



Proposal for the Unified High Elevation Observing Platform (UHOP)

For Monitoring, Understanding, and Predicting Climate
Change Phenomena across the World's Mountains

v1.0, 2 December 2024

Summary

Climate change impacts appear to be enhanced in mountain regions, which show rapid loss of snow and ice, shifting ecological systems, and increasing effects on mountain societies and human activities. Where we have data, the rate of climate change is often observed to be more rapid at higher elevations.

However, there remains a distinct lack of consistent “on the ground” climate measurements across elevation gradients worldwide, undermining our ability to effectively report, understand, and predict these changes and their impacts.

This document arose from a workshop hosted by the Mountain Research Initiative and GEO Mountains at the University of Bern, Switzerland, from 25–27 June 2023. In it, we outline a global approach for the observation of climate and weather variables across elevation gradients in the world’s mountains.

More specifically, we elaborate and invite community feedback on v1.0 of a standardised protocol – the Unified High Elevation Observation Platform (UHOP) – for making climate and meteorological observations across elevational gradients. We consider best practice in where to set up transects, and what type of stations to employ.

We also consider how other important objectives, such as weather forecasting, hazard prediction, and snow and ecological monitoring can be integrated. We envisage providing global accreditation to observation networks already meeting the criteria, and support for network enhancement. The work remains in progress, and further ideas and suggestions on the proposals are welcome.

We hope that the UHOP will ultimately provide benchmark data for scientists and government agencies wanting to understand climate change and meteorological forecasting in these regions, in turn enhancing community resilience in mountains and downstream.

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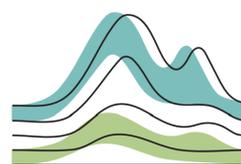
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1 Introduction and rationale

The impacts of recent climate change on the physical environment and society are becoming increasingly pronounced as the 21st Century progresses, and this trend is particularly apparent in the world's mountain regions. Increasing temperatures enhance melt of the cryosphere, leading to rapid loss of snow, glaciers, and permafrost. This will ultimately result in, and in many regions has indeed already caused, negative implications for water resources for millions of people living in and downstream of mountains.

For instance, mountain snowpacks provide a critical water supply in India and China, the two most populous countries on Earth. Higher temperatures mean more rain and less snow, as the occurrence of freezing temperatures becomes less common. Increased rainfall intensities in mountains is also exacerbating many mountain hazards including flooding, landslides, and glacial lake outburst floods (GLOFs). With warmer temperatures, plants and animals have to migrate upslope to find suitable habitats, while alpine species already near the mountain summits may have nowhere to go. Forest fires are also known to be occurring at higher elevations, whilst increased frequency and severity of heatwaves further exacerbate snow and ice melt.

The phenomenon whereby different elevations can warm at different rates is known as **elevation-dependent warming (EDW)**. More specifically, there is increasing evidence that many high mountain regions are warming more rapidly than adjacent lowland areas. The concept may potentially extend to other meteorological variables such as precipitation, leading to the notion of **elevation-dependent climate change (EDCC)**.

In order to better understand EDCC, a standardised approach for making climate and environmental observation along elevational gradients is required. Quantifying these changes will improve our understanding of climate change in the mountains, and aid communities to become better stewards of these fragile environments. In addition, grouping different meteorological stations to establish networks along elevational gradients could greatly support meteorologists who are working to enhance forecasting of extreme weather events – which are also expected to increase due to climate change. For example, observations along elevational gradients will support forecasts of the rain/snow limit and prediction of floods that involve snow and snowmelt. In summary, it is critical that we understand a variety of phenomena as fully as possible in order to support mountain communities in becoming more resilient to climate change impacts.

Unfortunately, there is currently a lack of widespread, reliable climate observations at higher elevations. For instance, in the Global Historical Climate Network (GHCNv4) dataset, which comprises mostly operational stations, < 5% and < 1% of the stations are over 2,000 and 3,000 m, respectively, and there are no stations above 5,000 m. Yet the highest summit on Earth is Chomolungma / Mt Everest (8,848 m), and there are many extensive mountain areas without any weather stations at all.

Unlike the polar regions which have seen considerable recent investment in scientific observation, investment in mountain observations appears to have remained comparatively limited. This could (at least in part) be because mountain regions are scattered

all around the world, spanning many different countries. Indeed, mountain divides often form international borders. In common with polar regions, the extreme and often difficult-to-access (both physically and politically) nature of mountain environments make implementing and sustaining long-term observation programs challenging. In recent years, some weather stations have been installed at extremely high elevations, including on the slopes of Chomolungma / Mt Everest, but the corresponding records are short and costs high.

Thus, most high mountain stations are associated with short term research projects run by small research groups, for instance from universities. When grant periods finish, there is often little option but for stations to be removed. As such, **there is a clear need for a global, standardised protocol to support consistent and long-term climate and environmental measurements across elevation gradients.**

2 Definition of an elevation gradient and positioning of the main transect line

Central to the definition of the UHOP is the identification in each study region of a main linear gradient or transect line, which should correspond to the large-scale elevation gradient of the mountain range. Ideally, the transect line should cover the entire elevation difference (ED), from adjacent plain (within the same climatic region) to the highest mountain summit. For example, the highest summit in the Colorado Front Range is Grays Peak (4,352 m), while the lowest plain elevation is that of Denver (1,608 m), giving an ED of approximately 2,750 m. The gradual decrease in elevation across the high plains to the east of Denver would not be considered part of the transect.

