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Glaciers and Ice Sheets in a Warming World: Impacts and Outcomes



A contribution by UK scientists to the 2025
International Year of Glaciers' Preservation

Edited by David J Drewry
October 2025



2025
International
Year of Glaciers'
Preservation

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Glaciers and Ice Sheets in a Warming World: Impacts and Outcomes.
A contribution by UK scientists to the 2025 International Year of Glaciers' Preservation.
Edited by: David J Drewry.

United Kingdom National Commission for UNESCO, London, UK. 110 pages

Cover photo: Lake Palcacocha, Cordillera Blanca, Peru, one of many potentially dangerous glacial lakes in the Andes. ©Caroline Clason

About the United Kingdom National Commission for UNESCO

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Our core functions are: To provide expert, individual policy advice to the UK and devolved governments on UNESCO related issues, to support the UK government's agenda to help UNESCO achieve its core goals, to advise and assist individuals and institutions in the UK and its' Overseas Territories and Crown Dependencies, with accessing UNESCO accreditation and prizes. We also support and enhance the value of the UK's UNESCO sites and projects. For more information see: www.unesco.org.uk

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Preface

This publication had its origins in a conversation with Lidia Brito, Assistant Director-General (ADG) for Natural Sciences, UNESCO in the margins of the UNESCO General Conference in November 2023. We were attending a side meeting on glaciers and the cryosphere, one of the steps that has led to the International Year of Glaciers' Preservation (IYGP). Professor Brito commented that, to her knowledge, scientists in the United Kingdom have a long and significant engagement with glacier research. Would it not be a positive move, she intimated, if they were to be encouraged to contribute to UNESCO's forthcoming initiatives? I responded that I knew several researchers were already working on the climate-related responses of glaciers in mountain regions of the world such as the Andes and Himalaya.

I agreed to engage with the UK glaciological community and seek their interest in contributing to a publication that would demonstrate their active research and raise awareness of the impacts of climate change on glaciers and mountains. The publication would highlight the critical functions of glaciers, and the implications of climate change for ecosystems, water resources and local populations and their livelihoods. I am delighted that, in closing the circle, ADG Brito has written a Forward to this volume.

This report is, therefore, the outcome of a process that commenced in September 2024 as a contribution to the IYGP supported by the UK National Commission for UNESCO. In seeking articles for a volume, I highlighted two categories for contributions:

- i) glaciological/hydrological research in mountain regions that factor primarily into the human-focused impacts of glacier change, and
- ii) ice sheets and ice caps that have considerable global influence through raising sea levels.

It was also clear that the contributions should be short and written to be accessible to a wide range of interested parties and to policy makers.

I was delighted by the response from a significant cohort of the many UK scientists engaged in glacier-climate research. The final selection of reports covers up-to-date discoveries, a range of geographical settings, the use of innovative data-collection technology, satellite remote sensing and powerful modelling. All contributions focus on the dramatic changes that are taking place to the ice environment of our planet.

It is a pleasure to acknowledge the vital support of this project given by the UK National Commission for UNESCO (UKNC) and its Secretary-General, Mr James Bridge. Assistance and encouragement were also afforded by the UK Permanent Delegation to UNESCO and its Ambassador, Anna Nsubuga. Finally, my gratitude is extended to each of the contributors for their positivity and forbearance.

Professor David J Drewry DSc.

Vice-Chair and Director Natural Sciences
UK National Commission for UNESCO (2017-25)

Left: Walcott Glacier (rt) and Radian Glacier (l) descending southern end of Royal Society Range, McMurdo Sound, Antarctica. Highest peak Mt Rucker (3815m). ©David Drewry



Iceberg on Lago Argentino, Los Glaciares National Park,
SW Santa Cruz Province, Argentina. ©David Drewry

Foreword

Climate change is accelerating the retreat of glaciers, reducing snow cover, intensifying permafrost thaw, and increasing the frequency and severity of extreme precipitation events and related natural hazards. These changes are contributing to increasingly variable and unpredictable water flows, underscoring the urgent need to strengthen mountain water governance through integrated river basin management, sustainable financing, and enhanced knowledge and capacity development.

Currently, over 67 UNESCO biosphere reserves, seven UNESCO Global Geoparks, and 50 World Heritage sites contain glaciers, collectively representing nearly 10% of the Earth's glacierized area. A recent UNESCO study warns that glaciers in one-third of these World Heritage sites are projected to disappear by 2050.

The concept of a global inventory of perennial ice and snow masses was first introduced during the International Hydrological Decade (1965–1974), led by UNESCO. Yet, significant gaps persist in monitoring, scientific understanding, and data availability on glacier systems.

Mountain regions serve as critical "water towers" for downstream populations. At least half of the global population depends on water originating from mountain headwaters, and over 2 billion people rely directly on glaciers and snow for water, food security, and energy. UNESCO's Intergovernmental Hydrological Programme (IHP) plays a central role in advancing scientific collaboration, building capacities, and supporting member states in assessing and monitoring changes in snow, glaciers, and water resources, while identifying viable adaptation strategies.

The year 2025 marks a pivotal moment with the proclamation of the **International Year of Glaciers' Preservation**. This global initiative reflects a shared recognition of the essential role glaciers play in sustaining ecosystems, regulating climate, and securing water resources for billions. UNESCO, in partnership with the World Meteorological Organization, is honoured to co-facilitate this Year.

2025 also marks the launch of the **Decade of Action for Cryospheric Sciences (2025–2034)**, announced at the third United Nations Ocean Conference (UNOC3) in Nice, France. Coordinated by UNESCO, this Decade will advance research on the planet's frozen regions, support the development of a global Cryosphere Atlas, and promote a comprehensive monitoring framework.

