Scientists’ warning of the impacts of climate change on mountains

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Abstract

Mountains are highly diverse in areal spread, geological and climatic context, ecosystems and human activity. As such, mountain environments worldwide are particularly sensitive to the effects of anthropogenic climate change (global warming) as a result of their unique heat balance properties and the presence of climatically-sensitive snow, ice, permafrost and ecosystems. Consequently, mountain systems – in particular cryospheric ones – are currently undergoing unprecedented changes in the Anthropocene. This study identifies and discusses four of the major properties of mountains upon which climate change can impact, and indeed is already doing so. These properties are: the changing mountain cryosphere of glaciers and permafrost; mountain hazards and risk; mountain ecosystems and their services; and mountain communities and infrastructure. It is notable that changes in these different mountain properties do not follow a predictable trajectory of evolution in response to climate forcing. This demonstrates that different elements of mountain systems exhibit different sensitivities to forcing. The interconnections between these different properties highlight that mountains should be considered as integrated biophysical systems, of which human activity is part. Interrelationships between these mountain properties are therefore discussed through a model of mountain socio-biophysical systems, which provides a framework for examining climate impacts and vulnerabilities. Managing the risks associated with ongoing climate change in mountains requires an integrated approach to climate change impacts monitoring and management.

Introduction

There is increasing concern about Earth’s biophysical systems and sustainability in the light of ongoing anthropogenic climate change (global warming). To this end, world scientists have sent a Warning to Humanity regarding the impacts of climate change on different physical systems and environments (e.g., *Ripple et al., 2017; Finlayson et al., 2019; Albert et al., 2021*). This

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paper contributes to this debate by sending a Warning to Humanity on the impacts of anthropogenic climate change on mountain environments globally and the multifaceted, interlinked and long-lasting nature of these effects on both physical environments and on people and communities. This Warning to Humanity confirms and extends the findings of the IPCC Special Report on the cryosphere that shows that, in mountains, there is high confidence that human activities have contributed to decreased snowcover, glacier mass balance and permafrost area (*Hock et al., 2019b*). In addition, IPCC Assessment Report 6 evaluates climate change impacts on mountains, and states with high confidence that climate change has "observable and serious consequences" for mountain ecosystems and communities (*Adler et al., 2022*).

Mountains represent an important physical environment, with 15.38% of the global land surface lying above 1000 m asl, and 7.67% lying above 2500 m asl (calculated from *Owens & Slaymaker, 2004*, their Table 1.3). The presence of snow and ice has an important role in the regional heat balance of mountains through albedo feedbacks (*Knight & Harrison, 2022*). Decreased snow cover and increased supraglacial debris, however, can dramatically increase the rate of mountain warming, especially where snowline elevation is rising (*You et al., 2020*). This climate amplification found in mountains, known as elevation-dependent warming, has been identified in many mountain blocks worldwide. For example, in the Tibetan Plateau, warming from the 1950s onwards across a range of stations averages 0.31^{o}C/decade^{-1} with values from the 1980s onwards between 0.50–0.67^{o}C/decade^{-1} (*Kuang & Jiao, 2016*). This compares with averaged global surface temperature increases from the 1980s onwards of 0.18^{o}C/decade^{-1} (*NOAA, 2022*), meaning climate change is amplified by around a factor of three in mountains. Such rapid anthropogenic warming in turn has implications for mountain hazards, ecosystems and human activity.

Mountains also represent important scenic and heritage landscapes because of the common presence of rare ecosystems, endemic species, and indigenous communities and cultural practices (*Debarbieux & Price, 2008, 2012; Rasul & Molden, 2019; Chakraborty, 2021; Thornton et al., 2021*). The close genetic relationship between these properties means that mountains can be considered as integrated biosystems, describing the interplay of climate, physical processes, ecosystems and people (e.g., *Nowak et al., 2014; Stanisci et al., 2016; Allegrezza et al., 2017*). Globally, these biosystems are now operating beyond their natural planetary boundaries because of their sensitivity to radiative forcing and their land surface feedbacks in response to the changes? (*Nogués-Bravo et al., 2007; Pepin & Lundquist, 2008; Huggel et al., 2010*). Recognising this, the United Nations' "International Year of the Mountains" was declared in 2002 (*Ives & Messerli, 1999*), and the "International Year of Sustainable Mountain Development" was declared in 2022 (*Romeo et al., 2022*).

Globally, mountain systems are currently undergoing rapid, significant and likely permanent change (*Gerrard, 1991; Marston, 2008; Messerli, 2012; Hock et al., 2019b; Thornton et al.,*

Comentario [GP1]: This is not a typical climate change, this is a human-produced change on the atmospheric conditions that may led to produce seasonal warming at some regions. To argument for a typical climate change it is necessary to look for some information about climate changes in the past to see more clear the differences. If we do not give the real weight to dangerous human activities, environmental changes will increase in the future because will not be according responses from the involved producers of the change.

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Comentario [GP2]: See how many times you mention climatic change without define causes and effects. Identifying the sources of the change would be the best goal to treat them and so, minimize the impact on the mountain systems and other natural ecosystems of the Earth. I understand that your article is a compilation of previous papers but if more than 90% of scientists that support a global warming believe that it has an anthropogenic origin, it should be ...

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Comentario [GP3]: But this is if we compare only temperature, bu ...

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Comentario [GP4]: But if this is a datum exclusively coming from th ...

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Comentario [GP5]: As also occurs in other regions of the planet, ...

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2021). These changes are manifested in the physical properties of mountains and their dynamic behaviour, including mountain climate, geomorphology and ecosystems. This provides the driver for changes in the human environment. In particular, decreases in mountain glacier volume and extent over the last decades are unprecedented in the wider context of the late Holocene (*Zemp et al., 2015; Cogley, 2016; Beniston et al., 2018; Veettil & Kamp, 2019*), with associated impacts on the sustainability of the mountain biosphere and human activity (*Muccione et al., 2016; Klein et al., 2019*).

