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Meeting Summary

A Workshop on Advances in Our Understanding of Elevation Dependent Climate Change

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"From Elevation-Dependent Warming to Elevation-Dependent Climate Change (EDCC)" Workshop

***What*:** Scientists and interested stakeholders came together to discuss recent progress in our understanding of mountain climate change and specifically its dependence on elevation. In particular, they considered challenging questions concerning the processes affecting climate changes and their stratification with height as well as their impacts in high-altitude mountain areas.

***When*:** 15–17 September 2022

***Where*:** Innsbruck, Austria

KEYWORDS: Climate change; Mountain meteorology; Atmosphere; Ecosystem effects

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The workshop was designed to discuss the recent evidence and open questions on how climate change is variously affecting mountain environments and high-elevation areas. In particular, the focus was on elevational gradients of change in key meteorological and climate variables (beyond temperature) and on understanding the underlying physical processes, besides discussing their broader consequences both at high altitudes and downstream. The meeting was stimulated by developments of seminal ideas that originated in a previous international workshop on Elevation Dependent Warming (EDW) held in Payerbach, Austria, in April 2014, whose outcome had been summarized in the review paper by the Mountain Research Initiative (MRI 2015).

This second workshop, aimed at reflecting further on the changing status of our knowledge since the earlier workshop, expanded the discussion to consider a more holistic appreciation of climate change as manifest in high mountains, particularly taking into account more variables related to the mountain atmosphere, cryosphere, biosphere, and hydrological cycle. In fact, multivariate patterns and processes along the elevational gradients were considered, broadening the key concept of elevation-dependent warming (EDW) to a more inclusive elevation-dependent climate change (EDCC) that is not necessarily closely linked to EDW. In addition, regional similarities between mountain ranges and teleconnections with the broader climate system were considered. Finally, key gaps in our observations and models were documented, and future research priorities in mountain science were identified.

The workshop was arranged aside from the Second International Mountain Conference (IMC) held in Innsbruck, Austria, on 11–15 September 2022. Participants were hosted at the premises of the University of Innsbruck. Online attendance was allowed to remotely connect participants on two out of the three days of the workshop. Both of the workshops were supported by the Mountain Research Initiative (MRI), an international organization serving as a coordination network for research collaboration, bringing the global mountain research community together. In particular, the workshop outcomes are part of the activities of the MRI and CNR (Italian National Research Council) co-led GEO-Mountains Initiative (www.geomountains.org).

Participants

The meeting was attended not only by some of the scientists who had previously attended the 2014 EDW Workshop and contributed to the EDW review paper, but by a broader community that has emerged over the years representative of quite varied expertise: ecology, geography, meteorology, climatology, forestry, numerical modeling, glaciology, hydrology, etc. Some environmental managers also attended. There were 39 attendees (11 online and 28 in person), including sizable numbers from Europe, North America, and Asia. Limited travel bursaries were available from MRI to support attendance from people in India and Pakistan. There was a wide variety of career stages represented, from PhD students, post-docs, and early career researchers to full professors, and the workshop was designed to enable diverse representation and participation and was organized into sessions that encouraged a high level of interactivity.

Program

The workshop was organized over three days, each divided into several sessions as shown in Table 1.

Session 1: "What have we learnt since the last workshop on elevation dependent warming in 2014?", chaired by Nicholas Pepin. This session focused on the science behind recent research developments in mountain climate change, in particular enhanced and/or subdued climate changes at high elevations. An introductory overview on the state of science was offered by Nick Pepin, Reader in Climate Science at the University of Portsmouth. Then four flash talks were given by participants who responded to a solicitation circulated by the organizers before the conference. They highlighted recent results on EDW/EDCC from papers published after the previous workshop in 2014 (Table 2). The above talks stimulated a rich and fruitful discussion among the participants.

