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1 Mountain glaciers under a changing climate

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9 **Mountain glaciers are found around the world in ranges such as the Himalaya, the**
10 **Andes and the European Alps. The majority of mountain glaciers worldwide are**
11 **shrinking. However, the rugged alpine topography through which these glaciers flow**
12 **governs the dynamics (behaviour) of these glaciers and impacts on the regional climate**
13 **systems that modify glacier mass balance. As a result, the response of mountain glaciers**
14 **to climate change is difficult to predict, and highly spatially variable even across one**
15 **mountain range, particularly where orography controls precipitation distributions. To**
16 **understand how mountain glaciers behave and change, geologists combine many**
17 **different techniques based on direct observations and dating of glacial geology,**
18 **measurements of present-day glaciers, and predictive numerical (computer) models.**
19 **Recent advances in these techniques and their applications to glacial environments has**
20 **demonstrated that the glacial geological record is a rich archive of information about**
21 **how climate has changed in the past, and gives greater confidence in predictions of**
22 **glacier change in the future, which is required if populations living in glacierised**
23 **catchments are able to adapt to the rapid response of these glaciers to a changing**
24 **climate.**
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26

27 Mountain glaciers

28 Mountain ranges around the world are often home to glaciers, or may have been glaciated in
29 the past. Air temperature generally decreases with increasing altitude and mountain glaciers
30 form where high topography means that the climate is suitable for sustaining snow and ice
31 over periods of decades to centuries. As a result of the cool climate found at high altitudes,
32 many mountain glaciers occur at low latitudes. Small glaciers are found close to the Equator,
33 such as on Killimajaro in Tanzania where glaciers occur around 5000 m above sea level.
34 Mountain glaciers are not always small however, and some of the largest examples are found
35 in the Himalaya. Gangotri Glacier in the Indian Himalaya is one of the longest mountain
36 glaciers in the world at 30 km. Glaciers change over time in response to climate change.
37 When climate changes, the mass balance of the glacier is changed, either becoming more
38 positive if additional snow is delivered to the glacier (accumulation) and melting (ablation) is
39 reduced, or becoming more negative if accumulation is reduced and ablation is increased.
40 The point on a glacier surface where the rates of accumulation and ablation are equal is called
41 the Equilibrium Line Altitude (ELA). The glacier responds to changes in accumulation and
42 ablation, represented by the position of the ELA, by redistributing ice mass from the upper
43 parts to the lower parts of the glacier (Fig. 1). Glaciers in the tropical and middle latitudes are
44 particularly sensitive to small changes in climate because an individual glacier can occupy a
45 wide altitudinal range, such that relatively minor vertical variations in ELA represent a large
46 area of the glacier surface. The flow of ice through mountain glaciers occurs at speeds of
47 hundreds of metres per year, but is unlikely to be fast enough to allow the glacier to respond
48 synchronously as climate changes. Instead, a mountain glacier typically takes between 20 and
49 500 years to rebalance after a change in climate.
50

51 Mountain ranges where large glaciers are found are often tectonically active, experiencing
52 rock uplift rates of between 1–10 mm per year. The combination of high rates of rock uplift,
53 high precipitation caused by the interaction of atmospheric circulation systems with
54 orographic barriers, and the erosive nature of fast-flowing glaciers means that these glaciers
55 produce large amounts of sediment. Glaciers can often be covered with a layer of rock debris
56 several metres thick, and this debris affects how the glacier mass changes in response to
57 climate change (Fig. 1c). These debris-covered glaciers tend to have a longer lifespan than

58 equivalent clean-ice glaciers, because the layer of debris acts as an insulating blanket and
59 reduces the amount of ablation at the glacier surface. Debris covered-glaciers, such as
60 Khumbu Glacier in the Nepal Himalaya or Tasman Glacier in the Southern Alps of New
61 Zealand, are therefore much larger and their tongues are at a much lower altitude compared
62 to glaciers with clean ice surfaces.