Various lines of evidence from mountain blocks worldwide reveal the impacts of climate change on mountain processes, properties and communities. This study presents a Warning to Humanity on the negative and likely irreversible impacts of anthropogenic climate change on mountain environments worldwide. This is informed by evidence of contemporary and past changes in mountain systems, and by climate model outputs reported in the literature that predict future changes in precipitation, temperature, snow and permafrost properties, and glacier mass balance. These then in turn have implications for mountain biophysical processes, ecosystems, resources and human activity. A significant result of this analysis is that mountain systems are confirmed to be highly vulnerable, and thus exhibit high sensitivity, to climate change and that, from almost all perspectives, negative outcomes to the physical and human environments are anticipated, and are indeed already taking place.

This study identifies and discusses the impacts of climate change on four key properties of mountain systems (including aspects of human activity), which provides an interpretive framework for a better understanding of mountain system evolution in the Anthropocene. This is done through development of a new socio-biophysical systems model. The purpose of this study is to highlight the interconnectedness of mountain system properties, thereby issuing a Warning to Humanity on the impacts of climate change on mountains. The specific terms used in this study focusing on hazards, risk and resilience follow IPCC Assessment Report 5 definitions (*IPCC, 2014*).

Survey methodology

Much work on mountains globally is site-specific and often deals with only certain aspects of the biophysical environment, in particular the changing cryosphere. There are fewer studies that have focused on mountain communities and their use of environmental and climate-related resources. However, relationships between different mountain system elements have not been examined in detail, from either individual mountain blocks or from across different climatic or geologic settings. This is a limitation in identifying globally-applicable relationships between mountain system elements, and thus in building biophysical system models to explain the impacts of climate forcing. The aim of this study is to integrate evidence from examples globally on mountain system properties and dynamics, and derive an overarching analysis of mountains as biophysical systems. To achieve this, relevant peer-reviewed published literature was

Comentario [GP6]: These changes are: evidenced by …??? You may describe at least synthetically but more specifically the events that prove these changes distinguishing between the impacts of anthropogenic warming on such mountain systems from the mid-latitudes compared to those observed in mountain systems from high latitudes. At the former the snow is just seasonal and for the last permanent. Therefore, describing the changes that you are referring to, and mainly the observable ones, can make the relevance of “the effect of warming in the physical properties and dynamic behaviour that impacts on human activities” more and better understandable for a wider scope of people..

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Comentario [GP7]: You can indicate here that these evidences will be detailed below.

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Comentario [GP8]: Which are those changes? Are they occurring in the present or are just prediction models for an incertain future? This have to be clarified.

Comentario [GP9]: Analysis or models? Please clarify what is “this analysis”

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Comentario [GP10]: To increasing temperature, permanent? Seasonal? explain

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Comentario [GP11]: Ok, phenomena are taking place, thus, describe them

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Comentario [GP12]: Very repetitive, you already said the same above several times. Rephrase or remove.

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Comentario [GP13]: Here you did not take into account the observation made by one of the ...

identified from ISI Web of Science using the search term of "mountain systems" and then the results refined based upon the search term "climate change". The resulting literature was included where it considered relationships between different mountain properties as developed in specific case studies. Therefore, the literature examined focuses on quantitative studies that examine the cause-and-effect relationships between mountain properties. The co-relationships between different mountain properties, and their dynamics, are then used in this study as the basis for developing a new socio-biophysical model for mountain systems. This provides a powerful way of conceptualizing both the integrated workings of mountain systems, and the potential sensitivity of these systems to climate forcing in the Anthropocene, and why this sends a Warning to Humanity of mountain environments.

Results

From the Web of Science literature search, 464 individual articles were identified using the search term "mountain systems" (Table 1), and 39% of all papers were published in the last 5 years. The earliest publications including such a term date from 1961. A similar temporal pattern is seen with the search terms "mountain systems" and "climate change" where 44% of all papers come from the last 5 years. It is notable that in all instances there is a big increase in the number of studies on mountain systems in the last 15 years (Figure 1). These publications were also examined for their Web of Science category of academic discipline (Table 2). Although this classification is only indicative, it shows that the most common academic fields of "mountain systems" are in ecosystems (Ecology/Plant Sciences/Zoology/Biodiversity Conservation; cumulatively 31% if the total), the physical landscape (Geosciences Multidisciplinary/Geography Physical; cumulatively 15% of the total), and Environmental Sciences (11%). This highlights the most common areas of research interest in mountain systems. Including the search term "climate change", a slightly different pattern emerges with, in percentage terms, a greater emphasis on Ecology, Environmental Sciences, Biodiversity Conservation, Meteorology Atmospheric Sciences, and Environmental Studies (Table 2). This shows the greatest areas of research interest in climate change in mountains, focusing on climate patterns/predictions and ecosystem responses. Only in Plant Sciences is there significant under-representation with "climate change" (3.7%) compared to without it (6.7%). Based upon the literature search results, four major mountain properties were identified (glaciers and permafrost related to the mountain cryosphere; mountain hazards and risk; mountain ecosystems; mountain communities and infrastructure). These properties and their dynamics are now discussed.

The mountain cryosphere

Mountain glaciers

As a consequence of global warming, mountains glaciers worldwide including ice caps, valley and cirque glaciers are undergoing a trajectory of enhanced melt and thus negative mass balance over recent decades (e.g., *Cogley, 2016; Azam et al., 2018; Cao et al., 2019; Ding et al., 2020*). The result of this can be seen through (1) long-term changes in glacier area or spatial extent; (2)

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Comentario [GP14]: Right, thus, you have to make comments on these specific results, right? Perhaps there would be other yet unexplored mountain sites that would react similarly, but if you have not direct observations or data you should treate them with caution.

Eliminado: From this research approach, four major mountain properties were identified (glaciers and permafrost; mountain hazards and risk; mountain ecosystems; mountain communities and infrastructure), and these are discussed in detail in this study. The co-relationships between these

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Comentario [GP15]: I think that the collapse that is being seen in all the world ecosystems, at the mountains or at the low lands forms, is warning the humanity.

