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How can geomorphology facilitate a better understanding of glacier and ice sheet behaviour?

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Abstract

Glaciers and ice sheets are an integral part of Earth's system, advancing and retreating in response to changes in climate. Clues about the past, present, and future behaviour of these ice masses are found throughout current and former glaciated landscapes. In this commentary, we outline recent scientific advances from a collection of articles in which geomorphological evidence is used to inform us about the behaviour of glaciers and ice sheets across a range of spatial (landform to continent) and temporal (seasons to millennia) scales. Through a diversity of approaches including field measurements, remote sensing and numerical modelling, these studies build on an extensive background literature to deepen our understanding of how ice flows, how glaciers and ice sheets respond to climate change, and of the processes of ice advance and retreat and the stability of the system. Further integration of knowledge across the fields of geomorphology and glaciology will have tangible benefits for managing the societal and environmental impacts of glacier change, and for improved projections of sea-level rise over the coming decades to centuries.

Keywords: glaciology, glacier, ice sheet, glacial geomorphology, sedimentology, glacial geology, modelling, remote sensing, landforms, climate change

1. INTRODUCTION

Glaciers and ice sheets cover 12.5% of the Earth's surface. They are found on most continents, and in temperate, continental and polar climatic zones (Bamber et al., 2018). Changes in their size (i.e. length, area, volume, mass) and dynamics (e.g. ice flow direction, speed, thermal state) serve as key indicators of climate change and affect global sea level, regional water resources, and local geohazards and biodiversity (Cauvy-Fraunié & Dangles, 2019; Ding et al., 2021; Huss & Hock, 2018; Pörtner et al., 2019; Zemp et al., 2015).

Whilst changes in the size of glaciers and ice sheets have been observed for over a century (e.g. Cruikshank, 2001; Esmark, 1824), recent measurements and numerical modelling reveal unprecedented states and trends. Near-synchronous global glacier retreat and ice sheet mass loss has occurred over the last 50 years, and human influence on the climate has very likely contributed to ice loss in Greenland and was the main driver for mountain glacier retreat (Bamber et al., 2018; Fox-Kemper et al., 2021; Malles & Marzeion, 2021; Otosaka et al., 2023). Together, glaciers and ice sheets were the primary contributors to global mean sea-level rise over the last two decades, and are expected to continue losing mass over the coming decades to centuries, and possibly millennia (Fox-Kemper et al., 2021).

There is an urgent need to better understand both past and contemporary glacial systems, principally to enhance our ability to predict future changes and their associated impacts. Knowledge of the past and present behaviour of glaciers and ice sheets can be gleaned from large swaths of Earth's surface as glacial ice is a principal agent of landscape evolution through the processes of erosion, transport, reworking and deposition of sediments (Herman et al., 2021). 'Glacial geomorphology'—broadly defined here as landform- to landscape-scale features produced by glacial ice, and their associated sediments (akin to 'glacial geology' in some literature)—describes this interaction between ice and the Earth's surface, reflecting the physics of ice flow and recording how glaciers and ice sheets respond to climate change.

The field of glacial geomorphology has typically focused on providing physically-based explanations for how glaciers and ice sheets contribute to landform and landscape development (e.g. Harbor, 1993). However, we reflect on how geomorphology can improve our understanding of glacier and ice sheet behaviour, and the role geomorphology may have in future ice mass change (Figure 1).