In practice, the transect line will usually be perpendicular to the main mountain ridge (see the hypothetical example presented in Figure 1), and may actually extend over the summit ridge and down the other side (although this would technically be two separate UHOP transects). Desirable transect lines will often follow either a valley with headwaters near the main ridge (V), or a “secondary” ridge extending transverse to the main ridge (R). It is inadvisable to mix valley and ridge exposures in the same transect. Rather, it is best to stick to either the valley bottom or the ridge top as far as possible to avoid additional (slope) aspect contrasts within the transect, which could be problematic.

There are disadvantages and advantages of using ridges vs. valleys for the main transect. Ridges are well ventilated and will generally give a better representation of the regional scale climate, free from microclimatic effects. Exposure to the free atmosphere will ensure that observations are representative of a wide area. However, in windy and/or snowy environments, stations on ridgelines may be impractical or yield unrepresentative data. In these circumstances, stations could be sited just off the ridgeline. Ideally, slopes with similar aspects to those elsewhere in the transect should be used (e.g., in Figure 1, R6 should preferentially be located on the near side of the ridge, broadly following the aspect of R4 and R5).

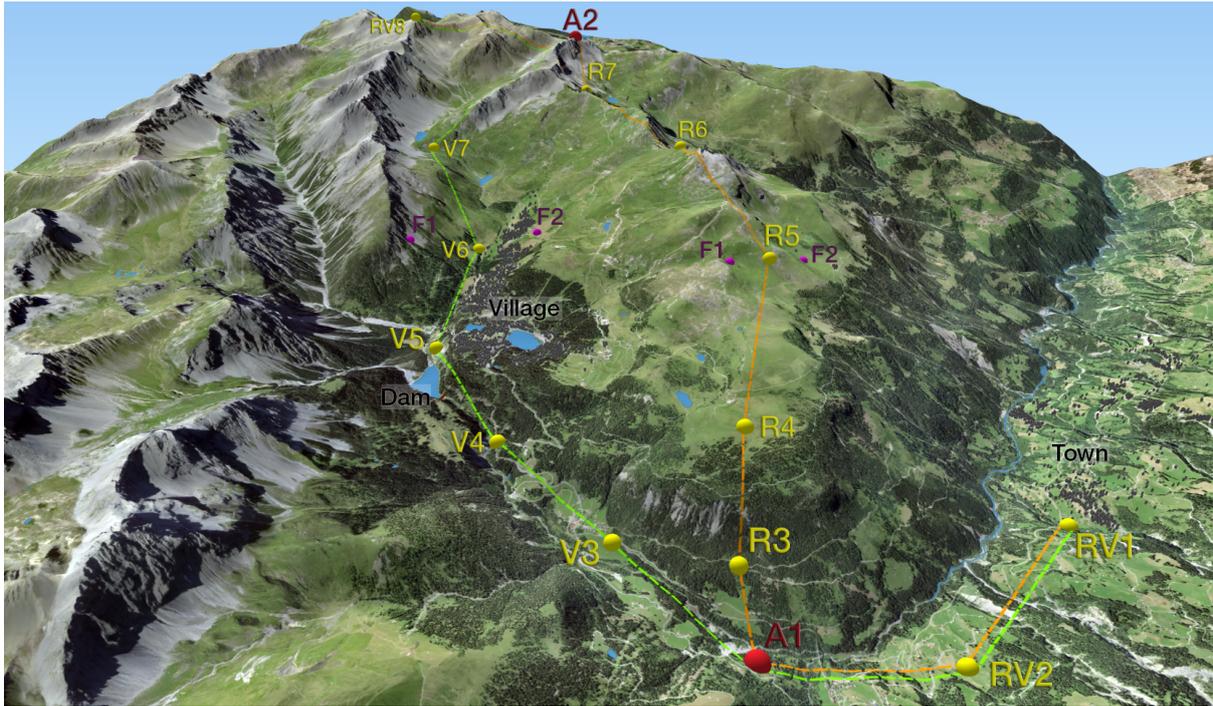


Figure 1: Hypothetical landscape representing a typical elevation gradient, with alternative routes for the installation of a UHOP (elevational transect). The main transect in a given region may follow a valley (V) or ridge (R). Sites RV1, RV2 and RV8 feature in both possible transect lines. Examples of possible ANCHOR, INTERMEDIATE, and FLOAT sites are represented in red, yellow, and purple, respectively. Ideally, the two ANCHOR stations (A1 and A2) should be situated near the ends of the transect to cover the maximum possible elevation range (see Table 2). That said, it is acknowledged that the highest and lowest elevations may be impractical locations, being inaccessible and/or highly unrepresentative, or highly urbanised, respectively. INTERMEDIATE station placement should seek to avoid large villages or urban areas (e.g., the town between V5 and V6 should be avoided as far as possible). Dams or lakes are also generally unsuitable for INTERMEDIATE stations since they create distinct microclimates. There should be minimal variation in the aspect of the slopes on which INTERMEDIATE stations are situated. For example, the slope at R6 has an aspect (facing away from the viewer) which is opposite to the main aspect of the near side of the ridge (towards the viewer), and so would be better situated in front of the peak between R5 and R6. In the V transect, it is best to avoid placing INTERMEDIATE stations on valley sides, which can also have distinct microclimates. FLOAT stations measure the additional aspect-driven and other spatial climatic variability at a given elevation (e.g., F1 and F2 around R5 or V6). Only a small number of FLOAT stations are shown, but in a real UHOP transect there may be many such stations. For example, additional float stations could be included in this example to monitor micro-scale climate variation around treeline (between R3 and R4) and/or local cold air pockets in valleys. Figure prepared by Jennifer Johnston, Inspirit Cartographics.

Since valley transects will often benefit from ease of access and infrastructure such as roads, which make maintenance easier, they can be more practical than ridgeline transects. However, they also frequently include other features such as mountain settlements and lakes/dams, which can create microclimates and so should be avoided as far as possible when siting stations. Some valleys can also be prone to extreme microclimates and cold air pooling. Where already known to be a feature of the local climate, primary transects spanning the ED should as far as possible avoid such

locations. Valleys which form broad basins at higher elevations but which are highly constricted at lower elevations (e.g., form narrow gorges) can be affected by intense cold air ponding. Such areas are often decoupled from the wider region, and do not provide much information about the broader elevation gradient.