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changes in glacier volume as expressed through mass balance; and/or (3) changes in glacier dynamics, as evidenced by oscillations of the glacier margin. As such, glacier responses to climate forcing can be diverse, and expressed differently according to topographic setting, elevation, climate, and glacier size. Mountain glaciers are generally less sensitive to temperature changes than lowland ice sheets due to their relatively small size and steep surface gradient (*Bach et al., 2018; Bolibar et al., 2022*). This is because subtle variations in temperature, driving glacier mass balance, can result in changes in the position of the equilibrium line altitude (ELA) which, globally, is rising due to climate change (*Six & Vincent, 2014; Lorrey et al., 2022*). Several studies have projected glacier ELA and thus mass balance responses across mountain blocks (e.g., *Liu et al., 2019; Žebre et al., 2021; Lorrey et al., 2022*) but in detail these responses are highly spatially variable. This may reflect both different sensitivity of climate by ice masses of variable sizes (*Bach et al., 2018*), but also microclimate effects which are particularly significant in areas of high local relief such as mountains (*Rankl et al., 2014; Six & Vincent, 2014*). This is highlighted by cryospheric models that suggest an over-reliance on temperature as a forcing factor in mountain glacier response (*Bolibar et al., 2022*), rather than consider system feedbacks such as supraglacial debris cover, snow depth, and wind-transported snow as factors influencing glacier mass balance (*Dobhal et al., 2013*). Although mountain glaciers have responded to climate changes throughout the Holocene, monitoring using field and remote sensing data over recent decades shows the imprint of global warming on the state of the mountain cryosphere (e.g., *Banerjee & Shankar, 2013; Huss et al., 2017; Beniston et al., 2018; Hock et al., 2019b; Gärtner-Roer et al., 2019*). Such studies also highlight the spatial and temporal variability of mountain glacier responses depending on their altitude, aspect, size and ELA (*Dehecq et al., 2019*). This is also reflected in future modeled projections of glacier volume and area change that show, for example, that different sectors of Tibetan Plateau mountains will have volume loss rates of -0.06 to -1.90% yr^{-1}, and area loss rates of -0.21 to -1.85% yr^{-1} between 2000 and 2050 (*Zhao et al., 2014*).

Many regional studies of historical mountain glacier changes, using a combination of field and remote sensing data, have been undertaken. These studies can inform on the rate and style of glacier change and link these derived parameters to climate forcing or coeval changes in environmental regimes in the local area. For example, Landsat and Sentinel-2 data in the Bolivian Andes show glacier area reduction of 51% between 1975 and 2016 (1.20% yr^{-1}), with the least change recorded for glaciers located above 5500 m asl (*Veettil et al., 2018*). This compares with a decrease in glacier area by an average of -0.57% yr^{-1} (1960–2010) over High Mountain Asia, but with high spatial variability with some 65% of datapoints statistically identical to zero change (*Cogley, 2016*). In the western Himalayas region (1977–2016) Landsat data show that the snow line elevation increased by 116±17 m, glaciers decreased in area (by 6.25±0.0012% or 0.16% yr^{-1}), average glacier snout recession rate increased (from 16±3.4 m yr^{-1} in 1977 to 23±3.4 m yr^{-1} in 2016), and glacier debris cover area increased by 80% (*Shukla et al., 2020*). In the Karakoram, Landsat data (1976–2012) show that 79% of glacier termini were

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stable, 5% advanced, 8% retreated, and 8% belong to oscillating (surging) glaciers (*Rankl et al., 2014*), confirmed by more recent mass balance studies (*Farinotti et al., 2020*). Glaciers across China show a long-term average mass balance decrease of -0.0135 m w.e. yr^{-1} (1960–2019) with the longest (40-year) record from Urumqi Glacier No. 1 showing a decrease of -0.0142 m w.e. yr^{-1} (1959–2019) (*Su et al., 2022*). All these values were statistically significant ($p<0.0001$). By contrast, for High Mountain Asia as a whole based on ASTER DEMs, average glacier mass balance change in the period 2000–2016 was -0.18±0.04 m water equivalent (w.e.) yr^{-1} (range +0.14 to -0.62 m w.e. yr^{-1}) (*Brun et al., 2017*). These studies provide a snapshot of individual glaciers, over different time periods and using different methodologies but implications of the trajectories of glacier change for the wider mountain environment are not discussed.

These studies and others highlight that responses of individual glaciers to climate change in different mountain massifs are highly variable, likely due to microclimate effects related to aspect, topography, elevation, snow blow and debris cover (*Huss & Fischer, 2016; Azam et al., 2018; Baldasso et al., 2019; Carturan et al., 2020*). *Mutz & Aschauer* (2022) show that the mass balance of different Andean glaciers is statistically related to different climatic variables including temperature, precipitation (both seasonal and annual), El Niño–Southern Oscillation and the Antarctic Oscillation, depending on glacier location. In addition, changing debris cover (thickness, debris size, distribution) is a critical influence on albedo and insulation effects, which can lead to marked reductions in glacier mass loss and frontal dynamics (*Banerjee & Shankar, 2013; Dobhal et al., 2013*). These factors highlight that glacier mass balance does not solely reflect climate forcing because the role of antecedent and geological factors. The multidecadal response times of many mountain glaciers also mean that they are likely out of mass balance equilibrium with prevailing climate, irrespective of their sensitivity to climate forcing (*Christian et al., 2018*). However, other studies have described a mode deterministic relationship of mountain glaciers to temperature (*Bolibar et al., 2022*), with *Geyman et al.* (2022) showing – based on historical photogrammetry – a mass balance response of -0.28 m yr^{-1} per 1°C temperature rise of Svalbard glaciers. Responses of mountain systems to deglaciation under climate change fall within the frame of paraglacial process regimes, and the nature of these responses in terms of slope and fluvial sediment yields have been examined from both late Quaternary and Anthropocene examples (e.g., *Cossart & Fort, 2008; Scapozza, 2016*). Such examples highlight that some mountain systems undergo very rapid change associated with ice retreat, and that these impacts are wide ranging with respect to ecosystems, geohazards, and mountain water and sediment yield (*Knight & Harrison, 2014*). Land surface models also show the changing sensitivities of glaciers, permafrost and mountain landforms to forcing through the paraglacial period, and this can help explain why mountain system responses to climate change may vary over time and space (*Knight & Harrison, 2018*). Field data, however, are not always interpreted in the context of such theoretical insights.

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Comentario [GP17]: For data spanning from 1960 to 2016 or 2019, it would be interesting to know if the impact of changes are measured taking into account an acceleration since 2000 and more yet in the last years. Could you comment on this? Thanks.

Comentario [GP18]: Changes in the albedo effects can be related to the loss of native environments such as the replace of forest or grassland by agricultural crops and this is a variable that is not related to climate

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Comentario [GP19]: Right?