The findings of the previous workshop and the review paper by Mountain Research Initiative EDW Working Group (MRI 2015) were the springboard for more in-depth observational and modeling studies, many focused, however, on Europe and the United States. Despite the sharp increase of studies in recent years, this highlights existing knowledge gaps on other mountain ranges, including mechanisms related to snow–albedo feedback, albedo changes due to vegetation, aerosol and cloud feedbacks, subsurface and surface processes, changes in land cover, changes of snow-line and tree-line and their feedbacks, and mountain convection. Knowledge gaps are also reflected in a poor representation in models. Many other scientific questions are still unanswered, including the elevation dependence of bias, elevation patterns of changing extremes, and changes in seasonality. The discussion also shed light on how the elevation-dependent mind-frame of scientists might influence the approach of researchers on this subject, diverting the attention from other possible factors affecting enhanced climate

Table 1. Program of the workshop.

First day: Thursday, 15 Sep		Second day: Friday, 16 Sep		Third day: Saturday, 17 Sep	
1500–1530 LT	Session 1: Welcome and general introduction	0900–1230 LT	Session 2: Introduction and discussion among groups (physical explanations of EDCC)	0830–0930 LT	Session 4: General introduction
1530–1600 LT	Session 1: Flash talks	1330–1700 LT	Session 3: Introduction and discussion among groups (similarities on large-scale patterns)	0930–1000 LT	Session 4: Flash talks
1600–1700 LT	Session 1: Discussion among groups (from EDW to EDCC)	1700–1800 LT	Session 3: Online attendees join the discussion, synthesis of the session, and feedbacks	1000–1130 LT	Session 4: Discussion among groups (the improvement of datasets)
1700–1730 LT	Session 1: Online attendees join the discussion, synthesis of session			1130–1300 LT	Final remarks and conclusions: Update on structure and writing of paper on EDCC with also possible online attendance
1730–1830 LT	Concept of a paper on EDCC				

Table 2. Flash talks of Session 1.

Presenter	Presentation	Reference
Anna Napoli	Variability of orographic enhancement of precipitation in the Alpine region	Napoli et al. (2019)
Sven Kotlarski	Twenty-first-century Alpine climate change	Kotlarski et al. (2023)
Elisa Palazzi	Comparison of elevation-dependent warming and its drivers in the tropical and subtropical Andes	Toledo et al. (2022)
João de Deus Vidal	Beyond the tree-line: The C3-C4 "grass-line" can track global change in the world's grassy mountain systems	de Deus Vidal et al. (2021)

change evidence. A different and more open mind-frame could help the research community in finding new interesting patterns of EDCC and avoid possible misattributions.

Session 2: "What is the physical explanation for changing elevation gradients in temperature, atmospheric moisture and precipitation patterns? Theory and data," chaired by Martha Apple. The second session primarily concentrated on highlighting mechanisms clearly driving EDCC and other possible ones, whose role is still debated. These mechanisms and their feedback were then discussed in different breakout groups. Each group discussed about the most influential variables, and these turn out to be precipitation, including partitioning between rain and snow, and its regimes, including extremes, atmospheric and soil moisture, winds, snow cover, biodiversity, aerosols, surface albedo (feedback), shortwave and longwave radiation components, and surface heat fluxes. The variability associated with seasonality, climatic zones, and local factors was also discussed. This session highlighted the strong limitations to our understanding of these processes and their combinations. Attempts were made to draw vertical profiles of expected changes in some of these variables in a variety of contexts, but this was not agreed upon.

Session 3: "What are the regional sensitivities to EDCC? How are different mountains similar or different? What are the broader teleconnections with the larger climate system?", chaired by Nicholas Pepin, Martha Apple, and Elisa Palazzi. The third session focused on all the different mountain regions in the world and their response to EDCC. The discussion concentrated on the relative importance of different processes and mechanisms in different locations, identifying synergies and similarities, as well as differences. Despite significant local effects due to mountain range characteristics (such as orientation, elevation range, slope, and shape), some areas were identified as responding similarly, as a consequence of similar reaction to large-scale features or to global teleconnections.