I commend the UK National Commission for UNESCO for its leadership in publishing the important volume *Glaciers and Ice Sheets in a Warming World: Impacts and Outcomes*. This publication makes a valuable contribution to both the International Year of Glaciers' Preservation and the Decade of Action for Cryospheric Sciences. It presents key findings from the UK scientific community on glacier, snow, and ice sheet dynamics, and highlights the importance of robust monitoring techniques and adaptation strategies.



Lídia Arthur Brito

Assistant Director-General for Natural Sciences
UNESCO

Introduction to the International Year of Glaciers' Preservation 2025

(UNESCO/WMO)¹

Glaciers are a crucial part of many mountain ecosystems. Billions of people, and two-thirds of irrigated agriculture, depend on mountain water resources that often include essential contributions from glaciers, especially in dry seasons.

Losing these glaciers due to global warming will impact strongly key economic sectors including power generation, tourism and agriculture, potentially increase transboundary water conflict, and increase downstream hazards.

“

Even with urgent mitigation efforts, some level of glacier loss remains inevitable given current reduction rates, which modelling shows will continue until temperatures stabilise.

”

In recognition of these risks, the United Nations General Assembly in December 2022 adopted the resolution to declare 2025 the International Year of Glaciers' Preservation (IYGP) accompanied by the proclamation of March 21st of each year as the World Day for Glaciers starting in 2025. Furthermore, the UN invited UNESCO and WMO, in collaboration with governments and relevant organizations, to facilitate its implementation as leading agencies. The key aim of the Year is to raise global awareness of the need for urgent climate action to preserve glaciers globally, given their critical importance to many regional economies and the impending economic, social and environmental impacts of their continued loss.

This Introduction provides a brief overview of the rationale behind the Year and the vital role that glaciers play including seasonal water resources and other ecosystem services; contributions to livelihoods and well-being; and the risk posed by glacier and ice loss in hazards such as glacial floods, landslides and rising sea levels.

¹UNESCO/WMO IYGP Intro for Policymakers (<https://www.un-glaciers.org/en>)

The IYGP argues that it will be essential to hold to the Paris Agreement to limit global temperatures rising in excess of 1.5°C above pre-industrial levels. This target requires the urgent and effective cutting of gas emissions primarily through reducing extraction and use of fossil fuels and is the only means to preserve glaciers worldwide. There are no “quick fixes” outside of rapid and sharp greenhouse gas emissions reductions. Failure to do so will have long-term and dramatic negative economic and social impacts that are largely irreversible on human timescales, and lead to loss of many economic and sustainable development gains. In some regions, dislocation and conflict will result from continued glacier and snowpack loss. These impacts will likely touch those living far from mountain cryosphere, raising the importance of the risks posed by shrinking glaciers that require urgent mitigation to address.

Even with urgent mitigation efforts, some level of glacier loss remains inevitable given current reduction rates, which modelling shows will continue until temperatures cease rising. Such stabilisation may be possible after mid-century should governments make a course correction back to 1.5°C and maintain it in subsequent Paris commitment periods.

National adaptation plans are urgently needed so that communities have time to respond to this reality. Under the Paris Agreement, adoption of glacier and snowpack indicators under the Global Goal on Adaptation process, as well as in the Nairobi Work Programme focusing on high altitude and high latitude regions, will be essential.

At the national level, planning for the future should involve both glacier and downstream countries, for both long-term adaptation efforts and risk management during extreme events such as landslides and glacial lake outburst floods. The involvement of Multilateral Development Banks, as well as investment guarantee mechanisms and the private sector, will be key in this transition.

The International Year of Glaciers’ Preservation

was launched in Paris on 21st March 2025. It highlights the challenges posed to all countries by a shrinking mountain and global cryosphere. Governments need to be aware that vital assets to their economies and industries are at risk and alongside local authorities need to take the appropriate steps regarding reducing emissions and adaptation. Changes in the amount of water and seasonal availability of water need to be studied and conveyed to the communities dependent on meltwater from glaciers and snowpacks. Flood preparedness and early warning systems are also needed, both downstream from glaciers where glacial floods may originate and in low-lying areas threatened by sea level rise.

By marking the International Year of Glaciers’ Preservation, the global community is both recognising the importance of glaciers and committing to taking the urgent steps needed to preserve them.



2025
International
Year of Glaciers’
Preservation

The Mountain and Polar Cryosphere – change and challenge

David J Drewry

UK National Commission
for UNESCO

David Drewry is Professor, Director Natural Sciences at the UK Commission for UNESCO (2017-25) and Honorary Fellow at Emmanuel College, Cambridge University. Previously he was Director of the British Antarctic Survey and Director of the Scott Polar Research Institute, Cambridge. His research interests are in radio echo sounding and satellite radar altimetry of ice masses and ice-climate interactions. He is recipient of the Polar Medal, Patron's Gold Medal of the Royal Geographical Society, Prix de la Belgica Gold Medal of the Royal Academy of Belgium, and the United States Antarctic Service Medal. He has a mountain and a glacier named after him in Antarctica.

Our planet is in trouble; it is warming at a dramatic rate. The likelihood of restraining global temperatures from rising above 1.5°C over pre-industrial levels, an ambition set out in the UN Paris Agreement, seems remote. There is an inexorable increase across most of the globe of 0.20°C per decade; the warmest years on record were all in the last ten years (Figure 1).