63

64 **Quaternary glaciations and past climate change**

65 The last 2.6 million years of Earth's history—the Quaternary Period—had a particularly
66 variable climate and many phases of widespread glaciation. During the first million years of
67 the Quaternary, the length of a glacial cycle was about 40 ka until the Middle Pleistocene
68 Transition around 1 Ma, after which the length of time between each glaciation increased to
69 100 ka and the amount of cooling during each cold part of the cycle increased. We can see
70 the impact of this change in the timing of climate cycles recorded in glacial landscapes,
71 where greater surface relief (i.e. mountain height relative to the valley floor) was formed by
72 larger, longer-lived glaciers occurring landscapes that had already undergone multiple glacial
73 cycles. The last major glaciation occurred between about 60 ka and 18 ka, which ended with
74 the Last Glacial Maximum (LGM) around 24 to 18 ka. After the LGM, climate warmed and
75 sea levels rose until the start of the Holocene period around 11 ka. The Holocene is a period
76 of relatively stable and warm climate compared to the rest of the Quaternary that may only
77 now be ending as rapid climate change occurs due to anthropogenic activity. Smaller, but
78 also widespread glacier advances have occurred since the LGM. As these glaciers have not
79 overrun the geomorphological record of the LGM glaciers, we can observe the impact of
80 recent, short-lived climate variations on the landscape. Two well-known cold periods that
81 interrupted the overall warming trend from the end of the LGM to the start of the Holocene
82 are the Northern Hemisphere Younger Dryas Stadial and the Southern Hemisphere Antarctic
83 Cold Reversal that occurred within a thousand years of each other around 12 ka and 11 ka.
84 Most recently, the Little Ice Age during the 14th to 19th Centuries caused existing glaciers in
85 the European Alps to advance, while marginal glaciers may have formed in areas where ice
86 had previously vanished such as the Cairngorms in Scotland.

87

88 **Measuring how and why glaciers change**

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

97

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

106

107 ***Remote sensing and photogrammetry.*** Satellite and close-range imagery collected since the
108 1960s can be analysed to provide 3-D data about the topography of glaciers and how glacier
109 extents and dynamics change over time (Fig. 3a), allowing glaciologists to determine the
110 rates at which glaciers are changing and infer the processes that drive these changes. Satellite
111 sensors can also collect data about, for example, the temperature of glacier surfaces and
112 surface albedo, although the spatial resolution of these data are often fairly coarse (10s m grid
113 spacing). More detailed data can be produced using close-range surveys, either from cameras
114 in low-flying aircraft or on the ground, and used to produce 3-D models using a technique
115 called Structure-from-Motion photogrammetry.

116
117 **Quaternary geochronology.** The timings of moraine formation and rates of glacier change
118 can be determined if an absolute date for a glacial landform or sediment is measured.
119 Radiocarbon (^{14}C) dating is traditionally used in the geosciences to determine the age of
120 organic sediments but is less useful in glacial environments where organic material is scarce,
121 and the duration of glacial cycles exceeds the limit of the ^{14}C technique (about 40 ka).
122 Fortunately, glaciologists can date silicate minerals, usually quartz or feldspar, extracted from
123 glacial sediments using either Optically Stimulated Luminescence (OSL) dating to look at the
124 time since burial of glacial sediments (Fig. 3b), or Terrestrial Cosmogenic Nuclide (TCN)
125 dating to look at the time elapsed since a moraine boulder or a glacially-eroded bedrock
126 surface was exposed after being covered with glacial ice. The chronological range of OSL
127 and TCN covers much of the Quaternary, and it is possible to produce ages that can resolve
128 events that occurred less than a few decades ago.