Midlatitude mountains were thought to be broadly similar but divided into those perpendicular to the westerlies (e.g., temperate Andes, Rocky Mountains) versus zonally oriented mountain ranges (e.g., European Alps). Midlatitudes are influenced by the jet stream flowing eastward: it may be subject to blocking patterns which influence the climatology of many areas, producing either drier or wetter zones on different mountain sides. Hence, in the Northern Hemisphere at midlatitudes, it appears of paramount importance to better understand changes in waviness of the jet stream, and their possible connections with Arctic amplification. Tropical mountains were also thought to be broadly similar to each other (e.g., tropical Andes), but the contrast between plateaus and isolated peaks was also an additional distinction. Despite tropical mountains being a separate category, the elongated range of the tropical Andes are also characterized by a similar two-side decoupling due to the response to El Niño (Garreaud 2009). On the contrary, any upper-level jet will flow around the peak of isolated mountains. Most tropical and subtropical mountains are probably more influenced by monsoonal circulations rather than the midlatitude jet.

The monsoonal circulation may undergo modifications and influence the elevation dependence of climate changes: more energy in the system with more surface heating at high elevations (and reduced snowpack) could mean more intense monsoons, but the feedback is not clear due to the elevation-dependent warming at play (Dimri et al. 2018; You et al. 2020). In addition, the interplay of EDCC/EDW with mountain thermally driven circulations at various scales (Zardi and Whiteman 2013) and boundary layer processes was discussed. The complex key interactions between surface properties (including albedo), snow line, and EDW deserve further investigations.

Session 4: "How can we improve observations, datasets and computer models aiming at quantifying EDCC?", chaired by Elisa Palazzi. The fourth session aimed at discussing the creation of a global dataset of observations and the improvement of climate models specifically meant to fill gaps in our understanding of EDCC, both in terms of the processes controlling them and in terms of their distribution over the globe. A central premise of this session was that, regardless of the success in the creation of a global dataset of existing observations, the demonstrated lack of observations at high elevations will require new coordinated observational campaigns in order to evaluate the various hypotheses. The session hosted flash talks, shown in Table 3, on new ideas or proposals to fill current gaps in our understanding of EDW/EDCC (as for Session 1, based on a request to registered participants made by the conveners prior to the workshop), and continued with discussion focused on three main topics: observational datasets, models and downscaling methods, and data analysis/methodologies.

The first topic highlighted that few observatories are operated at high altitudes, and generally it is quite difficult to get funding for new high-altitude observations, as well as for their maintenance over long periods of time. To solve in part the problem of limited data in high-elevation environments, it has been discussed how data from drones and satellites should be integrated into standard observational networks. Moreover, the scientific community could also integrate citizens' observation networks to fill spatial and temporal gaps by increasing the number of observations available. Moreover, some ecological data (such as phenology, flowering of plants, and iced lakes) could be a proxy for temperature and precipitation data, reducing the knowledge gap at high elevations.

The second topic focused on how we can improve the representation of local physical mechanisms in models. While wide valleys and plateaus are quite well represented, intermediate and high elevations are less so. More observational stations could help in studying mountain processes and improve their representation in models. In this light, the recently established international cooperative research initiative TEAMx (Multi-scale Transport and Exchange Processes in the Atmosphere over Mountains—Programme and Experiment;

Table 3. Flash talks of Session 4.

Presenter	Presentation
Arathi Rameshan	The impacts of different drivers on the elevation-dependent climate change at the third pole
Tanmay Dhar	Elevation dependent warming in the Mandakini basin of Garhwal Himalaya
Emily Potter	Elevation dependence of temperature and precipitation trends and extremes in the Peruvian Andes
Silvia Terzago	The dark side of high-mountain precipitation: The contribution of snowfall
Nikolina Ban	Climate simulation at kilometre-scale grid spacing
Dino Zardi	The international cooperation initiative "TEAMx: Multi-scale Transport and Exchange Processes in the Atmosphere over Mountains Programme and Experiment"
Elisa Palazzi	Geo-Mountains Initiative
Nick Pepin	UHOP: Unified High Elevation Observation Platform

