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Mountain glaciers under a changing climate

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Mountain glaciers are found around the world in ranges such as the Himalaya, the Andes and the European Alps. The majority of mountain glaciers worldwide are shrinking. However, the rugged alpine topography through which these glaciers flow governs the dynamics (behaviour) of these glaciers and impacts on the regional climate systems that modify glacier mass balance. As a result, the response of mountain glaciers to climate change is difficult to predict, and highly spatially variable even across one mountain range, particularly where orography controls precipitation distributions. To understand how mountain glaciers behave and change, geologists combine many different techniques based on direct observations and dating of glacial geology, measurements of present-day glaciers, and predictive numerical (computer) models. Recent advances in these techniques and their applications to glacial environments has demonstrated that the glacial geological record is a rich archive of information about how climate has changed in the past, and gives greater confidence in predictions of glacier change in the future, which is required if populations living in glacierised catchments are able to adapt to the rapid response of these glaciers to a changing climate.

Mountain glaciers

Mountain ranges around the world are often home to glaciers, or may have been glaciated in the past. Air temperature generally decreases with increasing altitude and mountain glaciers form where high topography means that the climate is suitable for sustaining snow and ice over periods of decades to centuries. As a result of the cool climate found at high altitudes, many mountain glaciers occur at low latitudes. Small glaciers are found close to the Equator, such as on Killimajaro in Tanzania where glaciers occur around 5000 m above sea level. Mountain glaciers are not always small however, and some of the largest examples are found in the Himalaya. Gangotri Glacier in the Indian Himalaya is one of the longest mountain glaciers in the world at 30 km. Glaciers change over time in response to climate change. When climate changes, the mass balance of the glacier is changed, either becoming more positive if additional snow is delivered to the glacier (accumulation) and melting (ablation) is reduced, or becoming more negative if accumulation is reduced and ablation is increased. The point on a glacier surface where the rates of accumulation and ablation are equal is called the Equilibrium Line Altitude (ELA). The glacier responds to changes in accumulation and ablation, represented by the position of the ELA, by redistributing ice mass from the upper parts to the lower parts of the glacier (Fig. 1). Glaciers in the tropical and middle latitudes are particularly sensitive to small changes in climate because an individual glacier can occupy a wide altitudinal range, such that relatively minor vertical variations in ELA represent a large area of the glacier surface. The flow of ice through mountain glaciers occurs at speeds of hundreds of metres per year, but is unlikely to be fast enough to allow the glacier to respond synchronously as climate changes. Instead, a mountain glacier typically takes between 20 and 500 years to rebalance after a change in climate.

Mountain ranges where large glaciers are found are often tectonically active, experiencing rock uplift rates of between 1–10 mm per year. The combination of high rates of rock uplift, high precipitation caused by the interaction of atmospheric circulation systems with orographic barriers, and the erosive nature of fast-flowing glaciers means that these glaciers produce large amounts of sediment. Glaciers can often be covered with a layer of rock debris several metres thick, and this debris affects how the glacier mass changes in response to climate change (Fig. 1c). These debris-covered glaciers tend to have a longer lifespan than equivalent clean-ice glaciers, because the layer of debris acts as an insulating blanket and reduces the amount of ablation at the glacier surface. Debris covered-glaciers, such as Khumbu Glacier in the Nepal Himalaya or Tasman Glacier in the Southern Alps of New Zealand, are therefore much larger and their tongues are at a much lower altitude compared to glaciers with clean ice surfaces.

Quaternary glaciations and past climate change

The last 2.6 million years of Earth's history—the Quaternary Period—had a particularly variable climate and many phases of widespread glaciation. During the first million years of the Quaternary, the length of a glacial cycle was about 40 ka until the Middle Pleistocene Transition around 1 Ma, after which the length of time between each glaciation increased to 100 ka and the amount of cooling during each cold part of the cycle increased. We can see the impact of this change in the timing of climate cycles recorded in glacial landscapes, where greater surface relief (i.e. mountain height relative to the valley floor) was formed by larger, longer-lived glaciers occurring landscapes that had already undergone multiple glacial cycles. The last major glaciation occurred between about 60 ka and 18 ka, which ended with the Last Glacial Maximum (LGM) around 24 to 18 ka. After the LGM, climate warmed and sea levels rose until the start of the Holocene period around 11 ka. The Holocene is a period of relatively stable and warm climate compared to the rest of the Quaternary that may only now be ending as rapid climate change occurs due to anthropogenic activity. Smaller, but also widespread glacier advances have occurred since the LGM. As these glaciers have not overrun the geomorphological record of the LGM glaciers, we can observe the impact of recent, short-lived climate variations on the landscape. Two well-known cold periods that interrupted the overall warming trend from the end of the LGM to the start of the Holocene are the Northern Hemisphere Younger Dryas Stadial and the Southern Hemisphere Antarctic Cold Reversal that occurred within a thousand years of each other around 12 ka and 11 ka. Most recently, the Little Ice Age during the 14th to 19th Centuries caused existing glaciers in the European Alps to advance, while marginal glaciers may have formed in areas where ice had previously vanished such as the Cairngorms in Scotland.