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Comentario [GP20]: Interestingly, climatic changes observed in the geological record also show variability of time (in geological magnitudes) and they are also related to changes in the albedo that are not well understood. We are used to see climatic changes as cyclic glacial and interglacial periods and excepting for the definitive installation of ice in a region that is generally large, the interglacial periods are variable, it can be warm or template or cold for long periods before the next glaciation is installed. Glaciations are often associated to extensive volcanism, and plate tectonic, mixed with periods of greenhouse warm conditions can be inferred from the geological and paleontological record, but different to what you are describing herein, they all are long term phenomena.

Climate models and historical trajectories of glacier mass loss have also been used to consider where, how and when mountain glaciers are likely to become functionally inactive, or melt completely, and the rate of water equivalent loss, under different climate change scenarios. For example, *Hock et al*. (2019a) used the four standard IPCC representative concentration pathways (RCPs) in order to consider regional glacier responses to future temperature patterns from 25 different GCMs. The predicted mass loss from different regions varies significantly according to glacier extent and type (lowland ice sheet vs mountain ice cap or cirque/valley), but all RCP scenarios show similar patterns until the mid-21st century after which these patterns diverge. The models also predict a high glacier mass loss (commonly ~60–>90%) for many mountain blocks worldwide by 2100 under the RCP8.5 emissions scenario. A similar approach with similar results was also used by *Shi et al*. (2020) for the Tibetan Plateau.

Based on a global temperature rise of 1.5°C by 2100 using Coupled Model Intercomparison Project Phase 5 (CMIP5) outputs and RCP2.6, high Asian mountains are predicted to warm by 2.1±0.1°C and result in a 36±7% total mass loss (*Kraaijenbrink et al., 2017*). Values for other RCP scenarios are much higher, but with temperature and mass loss responses varying by different mountain sector (*ibid*). More detailed regional studies also show complex glacier responses, such as in the European Alps where mountain glacier slope, topographic setting and debris cover control sensitivity to climate forcing (*Huss & Fischer, 2016; Žebre et al., 2021*). Such field data are confirmed across wider regions through monitored reference glaciers of the World Glacier Monitoring Service (https://wgms.ch/). These data show continues mass balance loss in all global regions and at a rate that has increased over time (since 1950), to a volume of 0.98 m w.e. yr^{-1} and 0.77 m w.e. yr^{-1} in 2019/20 and 2020/21, respectively. Glaciological and climate models have also been used to predict the fate of individual glaciers. For example, modelling of Austre Lovénbreen, Svalbard, suggests rapid area and mass balance decrease, and highest meltwater yield, in the middle of the 21st century, with the glacier wholly gone by 2120 (*Wang et al., 2019*). There are similar results using different RCP scenarios for Great Aletsch Glacier, Switzerland (*Jouvet & Huss, 2019*). However, such projections often use different model scenarios, different temporal starting points, and different input parameters and trajectories of temperature and precipitation. This means that such results may not be easily comparable. In addition, if there are glaciers of different sensitivities, then there may be a range of future glaciological responses (*Carturan et al., 2020; Bolibar et al., 2022*) but these factors are not really considered with respect to impacts on wider mountain systems.

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Mountain permafrost

Mountains worldwide already show increased permafrost temperatures, both near-surface and at depth (*Harris et al., 2003; Liu et al., 2017; Severskiy, 2017*). Sensitivity analysis of arctic permafrost to warming suggests areal changes of 4.0+1.0/-1.1 million km^2 per 1°C of warming (*Chadburn et al., 2017*). The sensitivity of mountain permafrost to climate forcing is more difficult to establish because of mountains' steep and topographically complex environments and microclimates. However, sensitivity analysis from finite element modelling highlights the roles of snow depth and mean annual air temperature (*Luetschg et al., 2008*) and subsurface ice content and temperatures (*Noetzli et al., 2007; Scherler et al., 2013*) on mountain permafrost stability.

Different field, remote sensing and modelling studies show the varied distributions and properties of permafrost in areas such as the European Alps (e.g., *Boeckli et al., 2012; Deluigi et al., 2017; Kenner et al., 2019*) and Tibetan Plateau/Himalayas (*Gruber et al., 2017; Liu et al, 2017; Gao et al., 2021*). Variations in active layer thickness and subsurface temperatures are the key indicators of permafrost degradation used in monitoring studies (e.g., *Hanson & Hoelzle, 2004; Pogliotti et al., 2015; Kellerer-Pirklbauer, 2019*). Several studies also show that permafrost distributions and properties are influenced by local-scale and site-specific slope properties including subsurface moisture content, debris size, slope aspect, length and backwall height (e.g., *Noetzli et al., 2007; Kellerer-Pirklbauer, 2019*). There are also differences between active and relict permafrost, identified according to whether the slope is or is not undergoing creep, largely related to moisture availability rather than temperature. Therefore, the factors contributing to permafrost instability under anthropogenic climate change is more complex than just temperature forcing alone (*Pogliotti et al., 2015; Gruber et al., 2017*), and permafrost system sensitivity must therefore be set in a topographic and geomorphic context (*Verleysdonk et al., 2011*). In addition, information on permafrost thickness, distribution and temperature regime is unknown or is poorly reported in many mountain blocks worldwide, including in Africa, South America and the Middle East. This is a limitation on projections of future permafrost change and their impacts on some mountains, including the loss of geoheritage. Particular attention has also been paid to the monitoring of permafrost within rock bodies, in particular steep rock walls where permafrost degradation can result in rock slope failure (*Gruber & Haeberli, 2007; Bodin et al., 2017; Keuschnig et al., 2017*). This also includes the development of rock glaciers, formed as a result of interstitial permafrost or glacier ice present within a coarse clast matrix (*Knight, 2019*). Rock glaciers represent a distinctive signature of cryosphere decay in mountains, and these landforms are projected to increase in number and significance upon deglacierization in the Anthropocene (*Knight & Harrison, 2014; Knight et al., 2019*).