Valley or ridge transects are not the only possible solutions. In some areas, mountain roads may give broad access to a slope with a given aspect, enabling the efficient establishment of an elevational transect. The protocol of the Mountain Invasion Research Network (MIREN) similarly makes extensive use roads. Again, the aspect of each individual station along the transect should be kept as constant as possible to prevent the introduction of additional confounding factors.

3 General UHOP protocol and station tiers

In climate monitoring, there is usually a trade-off between instrumentation specifications in terms of sensor accuracy and range (and hence the number variables measured) on one hand, and cost in terms of equipment purchase and time invested in installation and maintenance on the other.

Recognising this, the UHOP protocol employs a tiered system which combines the highest specification stations (referred to as ANCHOR stations), moderate level stations (INTERMEDIATE stations), and low-cost stations (FLOAT stations). In this way, a suitable balance can be struck between the number of stations installed in a given mountain transect network (for sufficient elevational and spatial coverage) and data quality and homogeneity. All three tiers have an important role in a fully coordinated UHOP transect.

A brief overview of each station tier is given below, with further details given in the following subsections:

- **ANCHOR:** A fully automated weather station, measuring the complete radiation balance, following World Meteorological Organization (WMO) standard protocols (as far as is practicable), preferably employing aspirated screening. There is a list of required variables.
- **INTERMEDIATE:** An automated stand-alone (tripod) weather station using standard screening, which may be battery powered or employ a data-logger. There is no list of required variables.
- **FLOAT:** Lower cost sensors (of variable type) using non-standard screening, which may be attached to trees or other structures. There is no list of required variables.

Each UHOP should, generally speaking, aim to incorporate as many stations in the higher tiers (i.e., ANCHOR and INTERMEDIATE) as possible. Depending upon the number and distribution of stations of a given tier implemented, along with various other

factors, each UHOP transect will receive one of three levels of accreditation: BRONZE, SILVER, or GOLD. Requirements for each level can vary somewhat depending on the specific UHOP objective (see Sections 4 and 5).

Table 1 provides an example of station attributes for each tier with respect to air temperature measurement. Equivalent tables will be produced for other variables following further consultation.

Table 1: Key properties of each UHOP station tier for air temperature measurement. *RH stands for relative humidity. †Costs are approximate (at order of magnitude) typical total station cost for equipment (not just for temperature measurement), and do not include maintenance and upkeep, valid for 2024. The aim is not to evaluate or recommend particular suppliers, but to give examples to assist understanding. Different sensors from the same supplier may fall into different tiers. Sensor accuracy is the most important criterion in determining station tier. Similar tables will be developed in due course for other variables that UHOP will likely measure.

Tier	Sensor Accuracy	Screening	Example Sensors for Temp/RH*	Expected Cost†
ANCHOR	±0.1°C	Aspirated standard	Rotronic HC2C3	~USD 10,000+
			Campbell HygroVue10	
INTERMEDIATE	±0.25°C	Standard	HMP155A-L	~USD 1,000+
			Hobo U23-001	
FLOAT	±0.5°C	Non-standard	Vaisala WXT530	~USD 100+
			Campbell HMP45A	
			Hobo Pendant	
			iButton	
			Tinytag Plus 2	

3.1 ANCHOR Stations

Function: To “anchor” observations across the gradient to global standards

As the name suggests, the primary function of ANCHOR stations is to “anchor” other observations, both within a given UHOP transect and between different UHOP transects, by providing high quality observations of the main “Essential Mountain Climate Variables” representative of conditions at the ANCHOR station elevations. These stations will ensure a standardised approach to climate monitoring. They should follow WMO standards, and should have undergone laboratory controlled absolute calibration. In this way, data from different ANCHOR stations (both within and between UHOP transects) can be compared.

