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Steep ice – progress and future challenges in research on ice cliffs

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Abstract

Ice cliffs are features along ice sheet margins, along tropical mountain glaciers, at termini of mountain glaciers and on debris-covered glacier tongues, that have received scattered attention in literature. They cover small relative areas of glacier or margin surface respectively, but have been involved in two apparent anomalies. On the one hand, they have been identified as potential hotspots of extreme melt rates on debris-covered tongues contributing to their relatively rapid ablation, compared to the surrounding glacier surface. On the other hand, they appear where the ice margin is stable (or temporarily advancing) even under conditions of negative mass balance. In this manuscript, we recapitulate why ice cliffs remain interesting features to investigate and what we know about them so far. We conclude by suggesting to further investigate their genesis and variable morphology and their potential as windows into past climates and processes.

1. Introduction

Ice cliffs can be roughly defined as parts of mountain glaciers or ice sheets with a slope > 30°, relative stability (i.e. excluding calving fronts of marine or lake terminating ice, ice falls or séracs) and a direct connection to the dynamic part of a glacier, i.e. excluding ice sails (Evatt and others, 2017) or dead ice. What we consider here as cliffs can occur at the land-based terminus of any glacier or ice sheet, on the surface of debris-covered glaciers, as well as along medial moraines on clean or partly debris-covered glaciers. While steep sections of ice can also occur in the accumulation zone (e.g. along *bergschrunds* or *randklüfte* Hanson and Hooke, 1994; Mair and Kuhn, 1994) here we only consider the ablation zone. Terminus cliffs constitute an equilibrium between the ice flux as accumulation and the cliff's ablation governed by the energy balance and dry calving. They can be persistent under rather constant climate and ice flux controls or short lived on advancing glaciers. Land-terminating ice cliffs have been documented in scientific literature as early as the 1950s in North Greenland (Goldthwait, 1971) and later in multiple locations in Antarctica (Chinn, 1987; Fitzsimons and Colhoun, 1995; Lewis and others., 1999) and on Kilimanjaro (Winkler and others, 2010). Similarly, early glaciological research in the Yukon Territory (Canada) described ice cliffs on the debris-covered Wolf Creek Glacier (Sharp, 1949) and later on Khumbu Glacier in the Himalaya (Iwata and others, 1980), but detailed research into their melting behaviour came decades later (Sakai and others, 1998). Complex models have only been applied in recent years (Buri and others, 2016b), along with the investigation of their distribution beyond the glacier scale (Steiner and others, 2019; Kneib and others, 2021a). More recently, they have also been described in the Alps (Reid and Brock, 2014), Andes (Loriaux and Ruiz, 2021) and Alaska Range (Anderson and others, 2021).

The terrestrial ice margin in Greenland and Antarctica is considerably larger than the marine-terminating part of the ice sheets, but ice flux and the resulting mass loss are approximately equal for Greenland (Shepherd and others, 2020). Locally, melt from the land-terminating margin can be important for ecosystems (Lewis and others, 1999). Cliffs on debris-covered tongues make up a relatively small proportion of mountain glaciers but have been identified as hotspots for melt and can accelerate ablation (Buri and others, 2021), with varying importance depending on the climate (Miles and others, 2022).

In this manuscript we aim to (a) describe why investigating ice cliffs is of interest, (b) revisit and synthesize our current knowledge of these features and close by (c) discussing some of the pertinent issues to investigate in relation to ice cliffs in future.

2. State of knowledge on ice cliffs

2.1. Morphology and ice dynamics

Topographic characteristics of ice cliffs across the globe vary due to their genesis. Ice cliffs on Kilimanjaro range between 3 and 50 m (Winkler and others, 2010, Fig. 1c), and like the ice margins along ice sheets (Weidick, 1968; Abermann and others, 2020) can span distances of several 100 m. They are generally near-vertical, with slopes of at least 60°. Cliffs in Antarctica were