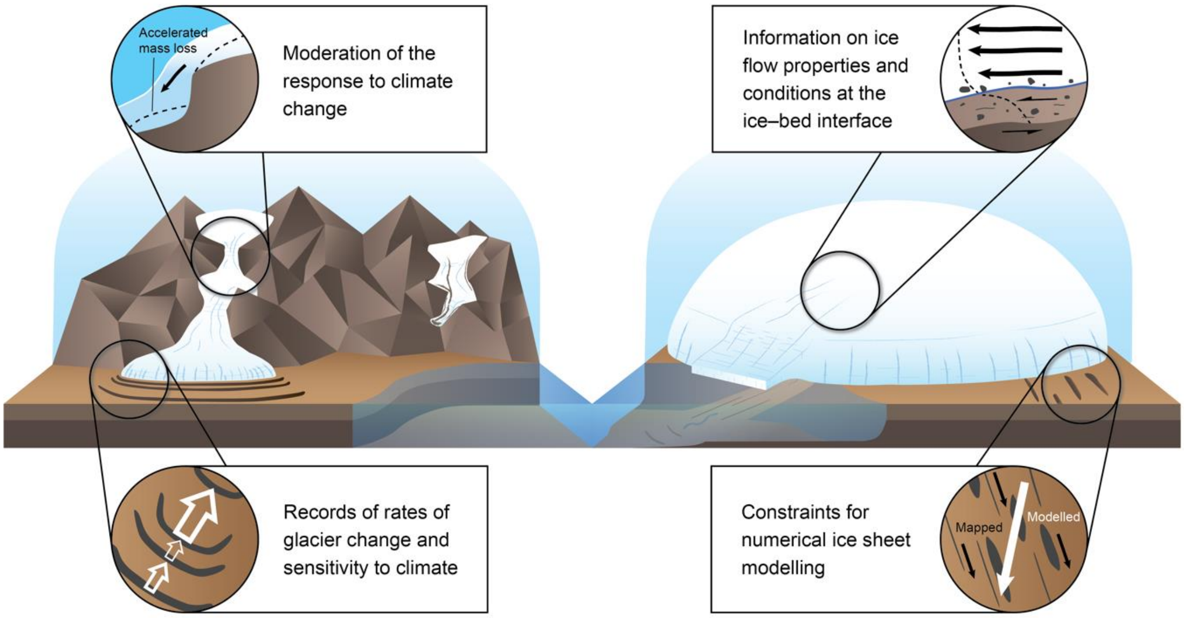

Figure 1. Geomorphology can facilitate a better understanding of glacier and ice sheet behaviour in several ways: by moderating glacial response to climate change; by providing rates of glacier change and sensitivity to climate; as information of ice flow properties and basal conditions; and as constraints for ice sheet modelling.

2. A BRIEF HISTORY OF GLACIAL GEOMORPHOLOGY

Our current understanding of glaciers and ice sheets, and arguably the field of glaciology broadly, can be traced back to early studies of glacial geomorphology. While speculations that glaciers modified the landscape have existed for centuries (e.g. Cruikshank, 2001), it was the scientists of the 19th Century that established the foundation of glacial geomorphology as we know it today (cf. Boulton, 1987; Clarke, 1987; Krüger, 2013). In particular, the 'Ice Age' theory stemmed from the recognition that glaciers could erode rock, transport erratic boulders and deposit poorly-sorted sediment (e.g. Agassiz, 1840; Esmark, 1824). Further discoveries in subsequent decades include (i) the recognition that glaciers moved as a result of internal flow and basal sliding, leading to subglacial abrasion (Forbes, 1842); (ii) that multiple glacial and interglacial periods existed due to oscillations in the climate (e.g. Croll, 1864; Geikie, 1863); and (iii) that glaciation impacted both global and local sea level (Jamieson, 1865; Whittlesey, 1868).

Building on these early ideas, the field of glacial geomorphology has grown substantially over the last 150 years. Much of this growth came from the refinement of existing methods and application of new technologies. For example, field-based mapping and sedimentology was carried out in increasing detail to better characterise current and former glaciated environments, resulting in the birth of the 'glacial landsystem' approach (Evans, 2003; Fookes et al., 1978). Meanwhile, the advent of the satellite era enabled higher-precision field measurements with the use of Global Positioning Systems (GPS), and remote sensing of ice masses and glacial landscapes (cf. Chandler et al., 2018; Gao & Liu, 2001). Numerical models also emerged as vital tools for understanding glacier and ice sheet behaviour (e.g. Oerlemans, 1986; Pattyn et al., 2017), with a rapidly rising number of glaciological and glacial geomorphological applications (e.g. Huybrechts, 1990; Tarasov et al., 2012).

3. SCIENTIFIC ADVANCES

Here we outline recent advances in the field of glacial geomorphology, with reference to new articles published as part of this collection (Table 1). These contributions highlight the role of geomorphology in glacier and ice sheet change over time—from a year (e.g. Lally et al., 2023) to decades (e.g. Evans et al., 2023) and centuries and millennia (e.g. Carrivick et al., 2023; Stutz et al., 2023)—and across space—landforms to landsystems (e.g. Balaban et al., 2024; Ben-Yehoshua et al., 2023), and individual glaciers to continental ice sheets (e.g. Kavan et al., 2024; McKenzie et al., 2022).

We identify three principal themes pertinent to our knowledge of current and future change: (1) the response of glaciers and ice sheets to climate change, (2) processes that could influence their behaviour, and (3) new methodological developments and their application that will further build this knowledge.

3.1 Glacier and ice sheet response to climate change

Glacier mass balance is sensitive to air temperature, and to a lesser degree precipitation (Oerlemans, 2001), and so glaciers advance and retreat in response to a changing climate. The glacial geomorphological record has long been utilised for improving our knowledge of the climate system (e.g. Nye, 1965; Porter, 1975; Schaefer et al., 2006; Shakun et al., 2015), particularly when combined with modern observations and numerical modelling (Mackintosh et al., 2017).