The consequences of this atmospheric heating are both increasingly evident and profoundly consequential for the natural and human worlds:

- Warming of the Oceans
- Rising sea levels
- Coral bleaching
- Ocean acidification
- Reduction in ocean oxygen levels
- Increased atmospheric storminess
- Increase in forest fires
- Widespread drought
- Extreme heat-waves
- Loss of biodiversity
- Spread of disease vectors
- Decline of human health
- Migration of plants, animals and humans

Melting Glaciers

One of the most visible changes with dramatic impact on communities is the rapid melting of glaciers in mountainous areas such the Greater Himalayan region, The Andes, the European Alps and East Africa.

The UN has reported that some two billion people in villages, towns and cities in these mountain regions or downstream on lowland areas rely, in varying degrees, on access to water from glaciers.¹ The water is vital for domestic consumption, crops, livestock, industry and electric power generation and sustaining regional ecosystems.

¹ UNESCO World Water Assessment Programme, 2025, Mountains and Glacier: water towers, 174pp; <https://doi.org/10.54679/LHPJ5153>

During the last two decades glaciers worldwide have lost some 273 ± 16 Gigatonnes (Gt) of ice every year.² In the Andes the ice loss is 25% since the Little Ice Age and at 2°C of warming 50% of the ice in the Hindu Kush region of the Himalaya will disappear¹. Melting glaciers are adding water to the Oceans and their contribution to global sea level rise is of the order of $0.75 \pm 0.04 \text{ mm yr}^{-1}$.

Chhireng Tamang has lived the whole of her 75 years in Langtang National Park, in northeastern Nepal. This is a place of high-altitude meadows, forests, impressive mountains to over 7000m with glaciers and snowpacks exhibiting considerable biodiversity. Chhireng Tamang recalls a period not too far distant when the mountains received regular and heavy snowfall, and the glaciers were “white and big.” This meant it was easy to farm yaks, an animal upon which many rural communities still depend for wool, milk and meat, along with sheep and horses. Rising temperatures, however, have

rapidly reduced the amount of water and fresh grass available for the livestock. From a herd of forty yaks, Chhireng Tamang now has just nine. “*There is not enough grass to feed them anymore. All the farmers face the same problem,*” she says³.

Héctor Basilio Poma is 64 years-old and lives on the slopes of Tuni Condoriri in the Bolivian Andes, making ends meet by raising llamas. In recent years his work has become tenuous amid shrinking of local pastures. Basilio says Tarija Glacier has halved in size since he was a boy, cutting the water supply.

“*We’ve had to reduce the herd and start trout farming instead*” says Basilio with great sadness⁴.

These are two of countless stories that tell directly of the circumstances experienced by inhabitants of the high mountains region as glaciers retreat with unrelenting atmospheric warming.

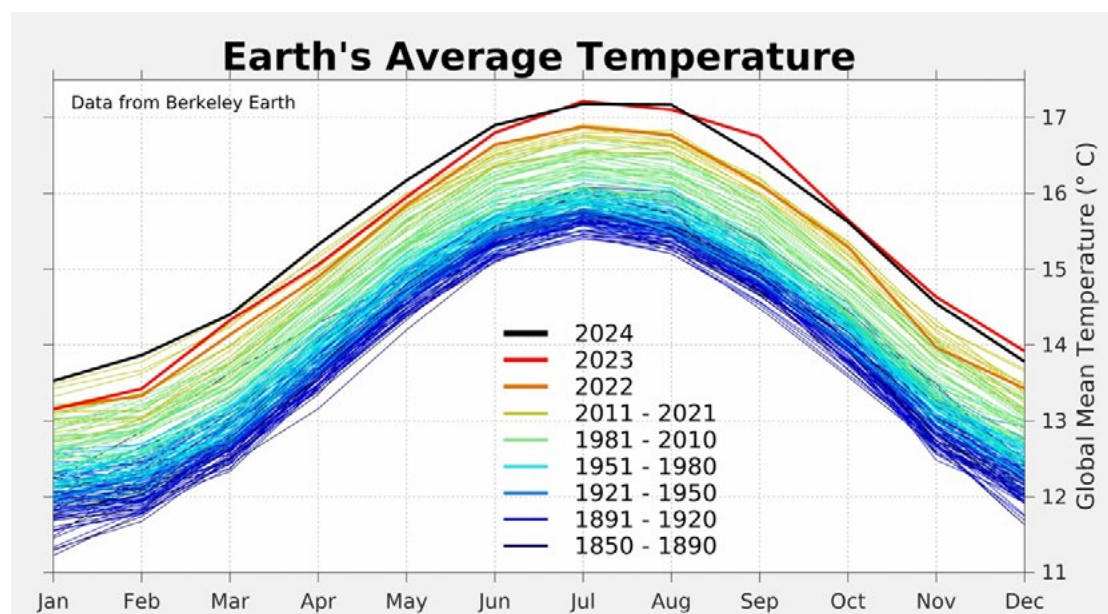


Figure 1. Average Global Surface Temperatures (Courtesy Berkeley Earth)

² The GlaMBIE Team, 2025 Community estimate of global glacier mass changes from 2000 to 2023, Nature 639, 382-388. <https://www.nature.com/articles/s41586-024-08545-z#Abs1>

³ Johan Augustin, 2021 As its glaciers melt Nepal is forced into an adaptation not of its choosing, MongaBay 27 December

⁴ Shrinking glaciers upend lives across South America 15 March 2023 UN Environment Program: Home, Story, Fresh Water.

Glacial Lake Outburst Floods (GLOFs)

An added concern in high mountain communities is the danger posed by the collapse of glacial lakes.