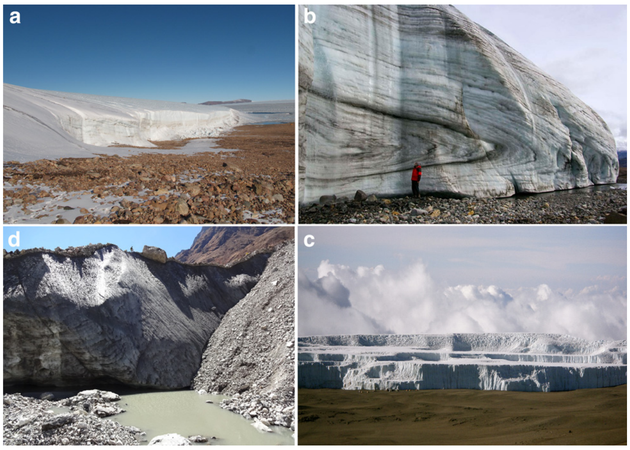

Figure 1. (a) Cliffs along the land-terminating ice margin in North Greenland (photo: Jakob Steiner). (b) The terminus of surging Crusoe glacier on Axel Heiberg Island (photo: Juerg Alean). (c) The vertical northern cliffs on Kibo, Kilimanjaro (photo: Lindsey Nicholson). (d) Ice cliff with adjacent pond on a debris-covered glacier in the Himalaya, person next to the main boulder on top of the cliff for scale (photo: Pascal Buri).

reported to be ~20 m high (Chinn, 1987; Lewis and others., 1999), observations in Greenland suggest heights of 20–30 m (Weidick, 1968; Abermann and others, 2020, Fig. 1a). No comprehensive assessment of the terrestrial ice margin of the Greenland Ice Sheet exists, but field observations suggest many sections with near-vertical portions (Weidick, 1968; Kjær and others, 2018; Abermann and others, 2020). In all cases the transition from vertical to shallow ramps happens within a few 10 s of metres of the margin (Fig. 1a, left part of the margin), and an understanding of what causes the margin to be vertical or a shallow slope is lacking. Ice mass changes have been consistently negative on Kilimanjaro, without indicative direct coupling to local climate variability over time (Kaser and others, 2010). There is no definite explanation how the ice cliffs formed in the first place, however some explanations exist for their persistence. With relatively stable air temperatures below the melting point throughout the year on the horizontal ice surface, ice temperatures fluctuate with changing solar radiation along the cliff face, resulting in stronger melting and sublimation, compared to the horizontal glacier surface. Maintaining the vertical wall is further supported by near constant longwave radiation emitted from the surrounding terrain (Fig. 2b, Kaser and others, 2010). Ice dynamics on the glaciers inside the flat Kilimanjaro crater can be neglected due to the horizontal bedrock and glaciers not being thick enough for significant ice deformation. Thus, once formed, the cliffs must inevitably retreat due to a lacking accumulation component (Kaser and others, 2010). For the ice sheet margin Goldthwait (1971) hypothesized that (a) ice cliffs are the product of the advancing ice margin, possibly surging initially in response to kinetic waves down the ice surface (Fig. 2a); (b) the vertical edge develops only where basal motion is much slower than upper ice motion, i.e. with a strong plastic shear zone near the base, overriding itself; and (c) no ice cliff will maintain itself more than 30 to 50 m high, inasmuch as the plausible stresses of forward motion cannot exceed the rate of vertical closure due to the creep rate in thick ice. Dry calving becomes a potent factor limiting cliff height.

Cliffs on debris-covered glaciers occur from ~1 m up to 20–30 m high and >100 m wide, but rarely are steeper than 60°. Exceptions are vertical and even overhanging sections at the cliff foot, caused by subaqueous or waterline melt, stream erosion or differential melt due to varying energy fluxes (Figs. 1d and 2c; Steiner and others, 2015; Watson and others, 2017; Mölg and others, 2020). Their aspect can vary widely within a single cliff and between different cliffs on a single glacier (Steiner and others, 2019). Ice cliffs cover < 15% of the area of the debris-covered tongue of glaciers (Steiner and others, 2019; Anderson and others, 2021; Kneib and others, 2021a; Loriaux and Ruiz, 2021). Their genesis has been hypothesized to be related to spatially heterogeneous debris thicknesses leading to differential melt and debris mobilization (Nicholson and others, 2018; Moore, 2021), subglacial streams or ponds leading to debris remobilization and undercutting (Sakai and others, 2000; Mölg and others, 2019), collapsing englacial channels (Benn and others, 2012; Reid and Brock, 2014) or crevasses (Reid and Brock, 2014; Steiner and others, 2019). However, the wide variety of cliff types and their varied behaviour in melt, is not conclusively explored, and their formation mechanisms have not been entirely understood to date.

