situ and remotely sensed data for mountain applications, and thereby exploit their complementarity characteristics. Such models can fill spatio-temporal gaps in historical observations and provide one of the primary means by which local scale, decision-relevant predictions (see Box 4) of possible climate change impacts can be generated under various plausible scenarios (see e.g., [52] for glaciers). The outputs of such models thus also represent an increasingly important form of mountain data and/or information.

Citizen Science

- Citizen Science (CS), whereby the public contribute to science by collecting or analysing data, has great potential to fill key spatio-temporal gaps in mountain observations and more generally increase the quantity of data available.
- Some known examples of CS projects include Mountain Rain or Snow [33] and GlacierMap [34]; various activities are also organised by CREA Mont-Blanc [35].
- In the Community Snow Observations (CSO) [36] project, snow depth observations made by participants are assimilated into numerical models to improve estimates of Snow Water Equivalent (SWE) across large and sparsely instrumented mountain regions in North America. The value added by the citizen observations to the model predictions is quantified, enabling the observers themselves to appreciate the value of, and be credited for, their contributions

BOX 3: TOWARDS A DEFINITION OF ESSENTIAL / SHARED MOUNTAIN VARIABLES

Given limited resources for monitoring and observation, scientific and policy-related applications alike could benefit greatly from efforts to identify – in a multi-disciplinary way – variables whose observation or derivation should be prioritised to provide a globally inter-comparable body of fundamental evidence on global change in mountains. Such a set of mountain-specific variables has already been proposed for aspects related to climate change and its impacts on physical components of mountain systems [51], and similar work is ongoing for variables related to biodiversity and society and economy. If corresponding minimum observational requirements for each of these variables can be defined, and the associated data collated, a global “State of the Mountains” report could be produced, as envisaged in GEO Mountains’ founding proposal of 2015. Such a report could significantly elevate the theme of mountains within global policy agendas.

Socio-Economic Data

- Integrating socio-economic with bio-physical data has been widely recognised as necessary and important [11], however, has often proven difficult in practice.
- Many socio-economic datasets (e.g., census results) are provided in spatially aggregated formats. Political boundaries that often span both mountainous and non-mountainous terrain are typically used for this purpose, which can make disaggregation to more granular and relevant spatial units within mountains technically challenging.
- Thanks largely to remote sensing, the availability of spatially distributed layers corresponding to some socio-economic variables is improving [37], and these data can be applied to answer policy-relevant questions, such as the assessment of human population and urbanisation dynamics in mountains [38].
- As for other components of mountain systems (see Box 3), a subset of highly informative or relevant socio-economic variables should be identified, specified, and collected. The attributes that such datasets must have (e.g., frequency, spatial resolution, etc.) to be useful for general applications must also be specified.

Regional, National, and Thematic Data Portals

- Given the geopolitically transboundary nature of many important mountain ranges, successful efforts have been made to collate and share mountain data and information on a regional level (e.g., ICIMOD's Regional Database System (RDS) in the Hindu Kush Himalaya [39], and the Caucasus GeoNode [40]).
- The national data portals of some countries with substantial mountainous areas (e.g., Switzerland [41], Canada [42], and South Africa [43]) also provide much relevant data and information.
- The GEO Mountains General Inventory [44] provides a list of (and links to) various other datasets and data portals, including thematic portals, that could contribute to mountain applications. Where these resources extend beyond mountains, they should be spatially filtered using a mountain delineation. Prospective data users should always evaluate the suitability of a given data resource for their intended application(s) (see Box 4).

Derived Indicators

- In contrast to scientists who often seek to obtain and use raw or lightly processed datasets, policy and other decision makers generally require derived and/or distilled information.
- Such information is commonly presented in the form of statistics, indices, or indicators, some of which are computed specifically to respond to metrics used in global policy framework requirements.
- For example, Fig. 3 [45] provides a clear visual summary of the expected impacts of climate change on temperature, precipitation, and snow across four regions of Chile.
- Other examples include a regional socio-ecological indicator platform for the Andes developed by CONDESAN [46].