ANCHOR stations should normally have a power source and communication links (for real time data transfer and download), and measure at least 2 m air temperature, relative humidity, wind speed and direction, all four radiation components (i.e., incoming and reflected solar radiation, emitted longwave and downwelling longwave), and precipitation (Figures 2a and b). Because solar radiation can be intense at high elevations, aspirated screening for temperature and humidity sensors is highly recommended to maximise measurement accuracy. Because measuring wind speed at 10 m (as suggested by the WMO) is impractical in extreme windy environments, 2 m is deemed sufficient for ANCHOR stations.

Siting stations in whatever land cover is dominant of the elevation zone at the intended location, as opposed to over grass cover as is commonly stipulated by the WMO, is also acceptable and often necessary; in areas of permanent snow and ice or thick forest, siting over grass cover is clearly impossible. The varied land-cover types within an elevation transect partly influence the regional elevation gradient.

Individual sensors should follow accuracy guidelines which will eventually be provided additional guidance tables, complementing those already developed for air temperature measurement accuracy (see Table 1).

ANCHOR stations are required for highly accredited UHOP transects. Ideally, SILVER and GOLD UHOP transects should be comprised of at least two ANCHOR stations, which should between them cover as much of the elevational gradient under consideration as possible (i.e., the ED between them should be substantial). Because maintaining ANCHOR stations on the highest summits is often very challenging, the UHOP protocol acknowledges that the highest ANCHOR station may be at a somewhat lower elevation than the very highest station (which could be of a lower tier) / highest peak. However, as one factor influencing SILVER and GOLD accreditation, the basic ANCHOR pairing should span at least 70% and 90% of the overall gradient if the highest peak is 6,000 m or below, respectively. If the highest peak is above 6,000 m, the percent coverage requirement is only calculated up to this elevation (i.e., any terrain above 6,000 m is ignored).

3.2 INTERMEDIATE Stations

Function: To fill gaps in the monitoring of the elevation gradient at an individual UHOP transect

The main role of the INTERMEDIATE stations is to fill in gaps in the characterisation of the main elevational gradient between the ANCHOR stations, providing better representation of the shape of the whole elevation profile and understanding of climate conditions over it.

At the lowest UHOP accreditation level (BRONZE), INTERMEDIATE stations are permitted to replace ANCHOR stations. INTERMEDIATE stations will have intermediate quality sensors (or higher). Normally, sensors will be mounted on stand-alone stations on tripods, and will be screened using standard methods (Figure 2c).

INTERMEDIATE stations may consist of data-logging systems; there is usually no requirement for these stations to have on-site power, nor for their data to be available in real-time (unless their objective is to support short-term forecasts, which do demand on-site power and real-time data transmission). Battery powered systems, which require manual downloading, are therefore normally acceptable. INTERMEDIATE stations will typically measure 2 m air temperature and humidity, sometimes alongside wind speed and direction, and may measure radiation components. However, unlike ANCHOR stations, there is no list of required variables. Other variables may be required depending on the specific thematic focus of the UHOP (see Section 4). Standard commercially available sensor screens should be employed (there is no requirement for aspirated screens).

Although stand-alone tripods are preferable (and would probably be typical for INTERMEDIATE stations), in certain circumstances suitable sensors may be mounted on other fixtures such as trees, fenceposts, etc. if locally practicable and sampling locations representative of the wider ecological zone. For example, within a densely forest zone, trees could be used rather than removing vegetation to install a stand-alone station in a clearing. However, using trees in areas where they are isolated is not advised because they create their own microclimate, which may be unrepresentative of the wider zone being measured.

The spacing of INTERMEDIATE stations also contributes to the determination of UHOP accreditation for SILVER and GOLD levels. For SILVER status, the spacing between adjacent stations in the upper two tiers (i.e., INTERMEDIATE or ANCHOR) must not exceed 20% of the ED (i.e., there need to be at least six INTERMEDIATE or ANCHOR stations in total along the ED). For GOLD status, spacing between adjacent stations in these tiers must not exceed 10% of the ED (i.e., at least 11 stations are required in total).

3.3 FLOAT Stations

Function: To measure fine-scale variability within and surrounding the elevation gradient of a given UHOP transect

The lowest tier is the FLOAT station, the primary purpose of which is to measure the finest scale variation within the elevation gradient, as well as additional lateral spatial variability surrounding the main elevation gradient. Complex mountain topography leads to distinctive microclimates. Many other factors besides elevation slope aspect, angle, and exposure, proximity to features such as lakes and trees, and other land cover contrasts induce much additional climatic variability. These effects represent an important part of understanding the overall response of a region to climate change, but cannot be quantified in a single elevation gradient.

FLOAT stations are typically low cost data-loggers which can be employed in a greater number of locations to capture spatial climate variability in a broader sense. Typical applications include monitoring cold air drainage patterns, and examining microclimates within and around vegetation and local topography (e.g., exposed rocks vs. adjacent

hollows). Their main advantages are low cost, ease of deployment, and “strength in numbers”.