Measuring how and why glaciers change

Glacial geologists use a range of techniques to understand how and why glaciers have changed in the past, combining observations of glacial and proglacial geomorphology, Quaternary dating techniques, remote sensing using satellite imagery and close-range photogrammetry, observations of present day glaciers, numerical (computer) modelling, and comparison with other climate proxy records such as sea surface temperatures from marine sediment cores. To predict how glaciers will vary in the future, numerical models that describe the relationship between glaciers and climate are needed. The applications of these methods to understanding the processes by which glaciers change are discusses briefly here.

Observations of glacial and proglacial geomorphology. The impact of glaciation can be clearly seen on the landscape even after glaciers have vanished. Glaciers reshape the landscape by eroding bedrock, moving large volumes of sediment around to form moraines (Fig. 2). Glaciers also release variable volumes of sediment and water downstream as they advance and recede. Proglacial rivers are strongly influenced by these variations in discharge and sediment flux and can form a stratigraphic record of glacier change. Geomorphological mapping of moraine positions and investigation of glacial and proglacial sediments can be used to infer the extent of past glacier changes.

Remote sensing and photogrammetry. Satellite and close-range imagery collected since the 1960s can be analysed to provide 3-D data about the topography of glaciers and how glacier extents and dynamics change over time (Fig. 3a), allowing glaciologists to determine the rates at which glaciers are changing and infer the processes that drive these changes. Satellite sensors can also collect data about, for example, the temperature of glacier surfaces and surface albedo, although the spatial resolution of these data are often fairly coarse (10s m grid spacing). More detailed data can be produced using close-range surveys, either from cameras in low-flying aircraft or on the ground, and used to produce 3-D models using a technique called Structure-from-Motion photogrammetry.

Quaternary geochronology. The timings of moraine formation and rates of glacier change can be determined if an absolute date for a glacial landform or sediment is measured. Radiocarbon (^{14}C) dating is traditionally used in the geosciences to determine the age of organic sediments but is less useful in glacial environments where organic material is scarce, and the duration of glacial cycles exceeds the limit of the ^{14}C technique (about 40 ka). Fortunately, glaciologists can date silicate minerals, usually quartz or feldspar, extracted from glacial sediments using either Optically Stimulated Luminescence (OSL) dating to look at the time since burial of glacial sediments (Fig. 3b), or Terrestrial Cosmogenic Nuclide (TCN) dating to look at the time elapsed since a moraine boulder or a glacially-eroded bedrock surface was exposed after being covered with glacial ice. The chronological range of OSL and TCN covers much of the Quaternary, and it is possible to produce ages that can resolve events that occurred less than a few decades ago.

Observations of present day glaciers. Where glaciers are present in the landscape, we can make direct observations of ice thickness, glacier velocities, rates of accumulation and ablation, glacier surface temperature, basal shear stress and hydrology, the thickness of supraglacial debris, and so on (Fig. 3c). Although many glaciers are difficult to access, particularly those accumulation zones at high altitude, direct observations using techniques such as ground-penetrating radar, emplacement of ablation stakes, and hot-water drilling through the ice can provide useful information about the present day state of these glaciers. Repeated surveys over a number of years can then be used to infer if glaciers are changing.

Numerical (computer) modelling. The processes by which ice flows can be described using a series of mathematical equations to make a glacier model (Fig. 3d). A wide variety of glacier models exist, although relatively few have been developed for mountain glaciers rather than ice sheets and larger ice masses. Numerical models can be used to reconstruct glaciers that match observed ice limits and infer the change in climate from the present day that was required to produce a particular advance. To do this, we need to be able to describe the present day climate generally using 30 years of local meteorological observations, and make assumptions about how the climate has changed in the past—for example, was glacier advance driven by cooling air temperatures or increased snowfall, or a combination of these factors? The simplified numerical description of climate and ice flow in glacier models combine to produce uncertainties in the model results, which indicate the level of caution with which the results must be treated. Comparing simulated glaciers with data collected in the field or from remote sensing and climate proxy records such as sea surface temperatures validates the particular application of a glacier model and gives confidence in model results.