Ice cliffs provide a window into the geomorphology around glacier ice. Their presence has been interpreted as an indicator of debris thickness around their edges, a variable that is crucial to estimate sub-debris ice melt (Nicholson and others, 2018). Debris transport has been a long standing discussion, with the main transport path likely being englacial (Kirkbride and Deline, 2013), but evidence of the commonly coarse surface debris within ice is rare (Miles and others, 2021), matching observations along cliff faces. Englacial debris is likely concentrated along medial moraine bands. Cliff surfaces can provide some insight into englacial processes, including foliation and basal thrusting (Fig. 1b, Hooke and Hudleston, 1978; Fitzsimons and Colhoun, 1995). This potential is also true for the ice margin, where distinctive stratigraphies hold a potential window into the past (see Fig. 1a). MacGregor and others (2020) showed that sediment bands on the much shallower margin match with data taken from ice cores further up the ice sheet. Hooke (1970) used foliation patterns and samples on steep sections of the margin in Northern Greenland to indicate past ice dynamics.

2.2. Melt and energy balance

Ice cliffs on the Greenland Ice Sheet (Fig. 1a) were initially studied for reasons of access to the ice sheet with heavy vehicles under a military purpose (Goldthwait, 1971). A peculiarity that remains not completely solved, is an apparent stability or even advance of the margin, during times of otherwise negative mass balance (Abermann and others, 2020). Similar observations were made in Antarctica, where any margin change was found to be an ambiguous indicator for mass balance conditions (Fitzsimons and Colhoun, 1995), assuming there to be a not yet explored dynamic connection.

In the Dry Valleys ice cliffs have been identified as important sources of local meltwater due to the high zenith angles at high latitude and hence the relatively strong solar irradiation onto the near-vertical cliff (Chinn, 1987). While on the horizontal ice surface more mass is lost due to sublimation, mass loss along the cliff face is melt dominated, driven by solar radiation, due to their favourable equatorward aspect (Lewis and others., 1999). Melt rates in the Dry Valleys were reported to be much higher along the cliff (~8 mm w.e. day^{-1}) than on the horizontal surface (~1 mm w.e. day^{-1}) over a three week period (Chinn, 1987). Similarly, during 41 days in the same region ablation rates on the vertical cliff face were ~7 mm w.e. day^{-1} (6% sublimation) and ~2 mm w.e. day^{-1} (42% sublimation) on the horizontal surface (Lewis and others., 1999, according to 1995–1996 data), suggesting mass wasting to be four to eight times higher along the cliff face. Initial unpublished readings from stake measurements along a south facing ice cliff in Greenland (see Abermann and others, 2020, for details on the field site) suggest ablation is strongly controlled by solar irradiance. During clear-sky conditions, frontal ablation is up to six times higher than on the rather flat glacier