Along the sides or at the fronts of the glaciers, often dammed by morainic debris, lakes form and fill rapidly as the ice melts. Fed by increased volumes of meltwater, more frequent high intensity atmospheric storms and massive landslides of ice and rock, these natural and unconsolidated “dams” burst releasing immense quantities of water (termed GLOFs) that surge down the high valleys to the populated foothills. Such events can be catastrophic for people living nearby. In the Cordillera Blanca of Peru, for example, over the last 70 years several thousands of people have been killed by GLOFs.⁵ In the Gilgit-Baltistan and Khyber-Pakhtunkhwa regions there are over 3,000 ice-dammed lakes of which over 30 have been identified

as vulnerable and at risk of bursting, endangering over 7 million people.⁶

In May 2022 unusually high temperatures were experienced in the Hunza Valley of the Karakoram giving rise to the intense melting of glaciers in the region. A large lake that had formed over the previous four years at the Shisper Glacier broke its banks. The water flooded down-valley wiping out an important bridge at Hassanabad along the Karakoram Highway (Figure 2). Many buildings including homes and two power plants were damaged severely.

Such examples underscore the ever-present danger in these environments and according to recent estimates one million people live within 10km of a glacial lake and 15 million around the World are exposed to the likelihood of such outbursts.⁷



Figure 2. Section of the Karakoram Highway in Gilgit-Baltistan region, Pakistan, destroyed by the 2022 GLOF from Shisper Glacier (courtesy A Majeed/AFP)

⁵ Emmer, A. et al. 70 years of lake evolution and glacial lake outburst floods in the Cordillera Blanca (Peru) and implications for the future. *Geomorphology* 365, (2020).

⁶ Melting glaciers, growing lakes and the threat of outburst floods, UNDP CLIMATE 26 August 2022

⁷ Taylor, C., Robinson, T.R., Dunning, S. et al. Glacial lake outburst floods threaten millions globally. *Nat Commun* 14, 487 (2023). <https://doi.org/10.1038/s41467-023-36033>

Alongside enhanced glacier melting in the summer Monsoon rainfall is increasing. In 2022 and 2023 this combination arose on a monumental scale in North-western India and the Hindu Kush. Glacier melt was greater than normal, so the Indus was already flowing at a high level when it was increased by ferocious and long-lasting Monsoon storms. These tracked into the western Himalaya bringing exceptional rainfall, eight times higher than the long-term average⁸ creating favourable conditions for extensive flooding in the hilly terrains and plains of Pakistan and north-west India.

Such incidences, more likely in future years, are jeopardising the lives, property, livestock, and livelihoods of remote mountain communities.

Thawing Permafrost

Associated more readily with vast tracts of Arctic terrain, permafrost is nevertheless a distinctive feature in high mountain regions, determined by elevation, topography, aspect, snow and vegetation cover. It is ground that is frozen from at least one winter season to the next and occurs in the Himalaya at elevations above 4000-5000m. The depth of permafrost varies with mean annual surface temperatures along with these other factors, and extends to many hundreds of metres. The upper stratum, subject to seasonal freezing and thawing, defines the “active layer” which can be several metres deep. There is poor knowledge of the extent and depth of permafrost in the greater Himalaya and Hindu-Kush regions (Figure 3). Recent estimates place this at about 1Mkm² excluding Tibet⁹.

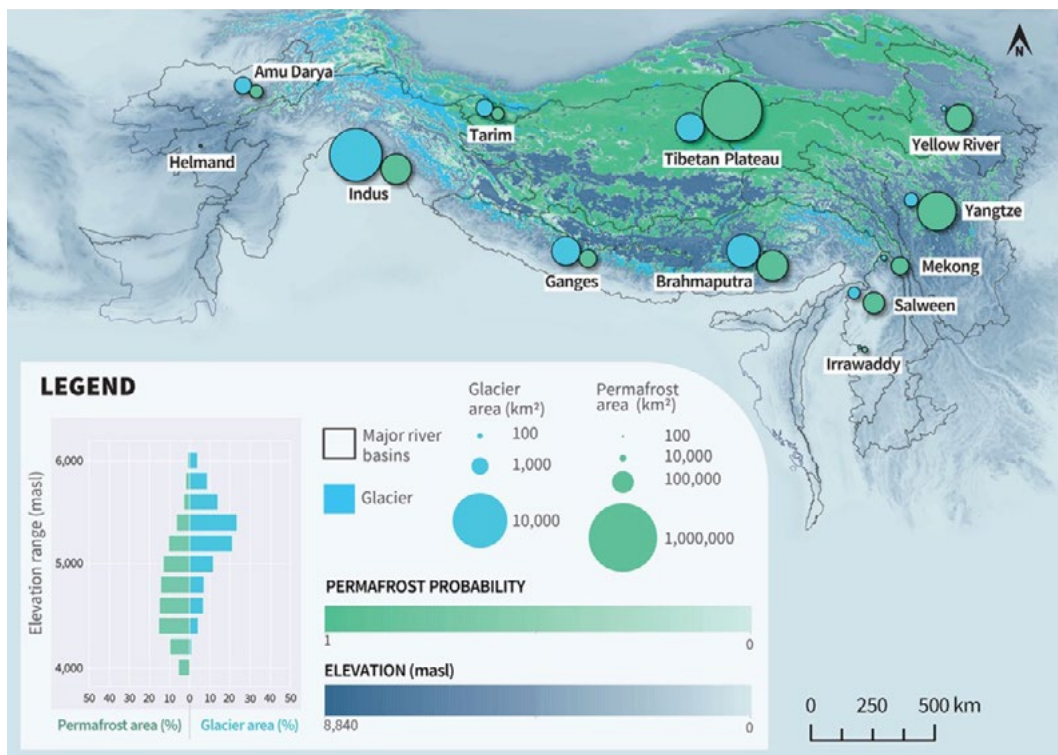


Figure 3. Permafrost (green) and glacier (blue) distribution in the Himalaya region. From Jackson et al (2023)