129
130 **Observations of present day glaciers.** Where glaciers are present in the landscape, we can
131 make direct observations of ice thickness, glacier velocities, rates of accumulation and
132 ablation, glacier surface temperature, basal shear stress and hydrology, the thickness of
133 supraglacial debris, and so on (Fig. 3c). Although many glaciers are difficult to access,
134 particularly those accumulation zones at high altitude, direct observations using techniques
135 such as ground-penetrating radar, emplacement of ablation stakes, and hot-water drilling
136 through the ice can provide useful information about the present day state of these glaciers.
137 Repeated surveys over a number of years can then be used to infer if glaciers are changing.

138
139 **Numerical (computer) modelling.** The processes by which ice flows can be described using a
140 series of mathematical equations to make a glacier model (Fig. 3d). A wide variety of glacier
141 models exist, although relatively few have been developed for mountain glaciers rather than
142 ice sheets and larger ice masses. Numerical models can be used to reconstruct glaciers that
143 match observed ice limits and infer the change in climate from the present day that was
144 required to produce a particular advance. To do this, we need to be able to describe the
145 present day climate generally using 30 years of local meteorological observations, and make
146 assumptions about how the climate has changed in the past—for example, was glacier
147 advance driven by cooling air temperatures or increased snowfall, or a combination of these
148 factors? The simplified numerical description of climate and ice flow in glacier models
149 combine to produce uncertainties in the model results, which indicate the level of caution
150 with which the results must be treated. Comparing simulated glaciers with data collected in
151 the field or from remote sensing and climate proxy records such as sea surface temperatures
152 validates the particular application of a glacier model and gives confidence in model results.

153
154 **Inferring climate change from glacial geology**
155 Understanding when glaciations and individual glaciers advance occurred can indicate how
156 climate changed in the past. Precise absolute ages for the timing of glacier advance are
157 essential to making these comparisons, and advances in the application of OSL and TCN to
158 glacial landscapes over the last two decades have allowed the investigation of regional and
159 interhemispheric glacier change in unprecedented detail. A particularly good location for
160 investigating glacial records of past climate change is the Southern Alps of New Zealand, one
161 of few landmasses in the southern middle latitudes that was extensively glaciated during the
162 late Quaternary. Recent studies using TCN and OSL to date moraines and proglacial
163 sediments combined with glacier modelling has revealed multiple phases of short-lived
164 glacier advance during the last 60 ka in the Southern Alps, which resulted in periods of
165 intense geomorphological activity that shaped the Quaternary sedimentary record of New
166 Zealand. Northern Hemisphere glaciations are relatively well studied compared to those in
167 the Southern Hemisphere, and comparing the timing of regional advances in mountain ranges
168 such as the Southern Alps and the Andes with those in the European Alps and Scandinavia
169 can demonstrate whether events such as the Younger Dryas Stadial affected glaciers around
170 the world. Geochronological data from moraines in New Zealand demonstrate that glaciers in
171 this region did not advance during the Younger Dryas but probably did advance during the
172 Antarctic Cold Reversal about 2,000 years earlier. Understanding the timing of glacier
173 advances in different regions allows us to compare when and where local climates cooled

174 with the processes that transfer climate signals around the globe through the ocean and the
175 atmosphere to discover how climate changes.