Inferring climate change from glacial geology

Understanding when glaciations and individual glaciers advance occurred can indicate how climate changed in the past. Precise absolute ages for the timing of glacier advance are essential to making these comparisons, and advances in the application of OSL and TCN to glacial landscapes over the last two decades have allowed the investigation of regional and interhemispheric glacier change in unprecedented detail. A particularly good location for investigating glacial records of past climate change is the Southern Alps of New Zealand, one of few landmasses in the southern middle latitudes that was extensively glaciated during the late Quaternary. Recent studies using TCN and OSL to date moraines and proglacial sediments combined with glacier modelling has revealed multiple phases of short-lived glacier advance during the last 60 ka in the Southern Alps, which resulted in periods of intense geomorphological activity that shaped the Quaternary sedimentary record of New Zealand. Northern Hemisphere glaciations are relatively well studied compared to those in the Southern Hemisphere, and comparing the timing of regional advances in mountain ranges such as the Southern Alps and the Andes with those in the European Alps and Scandinavia can demonstrate whether events such as the Younger Dryas Stadial affected glaciers around the world. Geochronological data from moraines in New Zealand demonstrate that glaciers in this region did not advance during the Younger Dryas but probably did advance during the Antarctic Cold Reversal about 2,000 years earlier. Understanding the timing of glacier advances in different regions allows us to compare when and where local climates cooled with the processes that transfer climate signals around the globe through the ocean and the atmosphere to discover how climate changes.

Mountain glaciers under a changing climate

Glaciers are of interest to geologists because they have a dramatic impact on the Earth's surface. Glaciers respond more slowly to changes in climate than these changes occur because the glacier response is controlled by ice flow. Therefore, glaciers are useful filters that translate climate signals into the erosional and depositional record. As glaciers advance and recede, large volumes of sediment are produced, stored and released downstream (Fig. 4). Advancing glaciers erode their beds and bulldoze large volumes of sediment from the valleys through which they flow. However, while a glacier is advancing, downstream water discharge decreases as precipitation (snow) is locked up in the glacier as ice, and the capacity of proglacial rivers to transport sediment is reduced. If the glacier remains stable over periods of decades to centuries, then moraines are formed (Fig. 2), indicating a phase in the glacier's history that can be linked to a particular palaeoclimate. When glacier mass balance becomes negative, likely due to a warming climate, the glacier starts to lose ice mass. The loss of ice mass increases downstream discharge and therefore the capacity of proglacial rivers to transport sediment. Glacier recession is often accompanied by the development of lakes on the surface of or in front of the glacier. Proglacial lakes can form in overdeepenings eroded into the bedrock by the glacier and are often held back by dams of moraine containing relict pieces of glacier ice. Over time, these lakes can pose a hazard to the downstream areas of the catchment, as events such as earthquakes or calving of icebergs from the receding glacier into the lake can destabilise the moraine dam leading to glacier lake outburst flooding.

Mountain glaciers have a profound impact on the lives of people who live near them, and on much larger populations in the catchments fed by glacier-fed rivers such as the Ganges and the Indus which rise in the glacierised Himalaya. Mountain glaciers around the world are generally shrinking. Satellite observations over the last 40 years demonstrate the loss of ice mass in many mountain ranges, including the Himalaya which contains the greatest volume of glacier ice outside the polar regions. Glacier mass loss cannot be definitely linked to climate change, as mountain glacier behaviour is governed by other factors such as the topography through which glaciers flow and short-term variability in regional weather systems (Fig. 5). However, even if we do not yet understand completely how mountain glaciers respond to climate change, understanding the processes that occur in deglaciating environments is important to many aspects of life. For example, over timescales of decades, these include ensuring predictable water supplies as glacial reservoirs shrink, understanding how variable catchment sediment and water budgets could affect surface processes such as river channel migration, economic adaptation in industries such as snow sports that rely on predictable glacial environments, and assessing the likelihood of glacial hazards including glacier lake outburst floods and landslides. Over longer timescales, understanding of glacier change is needed for decisions on locations for the disposal of nuclear waste that are safe for hundreds of thousands of years from exhumation by erosion if glaciers advance in the future. To understand how and why glaciers change, and make predictions about the impact of a changing climate on glacierised environments, geologists need to combine observations of glacier change in the past and the processes operating in present-day glaciers with numerical modelling that captures the dynamics of mountain glaciers.