⁸ Anjul Prakash Kushwaha et al 2024 Land and Atmospheric Drivers of the 2023 Flood in India, Earth and Space Science (Vol.11 (10) (AGU), <https://doi.org/10.1029/2024EA003750>

⁹ Gruber et al 2017 Review article: Inferring permafrost and permafrost thaw in the mountains of the Hindu Kush Himalaya region, The Cryosphere, 11, 81–99, 2017 www.the-cryosphere.net/11/81/2017/ doi:10.5194/tc-11-81-2017

Although time-series data are limited there is clear evidence of widespread thawing. For the western Himalaya one study has suggested a reduction in permafrost cover of 8,340 km² between 2002/04 and 2018/20 and active layers have been increasing in depth with increasing temperatures.¹⁰ The consequences are varied from damage to highways and buildings to impacts on hydrological processes, biodiversity and ecosystem functioning.

Rising temperatures are also destabilising frozen mountain slopes and weakening ice-bonded sediments resulting in severe and more frequent rockfalls and ice-debris avalanches. Often these have plunged into adjacent lakes – a further cause of severe flood events – GLOFs – referred to earlier. In the Peruvian Andes at Salkantay a massive rock avalanche

(some 1-1.5 M m³) in 2020 crashed into a lake triggering a major flood to villages down valley with loss of lives¹¹. In similar fashion, in 2023 in Sikkim, a permafrost landslide triggered a GLOF that travelled 385 km along the Teesta River from India to Bangladesh. The disaster caused 55 deaths, and destroyed the Teesta III hydropower dam.¹²

Rising Sea Levels – the polar contribution

Away from mountain glaciers the large ice sheets of the sparsely populated polar regions might appear to be of lesser concern. Here, however, there is a world-wide threat, increasing year by year. In the Arctic temperatures are rising at a rate faster than the global average by a factor of three, perhaps even higher. Ice caps and the Greenland Ice Sheet are responding with

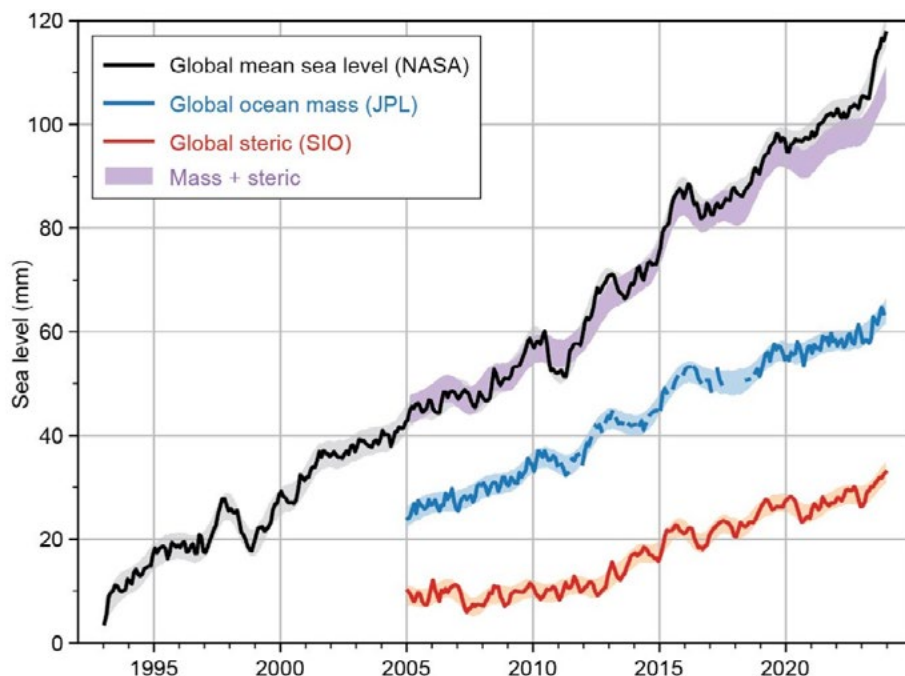


Figure 4. Rising sea levels¹⁴ The global ocean mass is a combination of all glacial melt (glaciers and polar ice sheets) plus land-based water storage. The steric component is due to thermal expansion of the oceans, principally in the upper 1000m. The average over the period since 1880 is about 21cm.

¹⁰ Jackson, M. et al. 2023 Consequences of climate change for the cryosphere in the Hindu Kush Himalaya in Water, ice, society and ecosystems in the Hindu Kush Himalaya: An outlook, ICIMOD, p17-71, <https://doi.org/10.53055/ICIMOD.1030>

¹¹ Petley, D, 2020, More information about the Salkantay landslide and mudflow AGU The landslide blog, 28 February, 2020

¹² Sattar, A et al 2025 The Sikkim flood of October 2023: drivers, causes and impacts of a multihazard cascade, Science 387 (6740) <https://doi.org/10.1126/science.ads2659>

melting, amplified on their lower surfaces and at their margins, feeding substantial quantities of fresh water into the world's oceans. Greenland is losing some 270 Gt per year, five times more ice than 20 years ago.