The outcomes of climate warming on mountain permafrost include an increase in the lowest elevations at which permafrost is found; permafrost thinning and disaggregation; warming subsurface temperatures and thickening active layer; decreasing slope stability and increasing mass movement hazards (*Gude & Barsch, 2005; Fukai et al., 2007; Bonnaventure & Lamoureux, 2013*). The precise nature of permafrost responses depends on its depth, distribution and temperature. Under different RCP scenarios using the CMIP5 climate model, active layer thickness across northern hemisphere cold regions to 2100 is projected to increase between 0.77±0.08 cm decade^{-1} (RCP2.6) and 6.51±0.07 cm decade^{-1} (RCP8.5) (*Peng et al., 2018*). Irrespective of future warming rates, these projections are all significantly higher than

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reconstructed historical rates of 0.57±0.04 cm decade^{-1} for the period 1850–2005 (*ibid*). In the Tibetan Plateau, CMIP5 modelling suggests permafrost area will decrease by 10.5% and 32.7% by 2040 and 2070, respectively, under the RCP8.5 scenario (*Chang et al., 2018*). Permafrost in the northwest Tibetan Plateau is likely to be most resilient to climate warming. More recent CMIP6 modelling using the updated IPCC shared socioeconomic pathway (SSP)5–8.5 (equivalent to RCP8.5) suggests permafrost temperature in the Tibetan Plateau will increase by 2.6±0.3°C and active layer thickness by 3.0±1.0 m by 2100 (*Zhang et al., 2022*). Based on a downscaled regional climate model (RCM), frost frequency in the Mont Blanc massif (French Alps) to 2100 is predicted to significantly decrease by 30–50%, depending on altitude, with implications for the rate and efficacy of physical weathering, permafrost melt, and land surface stability (*Pohl et al., 2019*). Similar future climate impacts on permafrost on other mountain massifs elsewhere in the world are not well understood.

Mountain geohazards and risk

Mountains generally are areas of high hazard risk because of their common co-location with earthquakes and volcanoes, their steep slopes, harsh climate, and presence of snow and ice (*Korup & Clague, 2009; He et al., 2012*). This creates a challenging biophysical environment for human activity. Apart from geophysical hazards that are unrelated to climate, the melting of glaciers, permafrost and snow gives rise to land surface instability and mass movement hazards (*Keiler et al., 2010; Ding et al., 2020; Kirschbaum et al., 2020*). Several studies have shown how these cryospheric hazards, individually and in combination, have been amplified in number and magnitude as a result of global warming (e.g., *Stoffel et al., 2014; Harrison et al., 2018; Ding et al., 2020; Stuart-Smith et al., 2021*). However, there is significant spatial and temporal variability in such patterns (e.g., *Schlögl et al., 2021; Heiser et al., 2022*). A negative glacier mass balance, resulting in increased meltwater yield, can give rise to a range of land surface instabilities and geohazards. For example, runoff and sediment fluxes in the Tuotuohe River (part of the Yangtze River, Tibetan Plateau) increased by 135% and 78% from 1985–1997 to 1998–2016, respectively, as a result of enhanced cryosphere melt and increased precipitation (*Li et al., 2020*). Ouflowing rivers from deglacierizing catchments show an increase in discharge as a result of this higher water availability (*Juen et al., 2007; Tahir et al., 2011; Li et al., 2020*). Further, this leads to changes in seasonality of maximum annual floods, with spring discharge corresponding to snowmelt freshets from snowmelt, and summer discharge corresponding to maximum glacier melt. Observation and modelling studies have been used to identify and then decouple different mountain water sources contributing to outflowing river discharge, and changes in total discharge over time and space and the balance between different sources (*Chen et al., 2017; Sanmiguel-Vallelado et al., 2017*). This is because water availability may correspond to both melting glaciers and changes in precipitation regimes. Catchment and hydrological modelling studies show that cryosphere changes in addition to climate-driven changes in rainfall seasonality affect discharge patterns of mountain rivers, contributing to hazard risk (*Huss et al., 2010; Mallucci et al., 2019*). Detection and attribution studies can

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Comentario [GP21]: However, during the last years there were severe droughts in areas around mountain systems. The Tibetan Plateau is an example where several rivers were lost. How can this explained? It looks as the opposite condition than that you are related here.

inform how these controls may change over time and space (*Mallucci et al., 2019*). Glacial melting can also lead to the development of proglacial lakes and glacial lake outburst floods (GLOFs) (*Harrison et al., 2018; Khadka et al., 2018; Stuart-Smith et al., 2021*). In Nepal, proglacial lakes have increased in number (by 181%) and area (by 82%) between 1997 and 2017 as a consequence of climate change, but these lakes vary significantly in their evolutionary trajectory depending on elevation, topography, glacier size and local climate (*Khadka et al., 2018*). GLOF size and recurrence interval likely shows a lagged relationship to climate forcing (*Harrison et al., 2018*), although this has not been fully explored. GLOFs have been noted from several mountain blocks worldwide, and their potential for geohazard risk examined (*Ahmed et al., 2021; Veettil & Kamp, 2021*).

Glacier retreat and permafrost melting in combination lead to unstable land surfaces and enhanced mass movement activity. This genetic relationship has been noted from several mountain massifs (*Sattler et al., 2011; Fischer et al., 2012; Haeberli et al., 2017*) in which several mass movement types can result, including landslides, rock slope failures, debris flows, colluvial fans and terraces, screen? and talus, and rockfall. First, glacier melt leads to increased number and/or magnitude of flood events within mountain catchments, and this pattern has been noted with respect to climate forcing over different timescales and affecting glacier and snowpack melt regimes (*Yao et al., 2007; Schulte et al., 2015*). In the Himalayas, river hydrology varies spatially according to the contribution of monsoon rainfall, snow or glacier melt to river discharge, and this meltwater contribution also varies throughout the year (*Qazi et al., 2020*). Increased water availability on and beneath the land surface can then lead to rockfalls, landslides, debris/mudflows (*He et al., 2012; Stoffel et al., 2014; Kirschbaum et al., 2020*), or avalanches within thicker or warmed snowpacks (*Muntán et al., 2009*). Analysis of dated mass movements of different types through the period of the European Little Ice Age (LIA, ~1550–1850 AD) shows that landslides are more common earlier in the LIA (~1660 AD), with the peak of avalanche events being later (~1720 AD) and rockfalls later still (~1710 AD) (*Knight & Harrison, 2013*). This may be indicative of these different mass movements having different sensitivities to forcing, and thus being triggered by different environmental conditions. This is an important consideration for predicting when and/or where certain mass movements may be found in present mountain environments. Bayesian analysis of debris flows in the French Alps shows that climatic and environmental variables explain 44% and 33% of variance, respectively (*Jomelli et al., 2015*). A time series of rockfall events in Austria does not show a close relationship to temperature and thus climate, but there is a spring peak in rockfall that likely corresponds to subsurface ice melt at the end of the winter season (*Sass & Oberlechner, 2012*). However, mass movements can also be generated by individual weather events such as the 2003 European heatwave and 2005 floods (*Gruber et al., 2004; Keiler et al., 2010; Bodin et al., 2017*). These extreme weather events are predicted to become more common under global warming, especially over mountain regions (*Huggel et al., 2010; Ding et al., 2020; Thornton et al., 2021; Adler et al., 2022*).