Individual FLOAT data-loggers may be screened using non-standard approaches. Figures 2d and e show such sensors, which can be installed in a variety of locations (e.g., in trees, under rocks, in the soil, etc.), depending on the application. Typically, there may be > 30 stations in a FLOAT network, and in some cases > 100. At the lowest UHOP accreditation level (BRONZE), FLOAT stations may be used to fill in the gaps between a smaller number of ANCHOR or INTERMEDIATE stations, especially in areas with a large ED to cover, lack of infrastructure, and/or limited budgets.

Because non-standard screening and/or lower quality sensors may be employed, the most useful information obtained is likely to be relative spatial variability between FLOAT locations (rather than absolute values). If the latter are of interest, careful field cross-evaluation between FLOAT stations at INTERMEDIATE and/or ANCHOR sites will be required. This would involve running the two methods (non-standard vs. standard screen and/or sensor) next to each other for multiple years to obtain the probability distribution function of the differences between the two observation series. As in UHOP more generally, comprehensive and accurate metadata will be required to document this process. Further guidance related to this will be developed in the future.

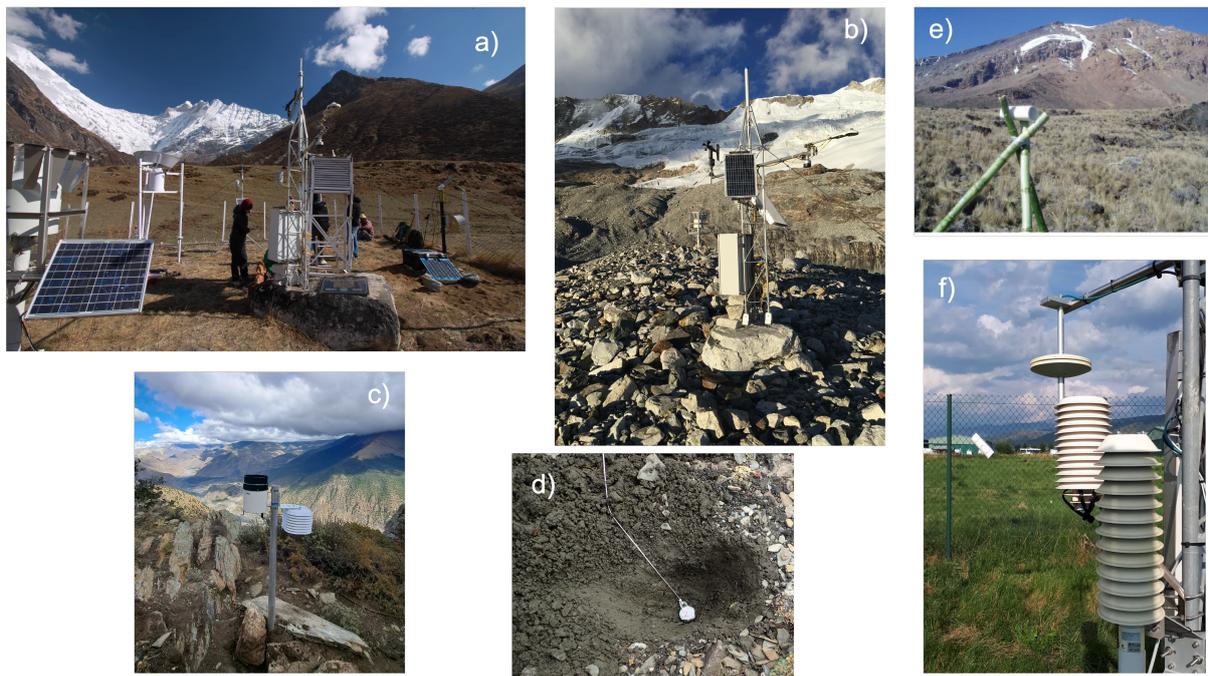


Figure 2: Examples of station types indicative of different UHOP tiers: a) Weather station compound with on-site power (ANCHOR), b) traditional automatic weather station (tripod), which would normally form part of an ANCHOR or INTERMEDIATE station, c) an INTERMEDIATE level tripod station, d) a low-cost FLOAT sensor (soil temperature logger), e) another example of a FLOAT station using unconventional screening (local materials), and f) cross-evaluation between an ANCHOR station and a FLOAT station (tube on fence).

4 Possibilities to apply the UHOP concept for other objectives

Although the main objective of UHOP, as originally conceived, is to measure elevation-dependent climate change (as discussed so far), in certain circumstances or applications there may be additional objectives. Every network along an elevational gradient therefore may have one of perhaps four main objectives (1) climate monitoring (especially elevation dependent climate change; EDCC), (2) microclimate monitoring, (3) extreme weather forecasting, and (4) hydrological (and hydrometeorological hazard) forecasting. A network being designed with a primary objective does not necessarily prevent it being leveraged to support other objectives. However, it is important for the primary objective of each UHOP transect to be clearly specified. Wherever possible, some fundamental climate monitoring should be maintained.