In Antarctica, glaciers in the Antarctic Peninsula and the ice sheet in West Antarctica are the fastest warming regions of the continent. In the second half of the 20th century temperatures rose by 3.2°C, contributing to the collapse of some of the smaller ice shelves. Overall, the continent is warming at a rate twice that of the rest of the world¹³. The ice sheet is, as a consequence, increasingly losing mass. In the period 1979-2022 the loss was 4790±987 Gt per year. West Antarctica contributed -80% and 18% was from the Antarctic Peninsula. The primary drivers of the former are the two ice streams feeding ice into the Amundsen Sea sector, Pine Island and Thwaites Glaciers.

The melting of the two great ice sheets combined (Greenland 22%, Antarctica 7%) with the contribution from mountain glaciers around the world as described earlier (~15%), account for about 45% of the increase in mean global sea level. The remainder is due to the addition from land waters and, importantly, thermal expansion of the upper level of the world's oceans (35%) (Figure 4).

Around the world vulnerable communities are living at or close to sea level whose futures are threatened by ocean flooding. These people number many hundreds of millions, are on every inhabited continent and on many hundreds of small islands scattered across all oceans. Developed nations and least developed

counties are equally exposed. By 2050 the additional rise in sea level is estimated to be 169 ±52mm.¹⁵

Newtok, a small village on the shores of the Bering Sea in Alaska, is home to a Yu'pik community living off a mix of sealing, fishing and State handouts. Change came in the early noughties – a combination of the rapid reduction in sea ice and rising sea levels. The winter sea ice is now forming much later in the year, allowing early season storms to wreak havoc on the boulder-strewn coastal plain eating back the coastline that is also sinking due to thawing permafrost. This situation has been exacerbated by the inexorable upswing in flooding as sea level keeps rising. Much of the settlement became uninhabitable, and a proportion of the villagers moved to Mertarvik to higher ground on nearby Nelson Island. The remains of old houses, stores and outbuildings, the modest infrastructure of a Yu'pik community, are fast disappearing into the sea as waves and spring tides have relentlessly and deeply eroded the shoreline.¹⁶

Small, low-lying island nations have been some of the first to be compromised by rising seas. Whilst their populations are typically tiny, their circumstances are totemic. The Maldives, the Marshall Islands, Tokelau and Tuvalu, and Kiribati possess few areas which are not submerged by storm surges. In 2000, 80% of the Maldives was determined to be lying below one metre above sea level. Already some islands are becoming increasingly inhospitable, and projections are that 77% of the archipelago will be lost to sea level rise by the end of the Century¹⁸.

¹³ Casado, M et al. 2023 The quandary of detecting the signature of climate change in Antarctica. *Nature Climate Change* 13, 1082-1088

¹⁴ Blunden, J and Boyer, T (Eds) 2024 State of the Climate in 2023, *Bulletin Amer. Meteor. Soc.*, 105(8), Si-S484 <https://doi.org/10.1175/2024BAMSStateoftheClimate.1>.

¹⁵ Hamlington, B D et al 2024 The rate of global sea level rise doubled during the past three decades, *Communications earth & environment*. <https://doi.org/10.1038/s43247-024-01761-5>

¹⁶ Craig Welch, 2019 "Climate change has finally caught up to this Alaska village" *National Geographic*, 25 October 2019

¹⁷ Drewry, D J 2022 A World beyond two degrees Celsius, The Oracle Partnership

¹⁸ The World Bank (<https://web.archive.org/web/20160609020349/http://go.worldbank.org/M3XBP80UGO>)

Elsewhere in the Indian Ocean, problems of comparable nature are being experienced at an entirely different scale, in the delta regions of the rivers Ganges, Brahmaputra, Irrawaddy (Ayeyarwady) and further east, the Mekong. These already low-lying and swampy tracts, supporting several hundreds of millions of people, have experienced widespread flood events from rising sea levels. The seaward girdle of mangrove, such as in the Sundarbans of the Ganges, is being stubbornly attacked by storms and high tides. Villages, towns and cities are being compromised and the agricultural base of these densely populated communities threatened. The extensive intrusion of saltwater has compounded the difficulties, rendering affected land useless for crops and contaminating drinking water supplies. That their misfortune relates directly to the progressive destruction of vast tracts of ice at the distant ends of the Earth seems implausible were it not clearly scientifically demonstrable.

A future of uncertainty

The retreat of mountain glaciers driven by unremitting climate warming and the melting of the marginal zones of ice caps and ice sheets are unlikely to lessen over the course of this century. Only a reduction in global temperatures will slow their retreat and loss of mass, the prospect of which will depend on the foresight and determination of today's policymakers.

The IYGP has been focused on bringing these circumstances to a wide audience and to influence decision making. Unless these issues confronting the international community are recognised, and action taken, Oceans will continue to rise and much of the ice in mountainous regions will disappear. For populations faced with the consequences of these dire circumstances the only pathway is a process first of adaptation and possibly later managed retreat (i.e. migration). Time is not on their side; their courage and fortitude undeniable but their resilience is limited.