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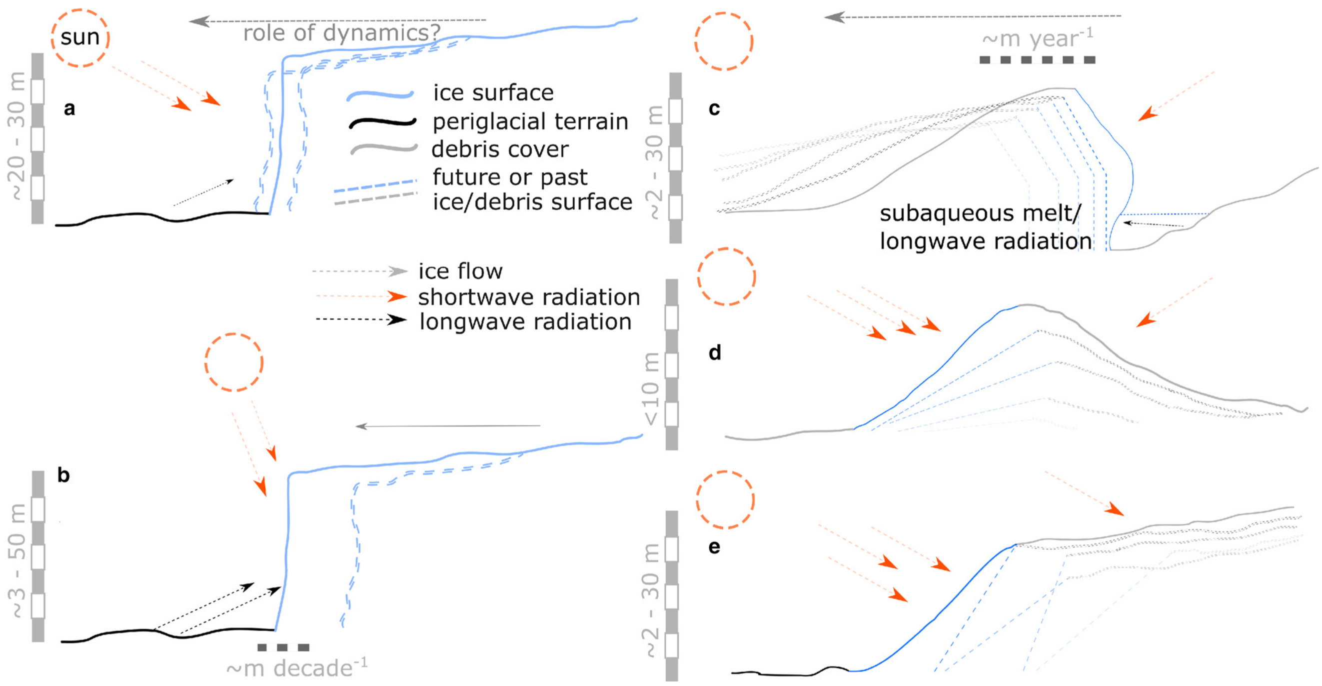

Figure 2. Conceptual examples of cliff development. The size and number of arrows for radiation and glacier flow indicate their relative magnitude. Dashed ice or debris surfaces represent past or future surfaces. Depending on the type of cliff these surface changes happen within months or years (ice margin) or days (debris-covered glaciers). The conceptual sun in the top left corner shows its approximate position around noon and the associated illumination of an idealized cliff at different latitudes. (a) The vertical ice margin in the Arctic/Antarctica is advancing or retreating and due to low temperatures receives relatively little longwave radiation from the terrain. The role of ice dynamics remains uncertain. (b) Cliffs on Kilimanjaro receive solar radiation at steeper angles and more longwave radiation, but ice dynamics play a minor or no role. (c) Persistence of cliffs on debris-covered glaciers is often defined by their aspect. Cliffs shaded from direct radiation potentially persist longer and develop complex patterns. (d) Cliffs on debris mounds facing the sun disappear faster and as a result are often also smaller. (e) Cliffs at termini recede rapidly but persist as more ice is supplied continuously.

surface. In contrast, during overcast conditions frontal ablation is about 30% less than on the flat surface.

At Kilimanjaro, close to the equator at 3°S, the radiative forcing is considerably different. Ice cliff aspect on the Northern Ice Field of Kibo Glacier is north or south only, allowing a minimum of solar irradiance at high zenith angles in the morning and evening and at low zenith angles during the day. Solar irradiance on the horizontal surface is very high, but snow accumulation, sublimation and refreezing of melt water inhibits ablation. The vertical south-facing ice cliff retreats only during the half year when solar radiation reaches the cliff face (13 cm month^{-1} or ~0.5 cm w.e. day^{-1}), reduced to just 1.4 cm month^{-1} between March and October when the cliff is permanently shaded due to the solar geometry (Winkler and others, 2010).