4.1 Climate monitoring (EDCC)

Many UHOP transects will likely be primarily designed to quantify EDCC through comparison of reliable climate observations over decadal timescales along numerous elevational transects sited across the world's mountains. Generally, it is not necessary for these data to be made available in real time, since the focus is quantifying climate change over many years in these high elevation environments.

Questions that these transects could aim to answer include:

To what extent are warming rates dependent on elevation? Do elevation-dependent warming patterns vary across the world's mountain ranges? Do particular elevation bands which act as warming "hotspots"? Are there a systematic seasonal or latitudinal contrasts? How are long-term changes in other climate variables (such as precipitation, snowfall and snow cover, humidity, cloud, and wind patterns) influenced by elevation?

4.2 Microclimate monitoring

Some UHOP transects may focus primarily on microclimate monitoring. These networks will measure temperature at (or very close to) the ground surface, and will predominantly support research around how vegetation and ecological communities are responding to climate change.

Questions that these transects could aim to answer include:

How does temperature and humidity at (or close to) the surface affect vegetation and ecological communities? What are the influences of climate change on soil moisture and temperature? How quickly will isotherms move uphill? Are there areas or niches which may be less impacted by the warming climate (e.g., where cool air pooling occurs)?

4.3 Extreme weather forecasting

Other UHOP transects may be designed to focus on lapse-rate monitoring, in support of meteorologists and other experts in the predication of extreme weather events. Lapse rate calculations require real-time temperature and relative humidity along elevational transects. Summit stations with wind sensors unobstructed by terrain are also a useful component to forecasters.

Questions that these transects could aim to answer include:

When and where are extreme events expected in a given region? What is the effect of topography and slope aspect on local susceptibility to extreme conditions (e.g., are ridges and valleys similarly exposed)? How does large-scale slope aspect influence weather patterns? Are extreme event frequencies changing? How might enhanced heatwaves impact the higher elevations?

4.4 Hydrological forecasting

Lastly, some UHOP transects may focus on the quantification and prediction of precipitation and hydrology, including hydrometeorological extremes (e.g., floods). UHOPs located in colder environments seeking to address this primary objective will likely focus primarily on monitoring snow accumulation and melt processes. However, these stations can also be leveraged in summer months, for instance to quantify the typically greater quantities of precipitation that high-elevation areas in mid-latitudes receive compared to surrounding lowland areas due to orographic enhancement.

Questions that these transects could aim to answer include:

How rapidly do snowpacks melt in particular mountain ranges, and to what extent could this snow melt contribute to flooding downstream? How will mountain snowlines and snowpacks shift over time, with implications for seasonal water resources downstream? How does the snow/rain line vary during mixed precipitation events, and how could this affect water retention and flooding? How will mountain precipitation patterns change? Are there positive feedback mechanisms which might amplify the impacts in certain elevation zones - for instance will the exposure of more bare rock with melting snow enhance warming rates at particular elevations via the snow-albedo mechanism, or will rain on snow events increase the propensity for downstream flooding?

Table 2: Indicative minimum requirements for UHOP types (based on primary objective) by accreditation level, which depends on the number and distribution of stations per tier, alongside other factors.

Accreditation Level	Objective 1: Climate monitoring (EDCC)	Objective 2: Microclimate Monitoring	Objective 3: Extreme Weather Forecasting	Objective 4: Hydrological Forecasting
BRONZE	<p>1 ANCHOR or INTERMEDIATE station, supplemented by ≥ 5 FLOAT stations (covering $>50\%$ of the ED) measuring air temperature (2 m)</p> <p>Real-time data transmission not required</p>	<p>≥ 5 FLOAT stations measuring temperature and relative humidity near the surface</p> <p>Real-time data transmission not required</p>	<p>≥ 3 FLOAT or INTERMEDIATE stations measuring temperature and relative humidity</p> <p>Real-time data transmission required at all stations</p>	<p>≥ 3 INTERMEDIATE or ANCHOR stations measuring precipitation and snow depth (snow applicable in cold regions only)</p> <p>Real-time data transmission required at all stations</p>
SILVER	<p>2 ANCHOR stations near the extremes of the transect, (covering $> 70\%$ of the ED), supplemented by ≥ 4 INTERMEDIATE stations</p> <p>Real-time data transmission not required</p>	<p>≥ 5 FLOAT stations measuring temperature, relative humidity near the surface and at 2 m</p> <p>Soil temperature near the surface</p> <p>Real-time data transmission not required</p>	<p>≥ 3 INTERMEDIATE or ANCHOR stations measuring temperature and relative humidity</p> <p>Real-time data transmission required at all stations</p> <p>Summit station has wind measurement unobstructed by terrain</p>	<p>≥ 3 INTERMEDIATE or ANCHOR stations measuring precipitation, soil moisture at various depths, snow depth, and Snow Water Equivalent (snow applicable in cold regions only)</p> <p>At least 2 precipitation gauges are heated (if in cold environment)</p>
GOLD	<p>≥ 3 ANCHOR stations (covering $> 90\%$ of ED), numerous (≥ 8) INTERMEDIATE stations to fill in the gaps along the main gradient, plus further INTERMEDIATE or FLOAT stations to examine additional spatial variation beyond the main transect</p> <p>Data transmission preferred, but not essential in real-time</p>	<p>≥ 5 FLOAT stations measuring temperature, relative humidity near the surface and at 2 m</p> <p>Soil moisture and temperature near the surface</p> <p>FLOAT stations paired with INTERMEDIATE stations at the bottom and top of the transect</p> <p>Data transmission preferred, but not essential in real-time</p>	<p>≥ 5 INTERMEDIATE or ANCHOR stations</p> <p>Real-time data transmission required at all stations</p> <p>All INTERMEDIATE stations are equipped with wind sensors suitable to the mountain's weather conditions</p> <p>Summit station has wind measurement unobstructed by terrain</p>	<p>≥ 5 INTERMEDIATE or ANCHOR stations measuring precipitation, soil temperature and moisture at various depths, snow depth, and Snow Water Equivalent (cold regions only)</p> <p>Real-time data transmission required at all stations</p> <p>At least 3 of the precipitation gauges are heated (if in cold environment)</p> <p>Physical observations of snow properties near to real-time observation sites twice per year.</p>