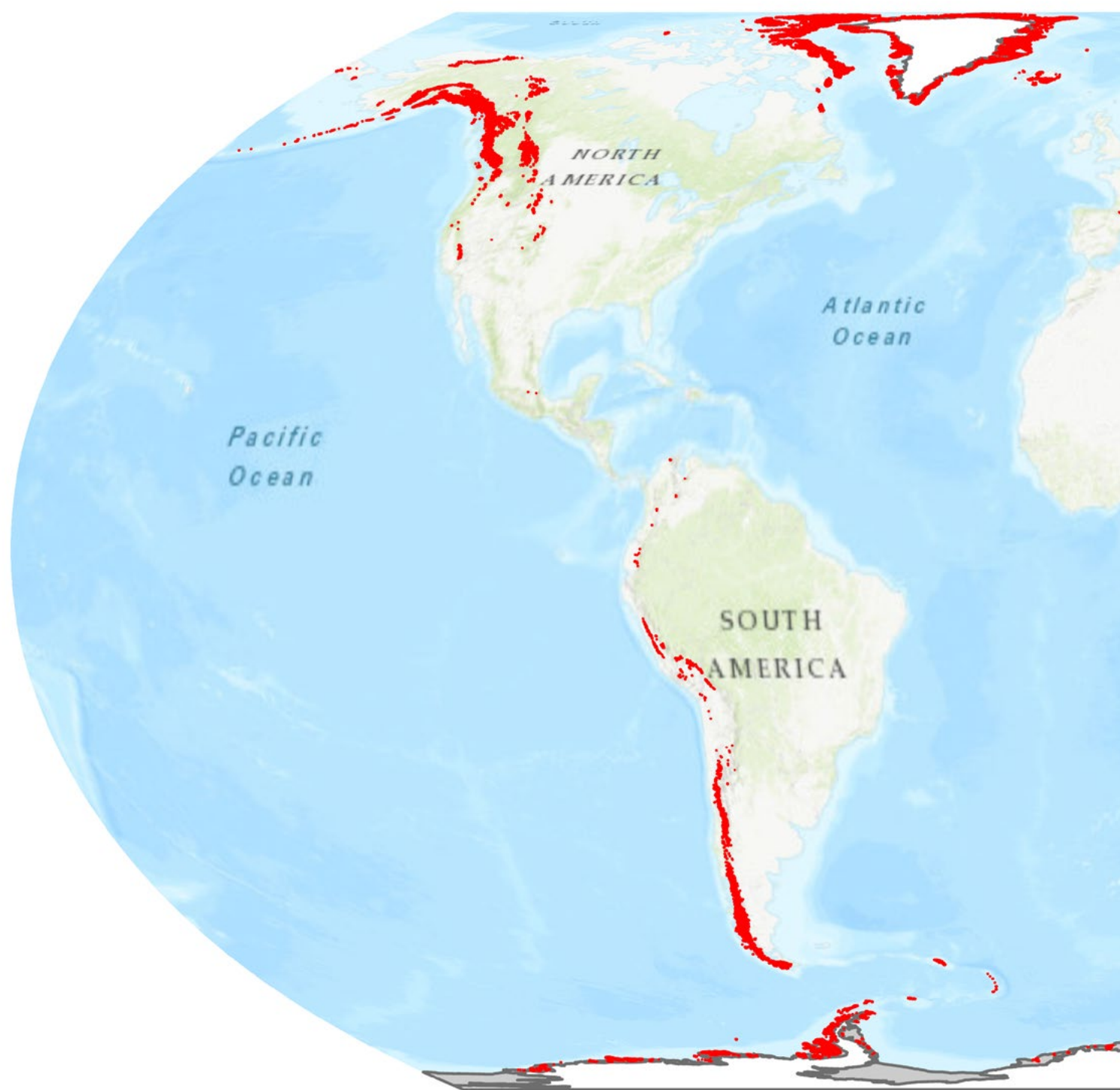


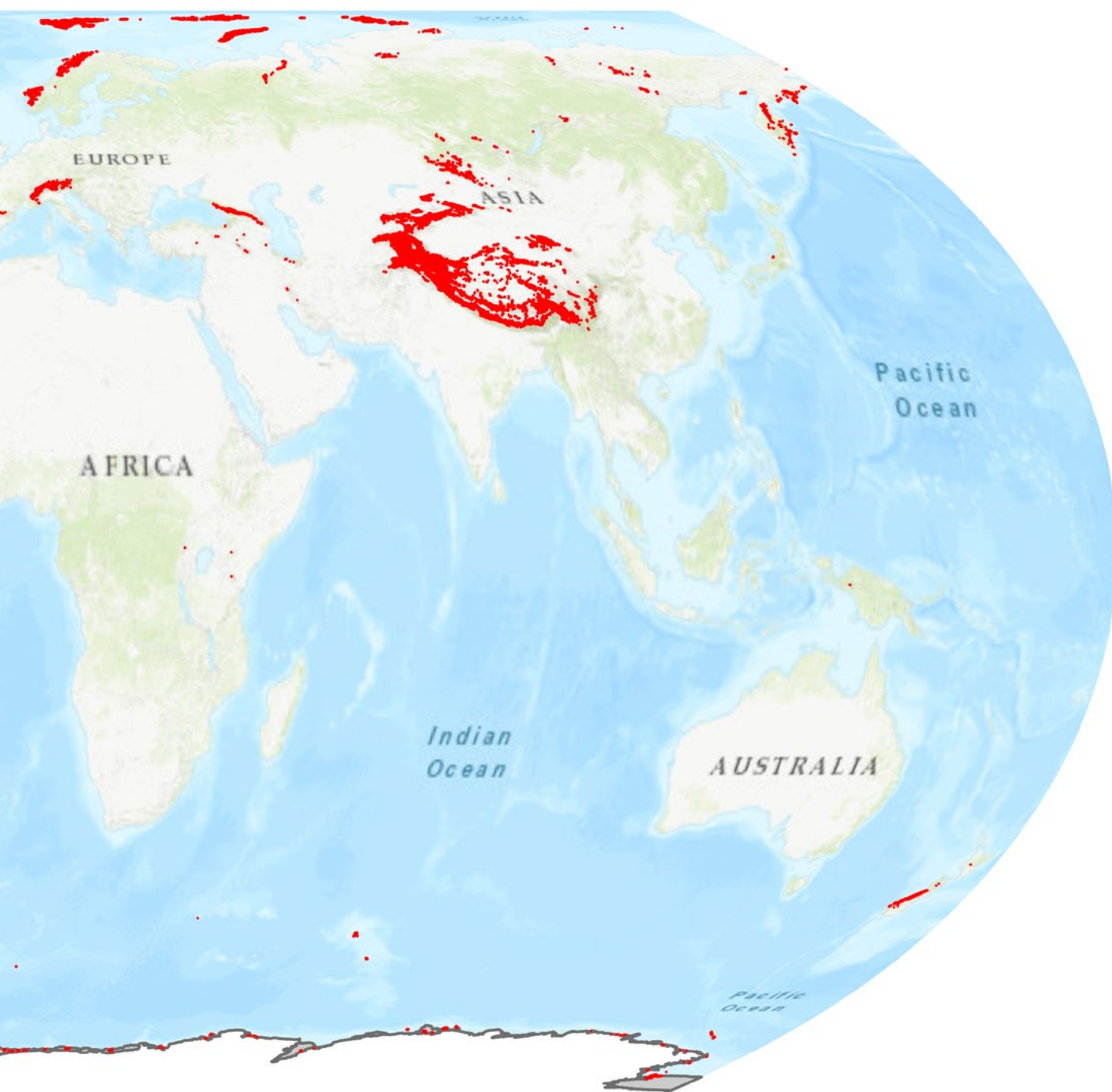
Figure 5. Collapsing buildings as coastal permafrost is thawed and wave action increases, Alaska¹⁷.