Acknowledgements

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Figure captions

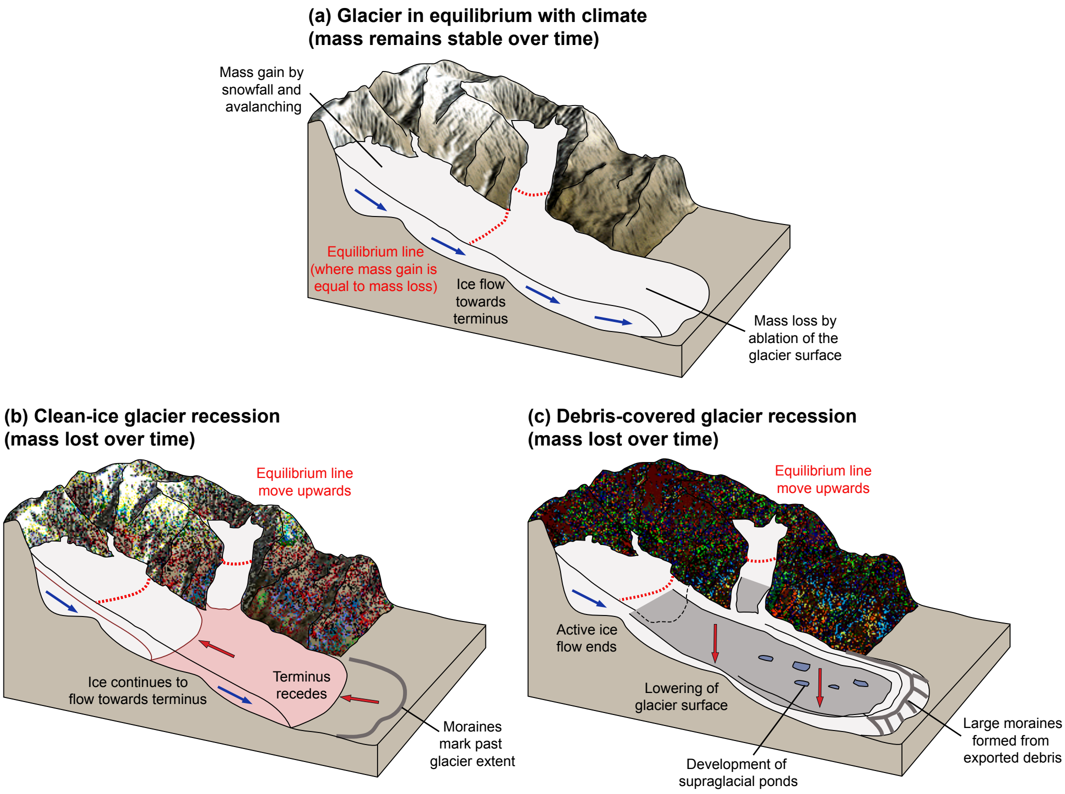

Figure 1. (a) A mountain glacier in balance with climate, and the differing responses of mountain glaciers with (b) clean-ice surfaces and (c) debris-covered surfaces to climate change resulting in a negative net glacier mass balance. The equilibrium line altitude (ELA) is shown by the dashed red line.