176

177 **Mountain glaciers under a changing climate**

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

197

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

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221

222 **Acknowledgements**

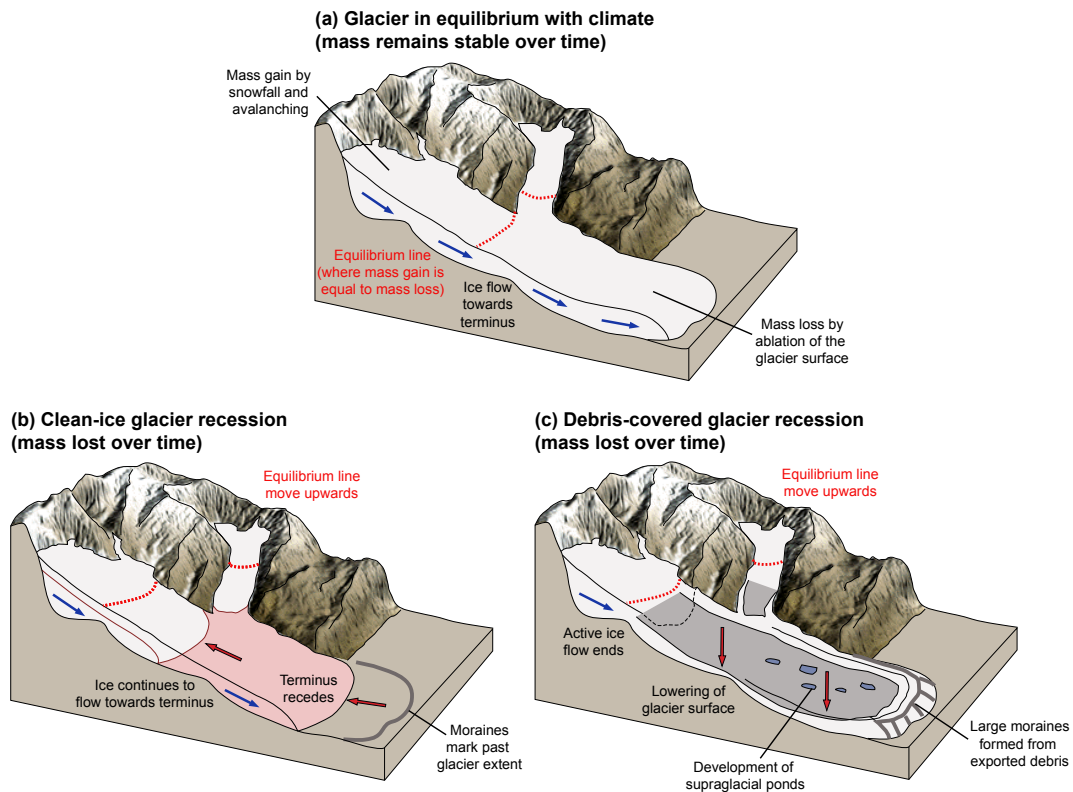
223 This paper is based on the Penck Lecture given at the European Geosciences Union General
224 Assembly in Vienna in April 2015, and the Quaternary Research Association is thanked for
225 supporting my attendance at this meeting.

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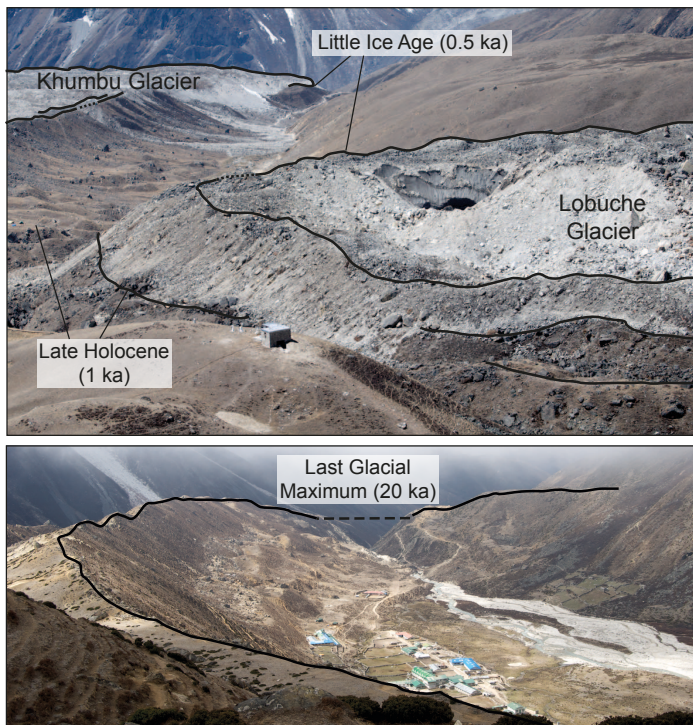
228 **Figure captions**