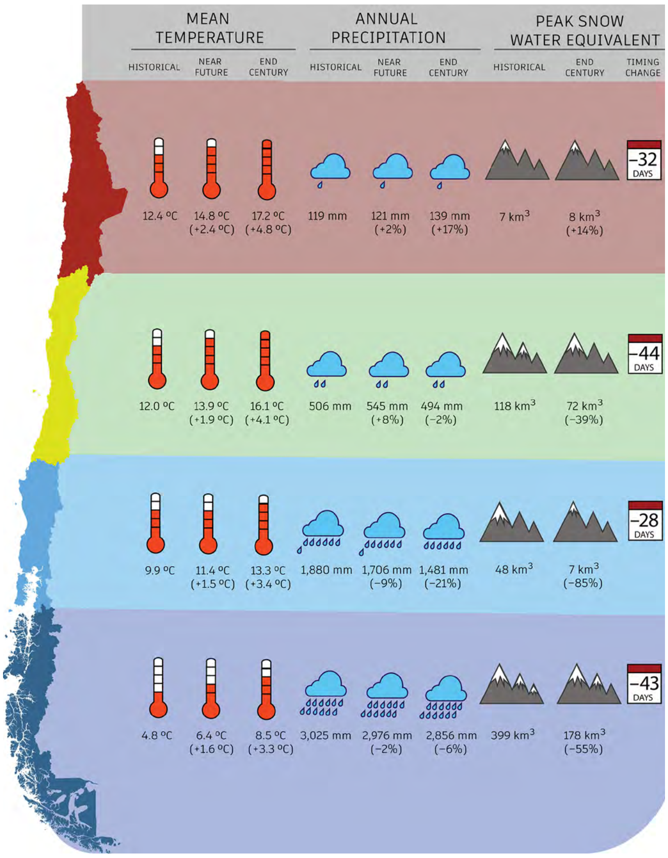

Figure 3. A summary of projected climate change impacts on mean temperature, mean annual precipitation, and median peak snow water equivalent and timing across four major regions of Chile. Source: Bambach et al. [45].

Indigenous Knowledge

- Indigenous communities have deep connections with their landscapes and extensive environmental knowledge.
- Because this knowledge is traditionally shared via oral stories and can be sacred, in the absence of appropriate protocols, it has historically been challenging or inappropriate to obtain and interrelate with western scientific processes.
- Novel approaches involving appropriate protocols and culturally sensitive knowledge co-production practices are now being developed and applied to combine western and Indigenous knowledge forms, as exemplified for instance by the work of the Canadian Mountain Assessment [47].

BOX 4: THE IMPORTANCE OF SCALE AND UNCERTAINTY QUANTIFICATION

Given the topographic and geological complexity of most mountain environments, most phenomena generally vary considerably over short distances. Many phenomena are also highly dynamic. As such, it is imperative that the spatio-temporal scales of mountain data and information are appropriate for the uses to which they are put. In addition, the various challenges associated with making mountain observations mean that data uncertainties, inaccuracies, and biases are often more substantial than elsewhere. To help users appropriately apply and interpret their products, data providers should seek to provide "quality flags", well-described caveats, uncertainty estimates, and other guidance wherever possible.

Summary, Recommendations, and Outlook

- Although mountain observation and monitoring remain challenging, a considerable amount of in situ monitoring infrastructure in place globally, and remotely sensed data volumes, are increasing rapidly. However, data availability and accessibility vary considerably according to region and discipline, and major gaps remain – especially with respect to in situ data.
- More extensive data coverage and information content analyses should be conducted as a basis for substantiating and optimising investments in establishing new, and maintaining existing, mountain monitoring initiatives.
- Optimal data coverage may not necessarily be uniform across all regions or disciplines. For example, in exceptionally ecologically or hydrologically important regions, monitoring of these aspects should be enhanced relative to elsewhere. Monitoring should similarly be comparatively enhanced in mountain regions which play a major role in the broader Earth System, and/or where projected warming is expected to strongly increase natural risks to societies, among other priorities.
- Investments and capacity sharing activities are required not only to install and maintain monitoring infrastructure, but to support the entire data lifecycle, which also encompasses data transmission, quality control, standardisation, storage, and exchange / publication.
- The potential benefits of feeding real-time streams of observational data from research-oriented sites in mountains into operational services related to weather and flood forecasting, for example, should be explored because such sites may often fill spatial gaps in operational monitoring networks.