On mid-latitude debris-covered glacier tongues similar processes are observed. Solar radiation is higher in the horizontal than along a poleward facing cliff (Fig. 3b) but melt on cliffs between 2 and 90 mm w.e. day^{-1} (Steiner and others, 2015; Watson and others, 2017) is much higher than below the surrounding debris (2 to 8 mm w.e. day^{-1} Steiner and others, 2021). This is largely due to insulation of ice below the debris, and the very low albedo of cliffs, that receive dust loading from the debris cover above.

The aspect of ice cliffs on debris-covered glaciers in the northern hemisphere was reported to be dominantly north facing, i.e. away from direct solar radiation (Sakai and others, 2002; Thompson and others, 2016; Watson and others, 2017; Steiner and others, 2019). A study investigating this hypothesis confirmed that the angle at which a cliff faces the sun likely plays an important role in ice cliff persistence (Buri and Pellicciotti, 2018). This can be compared to a similar phenomenon on Kilimanjaro, where vertical cliffs are predominately orientated towards the north and south (Winkler and others, 2010). The processes involved in cliff morphodynamics on debris-covered tongues are however more complex and include radiative fluxes from the surrounding terrain, the dynamics of supraglacial ponds and streams and the glacier itself as well as constant rearrangement of debris across the cliff face (Figs. 2c–d).

To date no studies exist modelling the dynamic component of land-terminating ice cliffs or cliffs on debris-covered glaciers in conjunction with the frontal energy and mass balance. For ice cliffs on debris-covered glaciers, energy balance studies with an incorporation of the dynamic change of the surrounding debris surface (Buri and others, 2016a) exist, however not accounting for glacier dynamics.

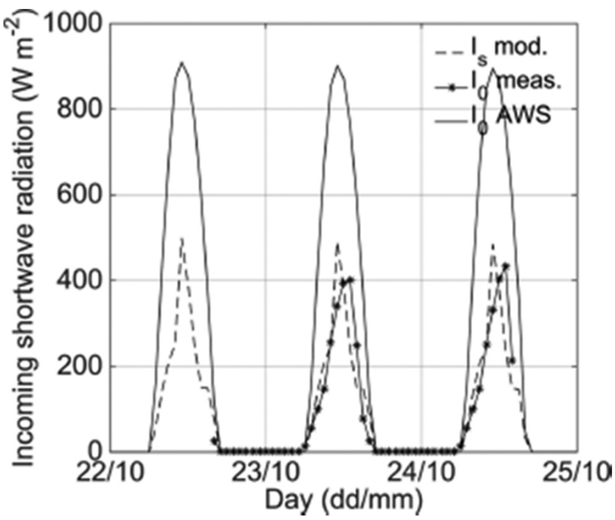

Figure 3. Incoming solar radiation measured at a horizontal AWS (I_0 AWS) and a station located on a north-facing cliff (I_0 meas.) on the debris-covered Lirung Glacier in the Central Himalaya (from Steiner and others (2015)). I_s mod. refers to the modelled radiation on the cliff. The radiation sensor is mounted parallel to the cliff face.

3. Future research needs

Below we discuss three crucial aspects of ice cliffs that should receive further scrutiny in future, namely (a) the collection and validation of high spatial resolution ice cliff topography data, (b) ice cliff genesis and associated numerical modelling and (c) dry calving processes.

3.1. High resolution datasets

There is no comprehensive understanding of the distribution of supraglacial ice cliffs in all mountain regions in time and space. Specifically, debris-covered mountain glaciers in the high Arctic as well as the Karakoram, should be a priority for more detailed assessments. The potential of increasingly high resolution satellite imagery combined with automated mapping (Kneib and others, 2021b) has already been shown on the catchment scale, providing a basis for upscaling. The Greenland ice sheet and ice cap margin has already been mapped at great spatial detail (Citterio and Ahlstrøm, 2013), for Antarctica a number of ice masks exist (Hansen and others, 2022), however in both cases without a characterisation of the margin's morphology. Given the nature of cliffs, with steep sections not adequately represented in most available topographic data, more high resolution DEMs able to capture (near-)vertical slopes (resolution <1 m) should be collected to validate the suitability of already available regional elevation data (>1 m, e.g. the ArcticDEM, Porter and others, 2022).