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Comentario [GP22]: Variability of lake persistence can also be explained because it was found that some of the melted subsurface ice that forms ponds can be refreezed (see Hubbard et al. 2016; Massive subsurface ice formed by refreezing of ice-shelf melt ponds. *Nat Commun* **7**, 11897 (2016). https://doi.org/10.1038/ncomms11897.

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Comentario [GP23]: Indeed, recently described landslides and strong avalanches have been produced by torrential rainfalls, mostly in South America and Asia, although similar events also were observed in Europe and the Middle East.

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Mountain ecosystems and services

Mountain (alpine) ecosystems are strongly climatically-controlled by direct forcing of mountain temperature and precipitation regimes, and indirectly through climatic influence on soils. As such, mountain ecosystems and ecosystem services are sensitive to climate and environmental disturbance and change, including by human activity (*Löffler et al., 2011; Elkin et al., 2013; Mina et al., 2017; Wei et al., 2022*). The different physical properties of mountains, including their elevation and remoteness, also provide different ecological niches and can favour endemics. In detail, many mid-latitude mountains that were affected by Pleistocene glaciations have present-day ecosystems that can be considered as ice age relicts or refugia, in which cold-climate ecosystems occupy small environmental niches at the tops of mountains that are particularly climatically sensitive (e.g., *Muellner-Riehl, 2019*). Progressive warming, whether from the late glacial into the Holocene or during the Anthropocene, results in distinctive trajectories of climate and environmental change on mountains that have implications for ecosystems (*Löffler et al., 2011*). These include an upslope migration of isotherms, increased number of degree days available for plant growth, longer summer growing season, warmer ground surface temperatures, enhanced biogeochemical cycling, decreased number and intensity of frost days, snowline/treeline position, reduced snow cover thickness and duration, and changed river discharge patterns and water quality (affecting aquatic ecosystems) (*Gonzalez et al., 2010; Cauvy-Fraunié & Dangles, 2019; Losapio et al., 2021*). These climatic changes then have implications for associated environmental regimes such as soil development and slope stability (*Perrigo et al., 2020*). Several studies also show there is a close correspondence between glacier retreat (*Cauvy-Fraunié & Dangles, 2019*), and permafrost warming as triggers for the altitudinal spread of plant species and thus mountain ecosystem development (*Wei et al., 2022*).

Detailed analysis shows that different mountain species and biomes exhibit different responses to climate change (*Thapa et al., 2016; Albrich et al., 2020; Losapio et al., 2021*). This includes range shifts and changes in phenology. Most work has been done on forests, because of their implications for C storage and timber harvesting in mountains, their role as habitats for other plant and animal species, and their role in land surface stabilisation. Studies on forest biome responses to climate forcing have mainly focused on temperature rather than precipitation (e.g., *Fischlin & Gyalistras, 1997; Jochner et al., 2017*) but it may be that the functional water balance is more important in certain altitudinal ranges but that this is more strongly moderated by site-scale topography rather than precipitation alone (*Albrich et al., 2020*). Climate model projections show that, although there is an upward increase in treeline position and thus a general upward zonal migration of alpine forests (*Lamsal et al., 2017*), this should not be considered as a simple deterministic response to climate warming. This is because it does not account for other factors determining biome responses, such as the role of species' competition, differential species' vagility, invasive species, and steeper slopes, thinner soils and increased windiness with elevation. Differential mobility and adaptive capacity of individual species undergoing climate

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forcing can result in changes in the overall composition of mountain plant communities and, more widely, of food webs (*Malanson et al., 2019*). This then poses problems for the ability of entire biomes to respond to climate change with, for example, individuals at the lowest altitudinal range limits being most vulnerable to climate change but exhibiting different inter-species dynamics than those elsewhere within the range (*Hampe & Petit, 2005; Iglesias et al., 2018*). Likewise, ecosystem services in mountain regions are not well known compared to other environments (*Palomo, 2017; Mengist et al., 2020*). These ecosystem services may include different biological functions such as gene flow (*Fady et al., 2008*) and carbon (C) storage (*Millar et al., 2017*); economic functions; and regulatory and cultural services (*Mina et al., 2017; Seidl et al., 2019*). There is less understanding of human interactions with mountain ecosystems compared with other environmental resources such as water use.

Climate models have been used in order to predict future mountain climates and, from this, to use ecological models to examine variations in biome spatial area, ecosystem composition, C storage, disease/pathogen spread, and the viability of certain endangered or invasive species (*Fischlin & Gyalistras, 1997; Elkin et al., 2013*). Key questions going forward focus on the role of detailed mountain topography and therefore micro-environmental niches for species migration routes (*Perrigo et al., 2020*) and therefore the potential for gene flow and survivability of endemics in specific locations (*Blanco-Pastor et al., 2019*). This therefore highlights the site-specific and species-specific nature of mountain ecosystems and their potential responses to climate change (*Gonzalez et al., 2010; Blanco-Pastor et al., 2019*).