5 Proposed accreditation system

Figure 3 provides a visual illustration of the indicative differences between accreditation classes for the climate monitoring objective (Objective 1), which has already been discussed in the previous section.

Table 2, meanwhile, provides an overview of how the main specification requirements for accreditation at each level (BRONZE, SILVER, and GOLD) may vary according to a given UHOP transect's objective. **Since the protocol is a work in progress, feedback on both aspects is welcome.**

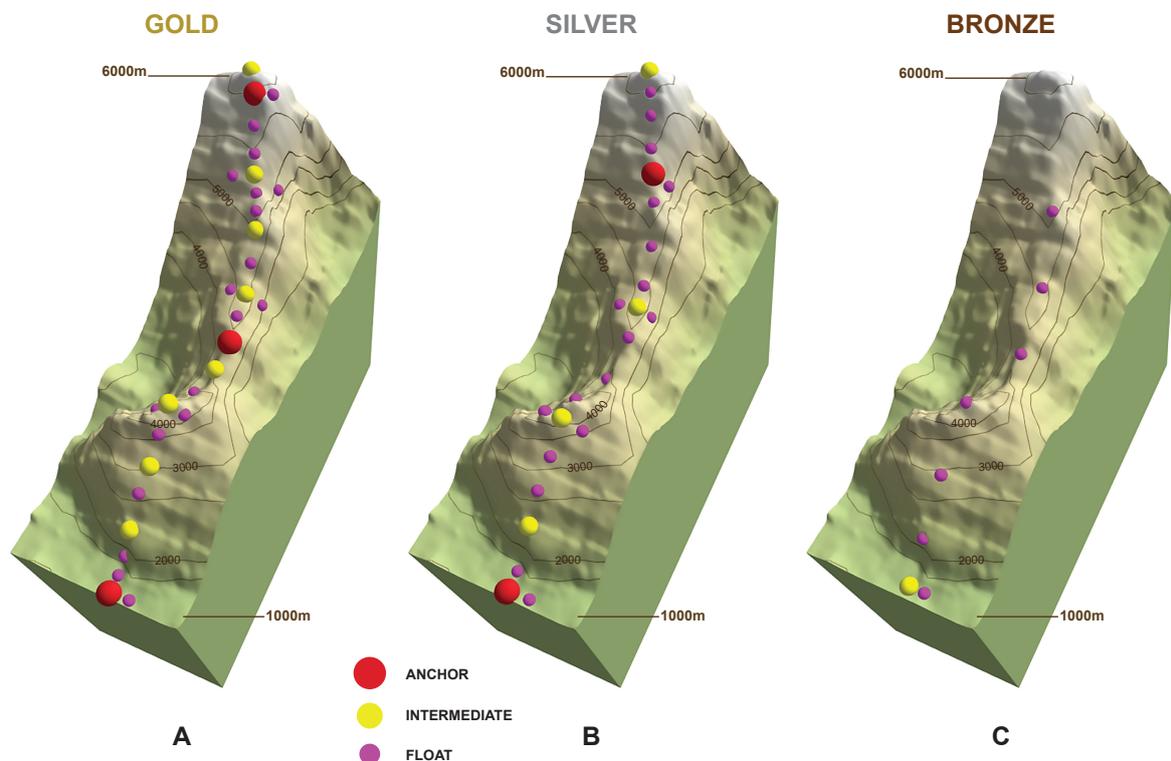


Figure 3: Indicative minimum requirements in terms of the number and distribution of stations of each tier in a given UHOP transect by accreditation level: A) GOLD, B) SILVER, and C) BRONZE. This example shows the requirements for monitoring elevation-dependent climate change (Objective 1; see the left hand column of Table 2). The overall elevation difference (ED) is defined as the difference in elevation between the plain and summit, but ignoring any elevations > 6,000 m (not shown in this particular example). To receive GOLD accreditation, ANCHOR stations (red) need to span $\geq 90\%$ of the ED, with the spacing between adjacent INTERMEDIATE or ANCHOR stations of $\leq 10\%$ of the ED. For SILVER accreditation, these criteria are relaxed to $\geq 70\%$ and $\leq 20\%$ of the ED, respectively. For BRONZE accreditation, a minimum of only one ANCHOR or INTERMEDIATE station (located anywhere on the transect) is required. Figure prepared by Jennifer Johnston, Inspirit Cartographics.