www.teamx-programme.org/programme) (Serafin et al. 2018; Rotach et al. 2022) aims at improving our understanding of exchange processes in the atmosphere over mountains and at evaluating how well these are parameterized in NWP and climate models. The main TEAMx campaign will take place in 2024–25 in the European Alps, with target areas in the Inn Valley (Austria), the Adige Valley (Italy), the Alpine Crest between these two, and the alpine foreland in southern Germany and in northern Italy. Meanwhile, it has been widely demonstrated that very high-resolution (2–3 km) numerical simulations are required to better represent local physical mechanisms (Schär et al. 2020; Coppola et al. 2020; Ban et al. 2021; Pichelli et al. 2021; Soares et al. 2023). Unfortunately, the available long-term simulations of projected climate changes at such resolutions are still too short in time (less than 30 years available) for robust climate change assessment. The discussion also focused on the management of the modeling setup in different mountain areas. The need of implementing downscaling chains using statistical or stochastic methods applied to the output of global or regional climate models was also discussed.

The third part shed light on the importance in broadening our methodologies of statistical analysis. Elevational sensitivity might be nonlinear (e.g., a change could be focused along the snow line); thus, the scientific community needs to define different methods to detect and quantify EDW and EDCC. This could help in finding different significant elevation patterns. It would be very useful if we could (globally) standardize methods for trend calculations, in a similar way to quantifying extremes (e.g., ETCCDI), and also standardize the unit of measurements (e.g., relative variations in percentage precipitation versus absolute values).

The workshop ended by sharing ideas and possible next steps (see “Future developments”) with the main aim of writing a new paper on EDCC.

Conclusions

The workshop has shown that the scientific community needs a change of viewpoints to move from the previous concept of elevation-dependent warming to that of elevation-dependent climate change, as already pointed out by Pepin et al. (2022). To do this, a starting point would be a review of scientific papers published after the seminal EDW paper (MRI 2015) and to produce a rational and systematic classification of mountain ranges according to the response to EDCC. Thus, in addition to elevation-dependent changes in temperature (both at global and local scales), the scientific community will need to focus on other variables such as precipitation (rain and snow), radiation balance components (clouds/aerosol), relative and specific humidity, and soil moisture. Also, it will be of utmost importance to investigate how elevation-dependent changes may affect feedbacks, e.g., through vegetation changes. Targeted field campaigns are also needed, including a variety of observational resources, both ground-based and from satellites, in order to better understand local to mesoscale physical mechanisms and their role in EDCC, and to improve their representation in our modeling of mountain-related processes.

Future developments

One of the next steps will be a thorough literature review to better consolidate existing knowledge about EDCC/EDW. A review paper outlining the expansion of the concept “from EDW to EDCC” is already underway based on the broad content of the workshop. Among the reference concepts that the scientific community needs, we should aim to include suitable representative “average” vertical profiles for additional mountain variables other than temperature [perhaps including essential mountain climate variables or EMCVs as identified in Thornton et al. (2021), the result of a previous MRI workshop]. Classifying broad patterns of EDCC across different classes of mountain ranges is also a future focus.

Observational issues in mountain areas must be summarized so that the research community can try to solve each of them. A new workshop is being organized by MRI in Bern, Switzerland, on 25–27 June 2023, following the 36th International Conference on Alpine Meteorology, which is being held in St. Gallen, Switzerland. The workshop will focus on the development of the Unified High Elevation Observational Platform (UHOP), a proposed protocol for coordinating climate measurements across elevation gradients.

In conclusion, the stimulating discussions throughout the workshop shed light on various additional open questions to be addressed. In particular, the next steps will include 1) a study concerning a global overview on elevation-dependent snowfall changes in different mountain ranges of the world, based on in situ long-term measurements and reanalyses (in progress), 2) a paper on modeling issues related to EDCC, and 3) the development of new statistical approaches for identifying EDCC.

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