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Mountain communities and infrastructure

Mountain environments and resources represents a ‘global common good’ made use of by mountain inhabitants and visitors alike (*Debarbieux & Price, 2008, 2012; Chakraborty, 2020*). As such, people and mountain environments are closely interlinked, through water and food resource use, ecosystems and ecosystem services, and human livelihoods (*Martín-López et al., 2019*). Mountain agricultural economies have historically been founded on pastoralism and viewed as insular and isolated systems (*Tahmasebi et al., 2013*), but these are now seen as extending into complex spatial networks comprising other mountain goods and services, including cultural patterns, and existing over long time periods (*Spies, 2018; Said et al., 2019*). Although also a product of more recent globalization, changes in human populations (density, locations) and activities in mountains (agriculture, tourism, industry) are influenced by climate change through changing ecosystems and snow distributions. This is framed through the lens of socioecological vulnerability and resilience (*Pandey & Bardsley, 2015; Nettier et al., 2017; Kumar et al., 2021*) which describe the co-relationships between mountain environments/resources and different human activities. *Fraser et al.* (2003) term this *environmental sensitivity* and *social resilience*, respectively. Several recent studies have discussed these elements in different sectors of the Himalayas (*Kaul & Thornton, 2014; Chettri et al., 2020; Kumar et al., 2021*) and highlight the importance of integrated hazard risk

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management and adaptive planning at the community level and with the involvement of indigenous knowledge systems. However, such an approach to minimising climate change risks in mountains has not yet been widely developed for many different mountain ranges (e.g., *McDowell et al., 2019; Payne et al., 2020*). An exception is the study by *Hossain et al.* (2020) that describes the feedbacks that exist within and between the socioeconomic and biophysical systems of rural communities in the Swiss Alps.

The most significant issue affecting people and communities in and downstream of mountains is changes in glacier- and snow-fed river discharge (*Viviroli & Weingartner, 2004; Milner et al., 2017; Li et al., 2020*). Such mountain 'water towers' contribute significantly to regional water supply to, for example, around 60 million people within the Indus and Brahmaputra catchments (*Immerzeel et al., 2010*), and in turn on regional food security (*Carey et al., 2017; Spies, 2018*). Based on a global topographic dataset, *Viviroli et al.* (2007) showed that 43% of mountain areas provide essential or supportive water resources for mainly urban populations, in particular during the dry season and in semiarid areas such as in central Asia. *Schaner et al.* (2012) estimated that 370 million people globally reside in catchments where glacier melt represents one tenth of seasonal river discharge, and 140 million people in catchments where glacier melt contributes one quarter of total river discharge. Enhanced glacier melt under global warming is progressively both increasing and causing more variability of river discharge (*Juen et al., 2007*). Several studies now identify the multiple ways in which mountain water sources impact on people (economy, culture, infrastructure, hydropower, food/water security) and the environment (geohazards, irrigation, ecosystems) (*Mukherji et al. 2015; Carey et al., 2017; Hill et al., 2017*). These are key areas of research interest because of the intersectionality between people and the environment in mountains, and with reference to sustainable development, and the nexus between food, water and energy security (*Rasul, 2014*). Further, based on climate model results, it is likely that continued glacier melt over the next decades will result in progressively lower and more variable discharges as glacier volume decreases (*Messerli et al., 2004; Juen et al., 2007*). This has implications for sediment yield and geohazards, as well as water supply (*Knight & Harrison, 2013; Mukherji et al., 2015; Milner et al., 2017*) and water management strategies (*López-Moreno et al., 2008*) including for hydropower production (*Bombelli et al., 2019*). Contemporary snow and glacier retreat in mountains is already impacting on the development and sustainability of mountain tourism and conservation of the natural environment (*Purdie, 2013; Pröbstl-Haider et al., 2016; Su et al., 2022*) and its built heritage (*Duvillard et al., 2019*).

Discussion

Mountain environments today are in a state of rapid transition as a consequence of anthropogenic climate change in the Anthropocene (*Gerrard, 1991; Marston, 2008; Milner et al., 2017; Rasul & Molden, 2019*). This study sends a powerful Warning to Humanity regarding the ways in which climate change negatively impacts on mountains and the people who reside in them, through the workings of social-ecological and physical systems. Many case studies from the

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world's mountains highlight the critical risks that climate change impacts pose for regional food, water and energy security, the maintenance of biodiversity and infrastructure, and the preservation of cultural heritage (e.g., *Rasul, 2014; Pandey & Bardsley, 2015; Chakraborty, 2020; Hossain et al., 2020*). Addressing these issues through adaptation and mitigation, and monitoring and modelling of mountain system dynamics, is critical for future sustainability of these joint human–physical systems, and for water security for millions of people (*Hill et al., 2017; Milner et al., 2017; Li et al., 2020*).

Figure 2 qualitatively illustrates the major biophysical properties of mountain landscapes and their likely future changes under ongoing climate change. Key elements of these landscapes include glacial and periglacial landforms and processes in highest altitudes, with mass movements on lower slopes, and aggradation within river valleys (*Knight & Harrison, 2009*). Warming climates give rise to spatial variations in mountain process domains, with glacial and periglacial areas shrinking, and slope instability reflecting paraglaciation increasing in prominence (*Knight & Harrison, 2013*). Several modelling studies suggest total deglacierization of some mountain sectors, along with spread of ecosystems, over coming decades (*Zemp et al., 2006; Rabatel et al., 2018*). This represents a fundamental first-order change in the operation of mountain systems, on a global scale (*Milner et al., 2017*). The full implications of this have yet to be realised through field or modelling studies, but include regional heat balance and climate (including impacts on monsoon circulation), biogeochemical cycling and hydrological balance. Full impacts on people – including mountain dwellers and those within mountain-sourced river catchments – have also yet to be realized, and this is important for developing adaptation strategies for future changes in both mountain geohazards and mountain socioeconomic and cultural systems (*Chakraborty, 2021*).