6 Prospective UHOP transects

The UHOP concept is designed to have the flexibility to work with, integrate, and further develop existing transect monitoring infrastructure, where present. Table 3 presents a short, non-exhaustive list of known existing sites that could potentially consider becoming part of UHOP in due course. **We especially welcome feedback on the UHOP protocol, and actively solicit expressions of interest in becoming involved, from representatives of these and similar sites.** Of course, there is absolutely no obligation for any site, listed or otherwise, to become involved in UHOP should they not wish to.

Table 3: Initial non-exhaustive list of existing transects which could potentially become UHOP transects. The presence or absence of a given site or institution in this list is not definitive, and neither commits nor precludes involvement in the UHOP initiative.

Location	Known Key Institutions / Stakeholders	Region
Mt. Kilimanjaro	Tanzania Meteorological Agency, Kilimanjaro National Park, University of Innsbruck, Philipps-University Marburg, University of Massachusetts Amherst, University of Portsmouth	East Africa (Tanzania)
North-East Appalachian Mountain Observatory Network	University of Vermont, The Research Foundation for the State University of New York (SUNY), Mount Washington Observatory	Appalachians (USA)
Langtang	University of Utrecht, The Norwegian Water Resources and Energy Directorate (NVE), The International Centre for Integrated Mountain Development (ICIMOD)	Himalayas (Nepal)
Poleka Kasué	Universidad EIA	Andes (Colombia)
Llanganuco	Ohio State University	Andes (Peru)
Great Basin / Wheeler Peak	Ohio State University	Rockies (USA)
Almaty (Region)	Central Asian Regional Glaciology Centre (CARGC), University of Reading	Central Asia (Kazakhstan)
Mont-Aux-Sources	South African Environmental Observation Network (SAEON), University of the Free State	Drakensberg (South Africa)
Northern Maloti-Drakensberg	University of the Free State	Drakensberg (South Africa)
Rofental	University of Innsbruck	European Alps (Austria)
Davos (Region)	WSL Institute for Snow and Avalanche Research (SLF)	European Alps (Switzerland)
St Elias, Yukon	Polar Knowledge Canada	Sub-Arctic (Canada)

7 Conclusion

The UHOP concept is intended to provide a flexible and pragmatic yet consistent global protocol to measure climate change and its impacts along elevation gradients in mountain terrain. Through its effect on temperature, elevation is the primary control on climate within mountain regions. It controls the distribution of the cryosphere (snow and ice) and vegetation or ecological zones as one moves uphill. It is therefore imperative to be able to characterise elevational gradients in environmental conditions and the rates at which they are changing. Some specific elevation zones may be critically sensitive to future change, but without detailed observations we will fail to identify this sensitivity. Financing, implementing, and sustaining the UHOP initiative should therefore be an extremely high priority for society.

Although this document sets out a UHOP transect accreditation scheme with three levels (BRONZE, SILVER and GOLD) and states four main objectives, the scheme absolutely does not intend to exclude existing transects. There are already many efforts underway to monitor climate change across elevation gradients. Even though some of these efforts may not currently fulfil some or all of the requirements of a given objective or accreditation level outlined here, we nevertheless very much welcome expressions of interest from the managers of such sites. Together, we could strengthen the case to obtain funding to enable improvements or updates to enhance alignment with UHOP.

Indeed, since long-term monitoring is paramount for detecting and attributing changes in mountain climates and environments, UHOP must build upon already established efforts. It may be that very small changes could fulfil the requirements of a higher accreditation level (or inclusion in the BRONZE tier). The system will be flexible enough for existing transect to upgrade from one tier to another as they develop. To that end, we intend to revise accreditation levels at regular intervals, say every 5 years, or following major changes occur (e.g., major equipment installation).

A related priority is to collect comprehensive metadata on as many as possible existing elevation transects (candidate UHOP transects) and evaluate the current infrastructure against the proposed BRONZE, SILVER, and GOLD accreditation requirements. This task, which is already in progress, will help us to establish whether the current proposals are realistic. We warmly welcome contributions of such metadata from those who operate such mountain transect observation networks globally.

Once the first UHOP transects are designated, it will be important for them to process and store their data in common formats, and (to the greatest extent possible) be committed to sharing it, both with other UHOP transects and (ideally) the wider community, for example via GEO Mountains. The development of common data templates or workflows (e.g., in the form of Jupyter notebooks, instruction manuals, etc.) covering aspects such as calibration (for ANCHOR stations), cross-validation (for INTERMEDIATE and FLOAT stations), data storage, processing, and analysis, is accordingly envisaged.

Further Reading

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An example of an ANCHOR station on the Northern Ice Field near the summit of Mt. Kilimanjaro, Tanzania (elevation 5,803 m). The station began operation in 2000, and was removed upon reaching the end of its useful life in 2023. Efforts are underway to replace it in order to restart this valuable climatic record. Photo: Douglas Hardy, University of Massachusetts Amherst, USA.