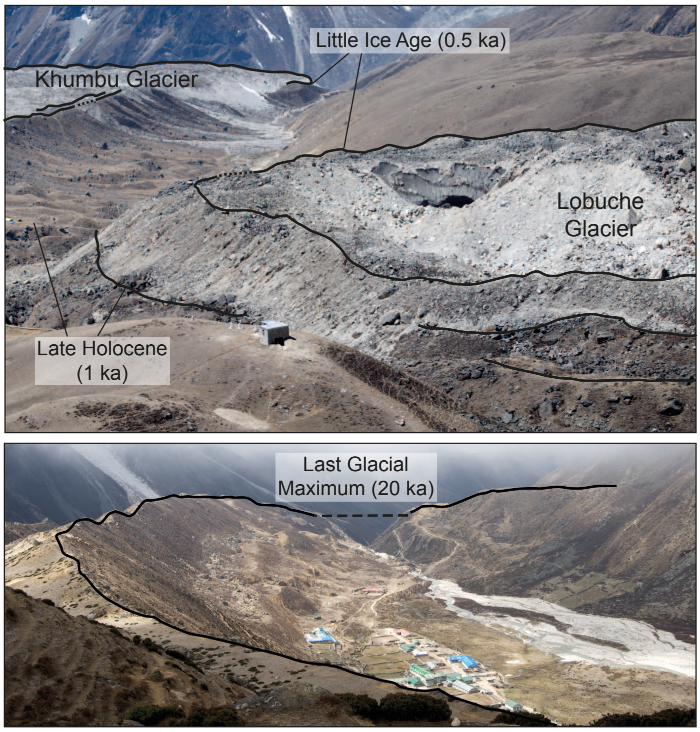

Figure 2. Late Quaternary moraines of Khumbu and Lobuche Glaciers in the Everest region of Nepal. Note buildings in both images for scale.

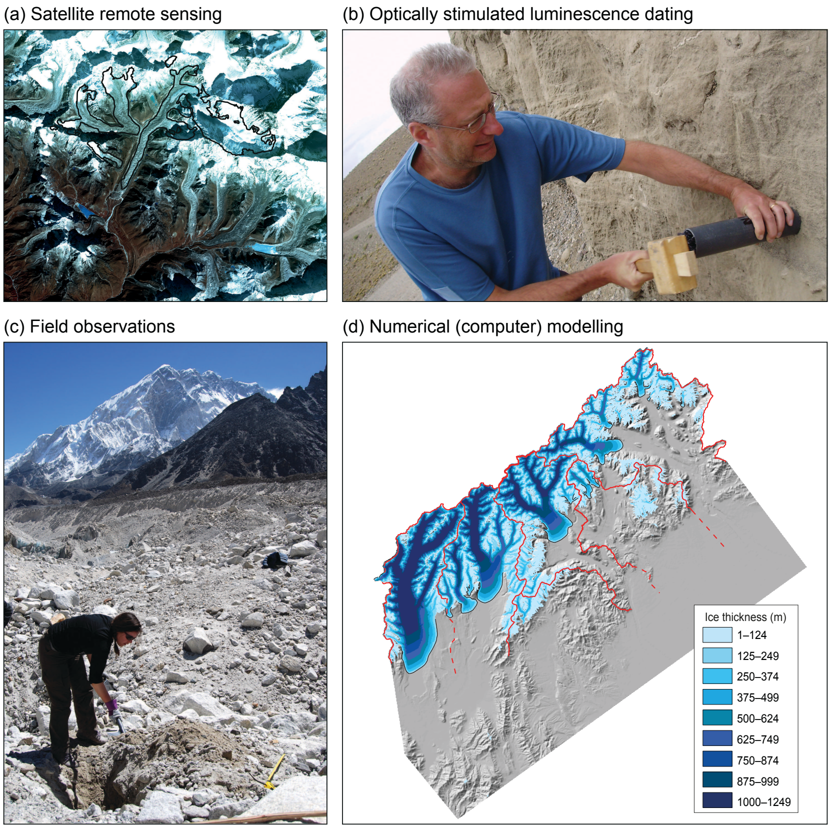

Figure 3. Investigating how and why glaciers respond to climate change; (a) satellite remote sensing imagery of Khumbu Glacier in Nepal, where the black line is the mapped glacier area, (b) collecting a sediment sample for optically stimulated luminescence dating from glacier lake sediments in Patagonia [photo by Rachel Smedley], (c) measuring the thickness of supraglacial debris on Khumbu Glacier, and (d) numerical (computer) modelling of glaciers in the central Southern Alps of New Zealand during recession from the Last Glacial Maximum.