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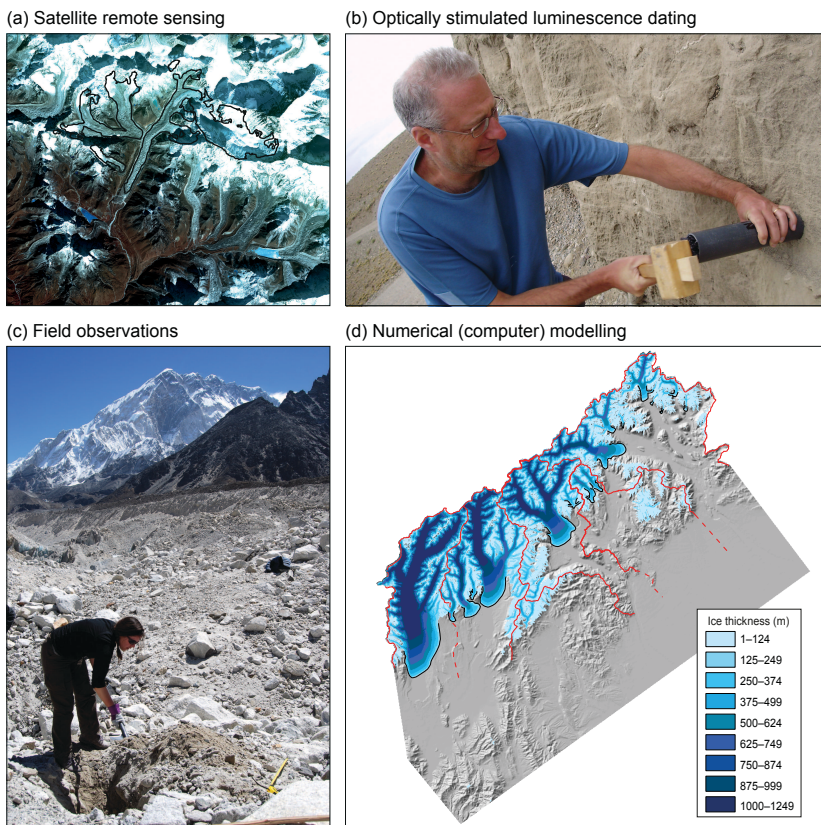
Figure 1. (a) A mountain glacier in balance with climate, and the differing responses of mountain glaciers with (b) clean-ice surfaces and (c) debris-covered surfaces to climate change resulting in a negative net glacier mass balance. The equilibrium line altitude (ELA) is shown by the dashed red line.



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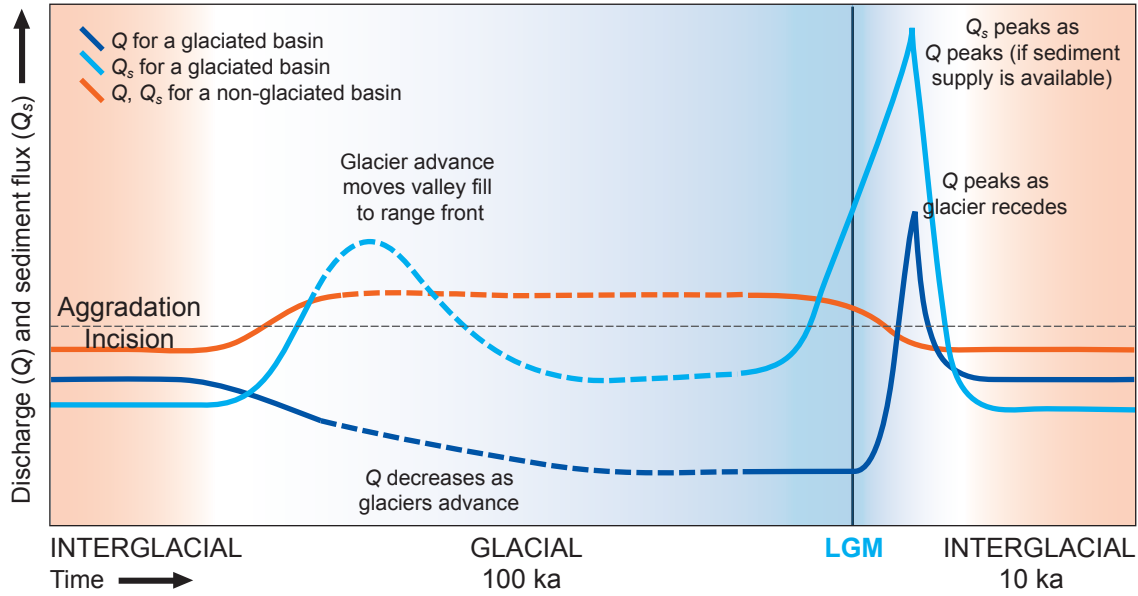
Figure 2. Late Quaternary moraines of Khumbu and Lobuche Glaciers in the Everest region of Nepal. Note buildings in both images for scale.