Moraines serve as archives of past glacier change, thus acting as proxies of past climate conditions. However, a comprehensive understanding of the relationship between climate and moraine formation is crucial for extracting accurate information from these records. Research by Rowan et al. (2022) shows that interannual climate variability can lead to moraine formation, while Boston et al. (2023) suggest that moraine spacing may be influenced by bed topography, complicating the interpretation of climate signals from these landforms. Nevertheless, moraines still record transient and equilibrium changes in ice volume, and the spatial characteristics (e.g. geometry, number and position) of moraines represent the rate of climate change relative to glacier response time (Rowan et al., 2022).

Geomorphological records can also shed light on how different parts of the glacial system could moderate the response to a warming climate. For example, two new studies (Carrivick et al., 2023; Stutz et al., 2023) combined mapped geomorphology or dated deposits with ice-flow modelling to identify how the glacier thermal regime affects ice dynamics. Perhaps counterintuitively, Carrivick et al. (2023) indicate that some Greenlandic outlet glaciers have transitioned towards a cold-based thermal regime during a warming climate, and Stutz et al. (2023) similarly suggest that reduced basal sliding occurred at an Antarctic outlet glacier at a time of rapid thinning.

Furthermore, specific geomorphological features can moderate glacial response to climate change. Davies et al. (2022) show that ice fields can have a non-linear response due to glacier hypsometry; topographic steps cause disconnections between glacier accumulation zones, leading to reduced downstream ice flow and increased rates of retreat. Similarly, Balaban et al. (2024) use a landsystems approach to identify a disconnect between glacier and plateau ice, attributing this uncoupling to the shape and elevation of topography as well as burial from excessive glacial debris. In the presence of rapid climate warming, Evans et al. (2023) show that such debris cover can ultimately lead to stagnation of the glacier snout within years to decades. Even on seasonal timescales, geomorphological factors could influence glacier dynamics. For example, Kavan et al. (2024) show that the snout of a lake-terminating glacier changed due to the subglacial bed topography as well as debris cover; over-deepenings encourage increased ice flow, mass loss and further lake expansion, whereas increased surface debris insulates some parts of the terminus, reducing ablation.

3.2 Processes of advance/retreat and stability/instability

Geomorphology influences glacier and ice sheet behaviour via feedbacks at the ice–bed interface, and provides insights into the processes governing the mass balance and broader stability of the system. For example, the potential for bed topography to accelerate retreat (e.g. Jones et al., 2015; Weertman, 1974), the dependence of glacier surging on thermal regime (e.g. Benn et al., 2019; Raymond, 1987), and the reliance of ice stream activity on subglacial conditions (e.g. MacAyeal, 1989; Stokes et al., 2007) are now well established through a shared glaciological and geomorphological understanding.

The geomorphological record at the margins of glaciers and ice sheets is indicative of styles of advance, retreat and even shutdown. A new study by Lane et al. (2023) examined the deglacial landsystem of a Greenland ice stream, revealing evidence of rapid ice shelf disintegration concurrent with or just before ice stream retreat, underscoring the important role of ice shelves for ice stream stability. Lee et al. (2024) find that ice flow and retreat patterns evolved differently during the advance and retreat phases of a marine-based ice sheet. Mapping and sedimentological analysis by Aradóttir et al. (2023) and Ben-Yehoshua et al. (2023) shed light on locations of crevasse-squeeze ridges formation and how they reflect stresses within the ice. These features are interpreted as indicators of surge behaviour, where an ice stream advance is followed by stagnation, melting and down-wasting. Iverson et al. (2023) also propose that ice sheet lobes can undergo stagnation and down-wasting during periods of quiescence.

Processes at the bed of glaciers and ice sheets are difficult to directly observe in contemporary systems, and subglacial landforms and sediments can provide novel signatures of ice–bed conditions and bed-modulated ice flow. Ely et al. (2023) describe a continuum of ice sheet behaviour reflected in subglacial landforms; ribbed moraines initially occur following an instability, which can evolve into drumlins under consistent sheet flow conditions or in ice stream onset zones, while mega-scale glacial lineations result from the elongation of drumlins under ice stream conditions. The degree of elongation and the density of such streamlined landforms could also reflect a combination of lithology and bed topography (McKenzie et al., 2022), and the presence of certain landforms (e.g. drumlins) may indicate a climate-driven advance of an ice stream (Iverson et al., 2023). Using subglacial landforms to reconstruct laminar ice-flow patterns, Kamleitner et al. (2024) propose that basal ice can flow at relatively high velocities despite varied bed topography, whilst McCerery et al. (2023) suggest that surge behaviour of ice streams could occur in oil sands due to enhanced slipperiness at the bed.