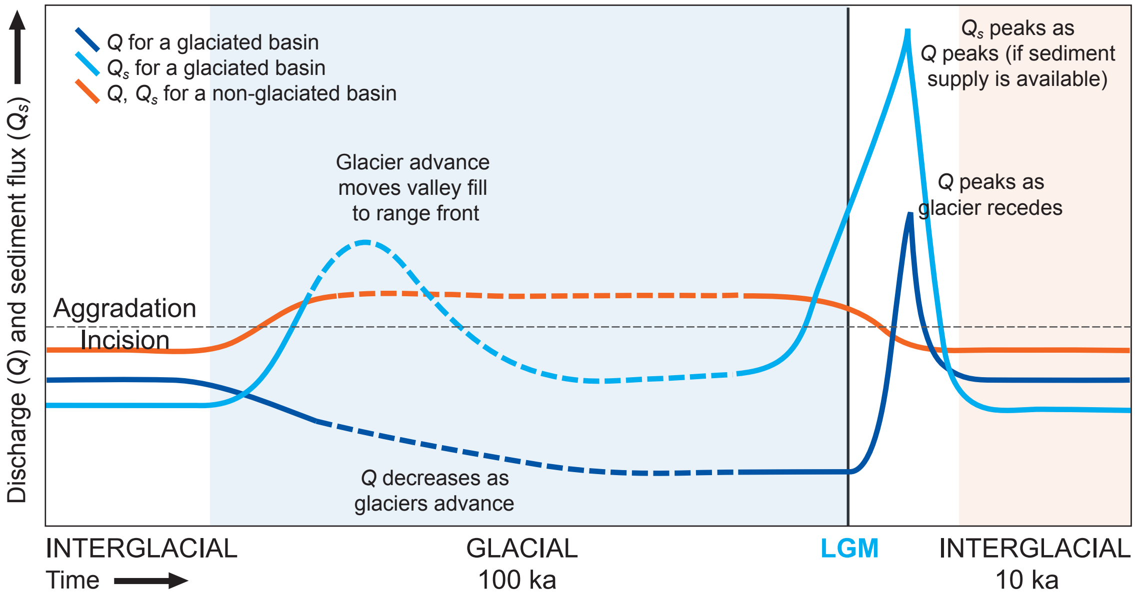

Figure 4. Variations in proglacial water discharge (Q) and sediment flux (Q_s) from glaciated and non-glaciated catchments in response to climate change over glacial–interglacial cycles.

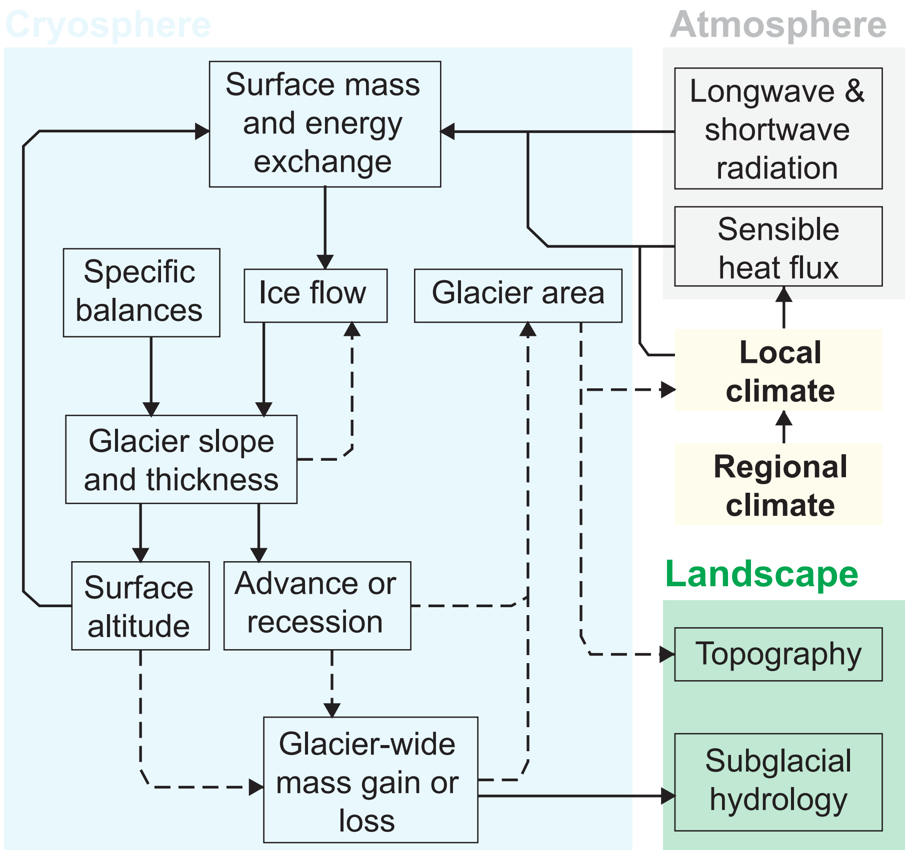

Figure 5. Factors determining the relationship between the atmosphere, cryosphere and landscape that govern how mountain glacier mass balance changes. Feedbacks are indicated by dashed lines [redrawn from Cuffey and Paterson, 2010].

Suggestions for further reading

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