- To support more globally consistent and inter-comparable assessments of global change in mountain systems, observation campaigns should focus on agreed priority variables ("Essential or Shared Mountain Variables"); at dedicated sites, these observations (and those corresponding to other variables) can be undertaken in detail (at "Mountain Observatories"; both approaches can help maximise information content relative to cost.

- The entire mountain observation community should work towards increased standardisation and interoperability in terms of both variables observed and means of data sharing and access, ideally converging to a common machine-readable metadata standard that is appropriate for both point time-series and gridded data. In this way, it may be possible to develop a single global mountain database from which data can be arbitrarily queried, retrieved, and/or processed.

- Specifically, greater interdisciplinary collaboration between the biophysical sciences, the social sciences, and the humanities regarding data and data integration methodologies are required to improve our collective understanding and ability to predict future changes and their impacts in complex mountain social-ecological systems.

- Improvements in monitoring, data, and information – along with adequate funding and other resources to sustain, scale, and coordinate these efforts – will help close mountain knowledge gaps identified during the IPCC's Sixth Assessment Reports [53,54]), and may furthermore enable the production of a global "State of the Mountains" report.

- The integration of multiple datasets with the latest process-based models and machine learning algorithms, along with purposeful science-policy-practice dialogues and iterative exchanges to define relevant applications, have the potential to revolutionise the translation of mountain observations into knowledge and subsequent action.