Several conceptual frameworks have been developed to better understand the workings of integrated mountain systems. A *biophysical systems* approach can be used to conceptualise relationships between the different biological, geomorphological and climatic elements that exist within mountain systems (*Hossain et al., 2020*). Most previous work on biophysical systems in mountains has focused on ecosystem processes and drivers such as fire regime (e.g., *Argañaraz et al., 2015; Zapata-Ríos et al., 2021*) and their implications for ecosystem and species' dynamics (e.g., *Zhang et al., 2018; Davis et al., 2021*). Fewer studies have examined the specific genetic linkages that exist between ecosystems and the physical environment itself (soils and substrate type, permafrost distribution) (*Bugmann et al., 2007; Xu et al., 2008; Ran et al., 2021*). These are important, however, because ecosystems are dependent upon substrate and climatic properties, and these in turn then link to the provision of different ecosystem services, in particular through agriculture (*Bagstad et al., 2016; Zhang et al., 2021*). The conceptual analysis of human activity in mountain landscapes has also commonly been undertaken through the lens of *socio-ecological systems* (e.g., *Hossain et al., 2020; Berrio-Giraldo et al., 2021; Fernández-Giménez et al., 2021;* Grumbine & Xu, 2021; *Gopiranjan et al., 2022*) but this approach deals

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only with human interactions with mountain environments, not changes in those environments because of climate and associated human adaptive responses. Thus, both biophysical and socio-ecological systems' approaches have some limitations when applied to mountain environments and lack integration. For this reason, here the portmanteau term *socio-biophysical systems* is introduced to describe the nature of human–environment relations in mountains (Figure 2). *Hossain et al*. (2020) considered some of the feedbacks that exist between human and biophysical systems, based on examples from rural communities in the Swiss Alps. They develop a 'mountain community coupled human landscape system' model (e.g., *Alberti et al., 2011*) to explain these relationships but with an emphasis on geohazard risk and mitigation rather than understanding the workings of mountain systems.

Figure 3 proposes a socio-biophysical systems model to describe and account for the co-relationships between different constituents of mountain systems, including the key transformative role of human activity and climate change in the Anthropocene. The model is organized according to the four thematic areas identified in the literature review of this study, and it highlights that there are multiple interconnections between different mountain elements that cross between these thematic areas. The elements described in this model build from and extend the limited socio-ecological connections identified in previous studies (e.g., *Alberti et al., 2011; Hossain et al., 2020; Kumar et al., 2021*). Figure 3 identifies that there are a number of items that cross different thematic areas, thereby demonstrating interconnections between socio-ecological and biophysical systems. These include anthropogenic climate/environmental change, physical landscape processes, land use/land cover change, geohazards, and tourism. Some of these elements have been included in some previous evaluations of socio-ecological and biophysical mountain systems (e.g., *Bugmann et al., 2007; MacMynowski, 2007; Hill et al., 2017; Hossain et al., 2020; Payne et al., 2020; Kumar et al., 2021;* Gopirajan et al., 2022), but some have not. The interconnections existing within this model also speak to the potential resilience and vulnerability exhibited by both human and environmental systems in mountains, whereby the negative impacts of ongoing changes within mountains can be mitigated. Understanding these interrelationships, including community adaptations to environmental change in mountains, is an important research priority (*Gentle & Maraseni, 2012; Grumbine & Xu, 2021; Kumar et al., 2021*). Figure 3 also highlights that important drivers of change in mountain systems include direct human activity through land use change, agriculture, tourism development and infrastructure, and that these activities can lead to negative impacts on slope stability and ecosystems, amongst others (*Hossain et al., 2020*).

Conclusions

Mountain systems are sensitive to global warming in the Anthropocene, and thus it is timely that a Warning to Humanity is issued, highlighting the serious negative impacts of global warming and associated societal responses for mountain environments and communities, both within mountain massifs and in their extensive surrounding hinterlands. A systems approach,

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considering and integrating together the different properties of mountain environments, is a useful framework for examining the co-variability of mountain environment dynamics (Figure 3). The impacts of warming, ice retreat and associated changes in the properties and dynamics of mountain systems have been widely examined from local case-studies (e.g., *Gude & Barsch, 2005; Singh, 2009; Gariano & Guzzetti, 2016*), but more work is needed to understand the spatial contingency of geohazards and therefore geohazard risk that arise as a consequence of climate change. This is an important future research priority (*Tullos et al., 2016*). Likewise, the impacts of environmental change on (often vulnerable) mountain communities, and their societal and socioeconomic responses, have also been examined from some locations (e.g., *Carey et al., 2017; Rasul & Molden, 2019*) but many mountains especially in the developing world have not yet been considered (*Yohannes et al., 2020*). These are also important research priorities because they focus on building community adaptation and resilience (*Gentle & Maraseni, 2012; Xenarios et al., 2019; Hossain et al., 2020; Grumbine & Xu, 2021*).

Analysis of the literature, examined in this study, shows that interactions between human activity and the physical environment contribute to the achievement of sustainable development in mountains (*Klein et al., 2019; Payne et al., 2020*). Conserving and managing mountain sociocultural and biosystems are specifically mentioned in the 2030 Agenda for Sustainable Development and in Chapter 13 of Agenda 21. Many local case studies, in particular in the Himalayas, have examined interrelationships between physical environmental change and community adaptations to challenges posed by water availability, hazards, agriculture, and ecosystem services (*Gentle & Maraseni, 2012; Sujakhu et al., 2019*). However, equivalent data are often lacking for many other mountain blocks. The proposed socio-biophysical systems model (Figure 3) provides a global framework for a better understanding of the dynamics of mountains in the 21st century, affected by climate change and increased human impacts. This highlights why a Warning to Humanity on the sensitivity of mountain systems to environmental disturbance in the Anthropocene is important.

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Eliminado: ¶
Figure 1.

Figure 1. Graph showing the number of published articles from the Web of Science database (accessed 30 July 2022) according to year of publication, using different search terms.

Figure 2. Schematic block diagrams illustrating the geomorphic patterns and processes taking place in mountains under (A) pre-Anthropocene, and (B) Anthropocene climates associated with a decline in the mountain cryosphere (sketches not to scale).

Figure 3. Interlinkages of different physical and human mountain elements, grouped under the four themes identified in this study, within a socio-biophysical model. Abbreviations are: LULC – land use/land cover; IKS – indigenous knowledge systems; GLOFs – glacial lake outburst floods; SDGs – Sustainable Development Goals.

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Table 1. Classification of cross-sectoral interconnections between mountain landscape socio-biophysical elements (Figure 2).¶

Table 1. Literature search results from the Web of Science (accessed 30 July 2022) using different search terms, according to year of publication (see Figure 1). The earliest items appearing in the search results were published in 1961.

Table 2. Categorisation of search results from the Web of Science database (accessed 30 July 2022). Note that individual published articles in the database may be classified under several categories. Categories with fewer than five and three published articles for “mountain systems”, and “mountain systems” and “climate change”, respectively, are not included in the table.