3.2. Cliff genesis and numerical modelling

Due to their slow evolution we have very limited documentation on how steep sections of the ice sheet margins develop (Abermann and others, 2020), and why the transition from steep to shallow occurs. Building on high resolution data mentioned above, an analysis across the complete margin of shallow versus steep sections compared to the respective ice dynamics (i.e. velocity fields) as well as the bed topography would help to test some of the hypotheses developed in individual field sites. Additionally, ice temperature measurements and documentation of their long term change would be required to better constrain high-resolution dynamical models along the margin. Collecting more evidence on linkages between ice dynamics and margin morphology would then allow for the refinement of ice dynamic models that concern themselves with margin evolution (e.g. Leysinger Vieli and Gudmundsson, 2010). A high resolution representation of the ice margin could also help to resolve micro climate in the complex transition between ice and non-glaciated terrain or steep and near-horizontal ice, applying numerical simulations as has been done for cliffs on debris-covered glaciers (Bonekamp and others, 2020).

For debris-covered glaciers the full *life cycle* of cliffs has been documented on single glaciers, limited to the Himalaya. Debris-covered surfaces exist across all glacier-covered mountain ranges (Scherler and others, 2018), on many of which cliffs have been observed but not documented (e.g. the Karakoram or peripheral glaciers in Greenland). Comparing cliff inventories with climate, mass change and ice dynamic data would allow us to establish more generalized concepts of ice cliff genesis and general occurrence. Combining numerical models for debris-covered glaciers (e.g. Scherler and Egholm, 2020) with concepts of cliff melt models (e.g. Buri and others, 2016a), would allow us to investigate the link between mass change and cliff occurrence over long time scales. A systematic comparison to data on ice mass change as well as numerical models could in turn elucidate if cliff occurrence or morphology provide an indication for ice sheet or glacier health.

3.3. Dry calving

Dry calving has been reported for all types of cliffs, along the polar ice sheets, on Kilimanjaro and debris-covered tongues, but no large scale estimates on its magnitude exist and how it is linked to ice dynamics. This process has been discussed for grounded lake-terminating cliffs (Kirkbride and Warren, 1997), but could be equally monitored for ice cliffs without a connection to water bodies. Development in employing SfM from timelapse imagery for change detection used on more rapidly changing sections of the ice sheet margin (Mallalieu and others, 2017), would allow for quantification of dry calving.

4. Conclusions

Ice cliffs in the ablation zones of debris-covered glaciers as well as along the margins of clean ice glaciers or ice sheets vary in geographical distribution, morphology and time scales of observable change. What unites them however, are the challenges associated to monitor and model steep sections of ice. The reason for their existence as well as their potential role in ice mass turnover and change, a seemingly puzzling behaviour of them remaining intact over longer time periods of overall mass loss as well as being a window inside the ice, providing a potential source for understanding past dynamic behaviour are all motivations to further invest in studies on these features. Some studies indicate that mass wasting on cliff faces in Antarctica and Greenland is up to four to eight times higher than on adjacent horizontal surfaces. On debris-covered glaciers, where the horizontal ice is covered in rocks this factor increases up to tenfold. Initial studies along ice sheet margins suggest that an advancing or stable ice margin results in steepness, making them a potential indicator for ice dynamics, while on ice fields on Kilimanjaro and debris-covered glaciers complex radiative fluxes help to explain their shape. On debris-covered glaciers cliffs are a result of wasting ice mass and collapsing englacial features but also potentially enhance the glaciers' demise.

We argue that more high resolution topographic data should be collected wherever these features appear to compare their occurrence to other data on ice dynamics and cryospheric change, in order to understand their role in and potential as indicators of change.

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Author contributions. All authors developed the content and proposed concepts and contributed to the writing. JFS initiated the manuscript and prepared the figures.

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