References

1. Sayre et al. (2018). A new high-resolution map of world mountains and an online tool for visualizing and comparing characterizations of global mountain distributions. Mountain Research and Development, 38(3), 240-249. doi: 10.1659/MRD-JOURNAL-D-17-00107.1
2. USGS. Global Mountain Explorer. https://rmgsc.cr.usgs.gov/gme/. Last Accessed: 29/10/2022.
3. Hawker et al. (2022). A 30 m global map of elevation with forests and buildings removed. Environmental Research Letters, 17(2), 024016. doi: 10.1088/1748-9326/ac4d4f
4. Snethlage et al. (2022). A hierarchical inventory of the world's mountains for global comparative mountain science. Scientific Data, 9(1), 1-14. doi: 10.1038/s41597-022-01256-y
5. Kochendorfer et al. (2017). The quantification and correction of wind-induced precipitation measurement errors. Hydrology and Earth System Sciences, 21(4), 1973-1989. doi: 10.5194/hess-21-1973-2017
6. Thornton et al. (2022). Coverage of in situ climatological observations in the world's mountains. Frontiers in Climate, 4. doi: 10.3389/fclim.2022.814181
7. Natural Resources Conservation Service (NRCS) of the United States. SNOTEL. https://www.nrcs.usda.gov/wps/portal/wcc/home/quicklinks/imap. Last Accessed: 29/10/2022.
8. Global Observation Research Initiative in Alpine Environments (GLORIA). https://www.gloria.ac.at/home. Last Accessed: 28/10/2022.
9. Mountain Invasion Research Network (MIREN). https://www.mountaininvasions.org/. Last Accessed: 28/10/2022.
10. Earth System Science Data (ESSD). Special Issue: Hydrometeorological data from mountain and alpine research catchments. https://essd.copernicus.org/articles/special_issue871.html. Last Accessed: 29/10/2022.
11. Becker and Burgmann (2002). Global Change and Mountain Regions: The Mountain Research Initiative. (IGBP/GTOS/IHDP). https://mountainresearchinitiative.org/images/About_MRI/Our_History/Global_Change_and_Mountain_Regions.pdf
12. GEO Mountains. Inventory of In Situ Observational Infrastructure, v2.0. https://www.geomountains.org/resources/resources-surveys/inventory-of-in-situ-observational-infrastructure. doi: 10.6084/m9.figshare.14899845.v2
13. World Meteorological Organization (WMO). OSCAR/Surface. https://oscar.wmo.int/surface/#/. Last Accessed: 29/10/2022
14. Dynamic Ecological Information Management System – Site and Dataset Registry (DEIMS-SDR). https://deims.org/. Last Accessed: 29/10/2022.
15. Global Runoff Data Centre (GRDC). https://www.bafg.de/GRDC/EN/Home/homepage_node.html. Last Accessed: 29/10/2022.
16. National Centers for Environmental Information. Global Historical Climatology Network daily (GHCNd). https://www.ncei.noaa.gov/products/land-based-station/global-historical-climatology-network-daily. Last Accessed: 29/10/2022
17. Gascoin et al. (2019). Theia Snow collection: High-resolution operational snow cover maps from Sentinel-2 and Landsat-8 data. Earth System Science Data, 11(2), 493-514. doi: https://doi.org/10.5194/essd-11-493-2019
18. Notarnicola (2022). Overall negative trends for snow cover extent and duration in global mountain regions over 1982–2020. Scientific Reports, 12(1), 1-16. doi: 10.1038/s41598-022-16743-w
19. Swiss Data Cube (SDC). https://www.swissdatacube.org/. Last Accessed 28/10/2022
20. Germann et al. (2022). Weather Radar in Complex Orography. Remote Sensing, 14(3), 503. doi: 10.3390/rs14030503
21. Luojus et al. (2021). GlobSnow v3. 0 Northern Hemisphere snow water equivalent dataset. Scientific Data, 8(1), 1-16. doi: 10.1038/s41597-021-00939-2
22. Planet Labs. https://www.planet.com/. Last Accessed: 31/10/2022.
23. European Climate Assessment & Dataset. E-OBS gridded dataset. https://www.ecad.eu/download/ensembles/download.php. Last Accessed: 02/12/2022.
24. Harris et al. (2020). Harris, I., Osborn, T. J., Jones, P., & Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Scientific Data, 7(1), 1-18. doi: 10.1038/s41597-020-0453-3
25. European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5. https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. Last Accessed: 02/12/2022.
26. European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5-Land. https://www.ecmwf.int/en/era5-land. Last Accessed: 02/12/2022.
27. Zandler et al. (2019). Evaluation needs and temporal performance differences of gridded precipitation products in peripheral mountain regions. Scientific Reports, 9(1), 1-15. doi: 10.1038/s41598-019-51666-z
28. World Climate Research Programme (WCRP). Coupled Model Intercomparison Project Phase 6 (CMIP6). https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6. Last Accessed: 29/10/2022.

29. World Climate Research Programme (WCRP). Coordinated Regional Climate Downscaling Experiment (CORDEX). https://cordex.org/. Last Accessed: 29/10/2022.

30. Baldwin et al. (2022). Outsize influence of Central American orography on global climate. AGU Advances, 2(2), e2020AV000343. doi: 10.1029/2020AV000343

31. International Centre for Integrated Mountain Development (ICIMOD). Climate change scenarios. https://www.icimod.org/initiative/climate-change-scenarios/. Last Accessed: 29/10/2022.

32. Hausfather et al. (2022). Climate simulations: recognize the 'hot model' problem. Nature 605, 26-29. doi: 10.1038/d41586-022-01192-2

33. Mountain Rain or Snow. https://rainorsnow.app/surveys Last Accessed: 29/10/2022.

34. GlacierMap. https://peruglaciers.org/. Last Accessed: 29/10/2022

35. CREA Mont-Blanc. Citizen Science. https://creamontblanc.org/en/citizen-science/. Last Accessed: 29/10/2022.

36. Community Snow Observations (CSO). https://communitysnowobs.org/. Last Accessed 28/10/2022

37. European Commission. GHSL – Global Human Settlement Layer. https://ghsl.jrc.ec.europa.eu/datasets.php. Last Accessed: 28/10/2022

38. Thornton et al. (2022). Human populations in the world's mountains: Spatio-temporal patterns and potential controls. PLOS ONE, 17(7), e0271466. doi: 10.1371/journal.pone.0271466

39. International Centre for Integrated Mountain Development (ICIMOD), Regional Database System. https://rds.icimod.org/ Last Accessed: 28/10/2022.