Additionally, process-based information about meltwater drainage within and beneath glaciers and ice sheets can be gained from the geomorphological record (Simkins et al., 2022). A new study by Lally et al. (2023) suggests that glacier meltwater drainage systems are likely more complex than previously considered, as englacial eskers are not always preserved in the geomorphological record. Where ice scour lakes are found, Mastro et al. (2023) propose that the density and orientation of these lakes is evidence for ice flow direction and locations of ice divides; an abundance of ice scour lakes in an area under a contemporary ice sheet could signify that an ice divide has migrated.

3.3 New methods to improve understanding of glaciers and ice sheets

Continued progress in understanding glacier and ice sheet change will occur in hand with methodological developments. Remote sensing continues to evolve rapidly, offering new technologies and supporting quantitative analyses in glacial geomorphology (cf. Chandler et al., 2018). For example, air- and space-borne Light Detection and Ranging (LiDAR) is being increasingly applied to generate regional-scale topographic datasets at high resolution (~1 m), enabling detailed geomorphological assessments (e.g. Carrivick et al., 2023; Iverson et al., 2023; McKenzie et al., 2022). To help optimise this resource, Eyles et al. (2023) provide a semi-automated, stepwise approach to utilise LiDAR databases for mapping of subglacial landsystems. Unmanned Aerial Vehicles (UAV) support the acquisition of even higher spatial resolution (<0.1 m) datasets, and are becoming a standard part of the geomorphological field toolkit (Chandler et al., 2018). Best suited to a glacier or glacial foreland, UAV technology enables relatively small spatial and/or temporal changes to be identified due to the resolution and repeatability of the measurements (e.g. Carrivick et al., 2023; Kavan et al., 2024; Lally et al., 2023). Investigating novel geomorphological or glaciological patterns in these higher-resolution geospatial datasets will also require new analytical methods and frameworks. Mastro et al. (2023), for example, used semi-automated morphometric analysis to characterise ice scour lakes at a national scale.

In addition to morphological characteristics, the sedimentology of a glacial landsystem can reflect glaciological processes (e.g. of transport, deposition, advance and retreat), and can influence ice dynamics (e.g. slipperiness at the bed). An emerging application of investigation is geochemical fingerprinting to glacial sediments. Kirkbride et al. (2023) use XRF-enabled sediment fingerprinting to understand the provenance and source of supraglacial debris, providing a method to assess glaciological changes within a high-mountain system over time. Similarly, McCerery et al. (2023) use geochemical fingerprinting to investigate oil sand mobilisation at the bed of a former ice stream, proposing that naturally-occurring hydrocarbons at the ice-sediment interface could enhance basal slipperiness.

Finally, applications of numerical modelling to investigate the relationships between geomorphology and glacier or ice sheet behaviour have been limited to date, largely due to the complexity of representing coupled glaciological and geomorphological processes. Adequately incorporating these processes in models, whilst leveraging ever-improving computational infrastructure, is already enabling scientific advances. Rowan et al. (2022) and Ely et al. (2023) exemplify, respectively, how glacial landscape modelling, and coupled ice-, water- and subglacial sediment-modelling can deepen our understanding of climate change and ice dynamics.

Despite such advances, the field of ice sheet modelling has not yet fully utilised the geomorphological record, instead relying largely on geochronological constraints and/or glaciological observations (e.g. Goelzer et al., 2017; Lecavalier et al., 2023). A study by Archer et al. (2023) introduces a new data-model comparison tool to quantitatively assess models against mapped subglacial landforms. Following this approach, records of glacial geomorphology can now be used to determine best-fit simulations of past ice sheet behaviour.

4. CONCLUSIONS

In recent decades, the fields of glacial geomorphology and glaciology have operated somewhat independently. There are, however, numerous advantages to be gained by these research communities working more closely together if we are to better understand current and future glacier and ice sheet change (cf. Bingham et al., 2010; Ely et al., 2021; Mackintosh et al., 2017; Simkins et al., 2022).

High-precision reconstructions of past glacier change that utilise geomorphological observations and numerical modelling will extend our understanding of glacier behaviour over timescales relevant to the 21st century and beyond. This could include bounds on possible rates of change, conditions under which glaciers may elude retreat in a warming climate, or glacier sensitivity to different environmental factors.