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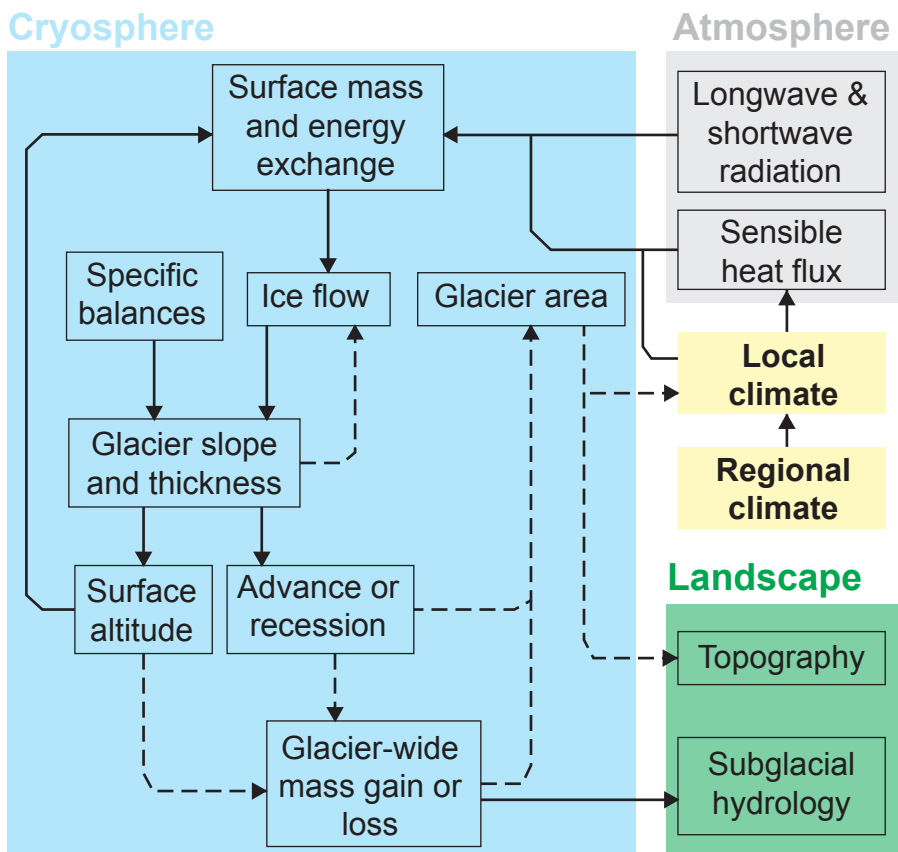
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Figure 3. Investigating how and why glaciers respond to climate change; (a) satellite remote sensing imagery of Khumbu Glacier in Nepal, where the black line is the mapped glacier area, (b) collecting a sediment sample for optically stimulated luminescence 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.



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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.



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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].

266 **Suggestions for further reading**

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