40. Sustainable Caucasus, Caucasus GeoNode. https://sustainable-caucasus.unepgrid.ch/. Last Accessed: 30/10/2022.

41. Maps of Switzerland. https://map.geo.admin.ch/. Last Accessed: 28/10/2022.

42. Government of Canada. Historical Data. https://climate.weather.gc.ca/historical_data/search_historic_data_e.html. Last Accessed: 28/10/2022.

43. South African Environmental Observation Network (SAEON). Data Portal. https://catalogue.saeon.ac.za/. Last Accessed: 28/10/2022.

44. GEO Mountains. General Inventory, v1.0. https://www.geomountains.org/resources/resources-surveys/general-inventory. doi: 10.6084/m9.figshare.19322573.v3

45. Bambach et al. (2021). Projecting climate change in South America using variable-resolution Community Earth System Model: An application to Chile. International Journal of Climatology, 42(4), 2514-2542. doi: 10.1002/joc.7379

46. Consortium for Sustainable Development of the Andean Ecoregion (CONDESAN). Plataforma de indicadores socioambientales en la Región Andina. https://indicadores-andinos.condesan.org/. Last Accessed: 29/10/2022.

47. Canadian Mountain Network (CMN). Canadian Mountain Assessment. https://www.canadianmountainnetwork.ca/research/canadian-mountain-assessment-group/canadian-mountain-assessment. Last Accessed: 29/10/2022.

48. Mountain Research Initiative. Mountain Observatories. https://mountainresearchinitiative.org/activities/community-led-activities/working-groups/2097-mountain-observatories. Last Accessed: 30/10/2022

49. Shahgedanova et al. (2021). Mountain observatories: Status and prospects for enhancing and connecting a global community. Mountain Research and Development, 41(2), A1. doi: 10.1659/MRD-JOURNAL-D-20-00054.1

50. ZAMG. Sonnblick Observatorium. https://www.sonnblick.net/en/. Last Accessed: 31/10/2022

51. Thornton et al. (2021). Toward a definition of Essential Mountain Climate Variables. One Earth, 4(6), 805-827. doi: 10.1016/j.oneear.2021.05.005

52. Marzeion et al. (2020). Partitioning the uncertainty of ensemble projections of global glacier mass change. Earth's Future, 8(7), e2019EF001470. doi: 10.1029/2019EF001470

53. Hock et al. (2019). High Mountain Areas. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner et al. (Eds.)]. https://www.ipcc.ch/site/assets/uploads/sites/3/2022/03/04_SROCC_Ch02_FINAL.pdf

54. Adler et al. (2022). Cross-Chapter Paper 5: Mountains. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Pörtner et al. (Eds.)]. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_CCP5.pdf.

Peat coring at Maua (flower) Swamp at around 4,000 m on the southern slopes of Kilimanjaro. Mustaphi et al. (2020). https://doi.org/10.1017/qua.2020.76

MOUNTAIN RESEARCH INITIATIVE

ISAC

ADAPTATION AT ALTITUDE
Taking Action in the Mountains

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Agency for Development
and Cooperation SDC

Please send enquiries to:

GEO MOUNTAINS
Observing Mountain Environments

Mountain Partnership

GEO Mountains
geomountains@mountainresearchinitiative.org

Mountain Partnership Secretariat
info@mountainpartnership.org

The views expressed in this Policy Brief are those of the Authors (J.M. Thornton, E. Palazzi, and C. Adler).
The Authors accept no responsibility for the accuracy or completeness of the contents and shall not be liable for any loss or damage that may be occasioned, directly or indirectly, through the use of, or reliance on, the contents of this publication.

Suggested citation: GEO Mountains (2022). Mountain Observations: Monitoring, Data, and Information for Science, Policy, and Society. Policy Brief: International Year of Sustainable Mountain Development 2022.