Further imaging of contemporary ice sheet beds in combination with knowledge gained from formerly glaciated landscapes could help identify regions vulnerable to future ice mass change. These could include locations susceptible to ice streaming or stagnation, ice divide migration, or englacial and subglacial meltwater drainage. Additionally, geomorphological landforms in front of, or beneath, contemporary ice sheets can now be leveraged to improve the predictive capability of ice sheet models that are projecting future sea-level rise.

Sustained climate warming will continue to prompt dramatic glacier and ice sheet changes, resulting in substantial societal and environmental impacts. This commentary, alongside the new findings published in this collection, underscore the important role of geomorphology in understanding how these ice masses could change into the future.

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Table 1. Articles published as part of this Special Issue.

SI paper	Region	Process domain(s)	Landforms of interest (non-exhaustive)	Methodological approach	Temporal scale
Aradóttir et al. (2023)	Europe (Iceland)	Subglacial (ice stream)	Streamlined subglacial bedforms, crevasse-squeeze ridges	Remote sensing	Millennia
Archer et al. (2023)	Hypothetical, Europe (UK, Ireland)	Subglacial (ice sheet)	Subglacial lineations	Modelling	Millennia
Balaban et al. (2023)	Europe (Romania)	Landsystem (ice cap, mountain glacier)	Moraines, ice-moulded bedrock, meltwater channels, protalus ramparts, rock glaciers	Remote sensing, field mapping	Millennia
Ben-Yehoshua et al. (2023)	Europe (Svalbard)	Landsystem (outlet glacier)	Crevasse-squeeze ridges, flutes	Remote sensing, field mapping	Year-decades
Boston et al. (2023)	Europe (Norway)	Foreland (outlet glacier)	Moraines, subglacial bedforms (various)	Remote sensing, field mapping	Decades-centuries
Carrivick et al. (2023)	Europe (Greenland)	Foreland (outlet glacier)	Moraines, outwash fans, kames, eskers	Remote sensing, field mapping	Millennia
Davies et al. (2022)	N. America (USA, Canada)	Landsystem (icefield, outlet glacier)	Moraines, glacial lakes, trimlines, flutes, cirques	Remote sensing	Decades
Ely et al. (2022)	Hypothetical	Subglacial (ice stream)	Streamlined subglacial bedforms (various)	Modelling	Centuries
Evans et al. (2023)	Europe (Iceland)	Landsystem (outlet glacier)	Outwash fans, moraines, overdeepenings, eskers	Remote sensing, field mapping	Decades
Eyles et al. (2022)	N. America (USA)	Subglacial (ice sheet lobe)	Drumlins, mega-scale glacial lineations	Remote sensing	Millennia
Lee et al. (2024)	Antarctica	Subglacial (ice stream)	Streamlined subglacial bedforms, grounding-zone wedges	Field surveying/mapping	Millennia
Iverson et al. (2023)	N. America (USA)	Subglacial (ice sheet lobe)	Drumlins	Remote sensing	Millennia
Kamleitner et al. (2023)	Europe (Switzerland, Germany, Austria)	Subglacial (outlet glacier)	Streamlined subglacial bedforms (various)	Remote sensing	Millennia
Kavan et al. (2024)	Europe (Iceland)	Proglacial (outlet glacier)	Glacier surfaces, glacial lakes	Remote sensing, field mapping	Decades
Kirkbride et al. (2023)	South Asia (Nepal)	Landsystem (mountain glacier)	Supraglacial debris cover	Field sampling, modelling	Millennia
Lally et al. (2023)	Europe (Iceland)	Englacial, subglacial (outlet glacier)	Eskers	Field mapping	Year-millennia
Lane et al. (2023)	Europe (Greenland)	Landsystem (ice stream)	Blockfields, erratics, moraine, hummocky topography	Remote sensing, field mapping	Millennia
Mastro et al. (2023)	Europe (Iceland)	Subglacial (ice sheet)	Ice-scour lakes, streamlined subglacial bedforms	Remote sensing	Millennia
McCerery et al. (2023)	N. America (Canada)	Subglacial (ice stream)	Till, moraines, subglacial landforms (various)	Field sampling, laboratory	Year-millennia
McKenzie et al. (2022)	N. America (USA, Canada), Europe (Iceland, Norway, Sweden)	Subglacial (ice sheet, ice stream)	Streamlined subglacial bedforms (various)	Remote sensing	Millennia
Rowan et al. (2022)	Hypothetical	Landsystem (mountain glacier)	Moraines	Modelling	Millennia
Stutz et al. (2023)	Antarctica	Landsystem (ice sheet, outlet glacier)	Nunataks, erratics	Field sampling, laboratory, modelling	Millennia