Part of the front of Bråselbreen,
Nordaustlandet, Svalbard. ©David Drewry

Glaciers and Ice Sheets in a Warming World: Impacts and Outcomes





Global Distribution of Glaciers, Ice Caps and Ice Sheets.

This map has been produced, with grateful thanks, by Professor Bethan Davies.

Note coverage of the Antarctic Ice Sheets is not depicted fully.

Info: Global equal area projection RGI v7.0 glacier outlines (infilled with red, with red outline).

Mosaic of Antarctica coastline and grounding line PROMICE 2022 ice mask for Greenland.

<https://dataverse.geus.dk/dataset.xhtml?persistentId=doi:10.22008/FK2/O8CLRE>



UK Research Programmes

1

Deplete and Retreat: The Future of
Andean Water Towers

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Will our mountains lose their snow and ice?
And does it matter if they do?

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Jeremy Ely is a Senior Lecturer in physical geography at the University of Sheffield. Born in the flatlands of Lincolnshire, he became fascinated by the dramatic topography of ice sheets and glaciers during his PhD. His research focusses on combining the numerical models used to simulate future ice change, with data on glacier/ice sheet behaviour. He has won prizes for his research from the British Society for Geomorphology and the Quaternary Research Association. He leads the Deplete and Retreat, Natural Environment Research Council (NERC) Highlight topic, the aim of which is to better constrain water resource change across the Andes.

Mountains as water towers

Mountains are sensitive to climate change, and simultaneously, play a vital role in the water cycle: in our warming world, this combination threatens the water security of approximately 1.9 billion people (Immerzeel et al., 2020). The protrusion of mountains into the atmosphere enables them to capture water, as they disrupt the movement of air and enhance precipitation. Once this precipitation falls upon the surface of the mountain, it is stored within glaciers, snow packs, lakes and wetlands. This storage delays the release of water for later use downstream, often providing vital water resources for the surrounding lowlands during otherwise water scarce dry seasons. The ability of mountains to capture, store and regulate the release of water means that they are often been referred to in the scientific literature as natures “water towers” (Viviroli et al., 2007).

Increasing water consumption and human-induced climate change have affected the efficacy of the world’s water towers to provide water to surrounding populations. Projections show a combination of both increasing reliance of populations on mountain resources, and a diminishing capability for mountains to provide water (Viviroli et al., 2020). Mountain environments are changing. These water towers exhibit shrinking glaciers, are impacted by increased extreme weather events, and warmer temperatures are leading to a shift from snowfall to rainfall. These symptoms negatively impact the ability of water towers to supply freshwater.

The glaciers of the Andes, as sensitive barometers of climate change, have responded by shrinking (Dussaillant et al., 2019). However, the latitudinal span of the Andes produces a diverse range of climates, which in turn creates a wide array of mountain environments. Different parts of the Andes also experience influences from differing modes of climate variability, namely the El Niño–Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) (Figure 1), both of which are projected to change due to anthropogenic warming. This complexity means that the glaciers of the Andes vary in their size and type, as well as the processes that govern their response;

thus making projections at a pan-Andean scale challenging. Furthermore, the dependence of different river catchments upon glacier resources varies. Some regions are heavily reliant upon glacier meltwater, whilst others are more susceptible to changes in snowfall magnitude and the timing of snowmelt.

“Deplete and Retreat: The Future of Andean Water Towers” is a four-year Natural Environment Research Council funded highlight topic (~£2.5 million) led by

the University of Sheffield and involving researchers from across the UK and South America. The aim of Deplete and Retreat is to upskill our ability to project water resource changes across the Andes, given the depleting stores of snow and the retreat of glaciers. The project focusses upon 10 river catchments, situated in Peru, Bolivia, Chile and Argentina (Figure 1).

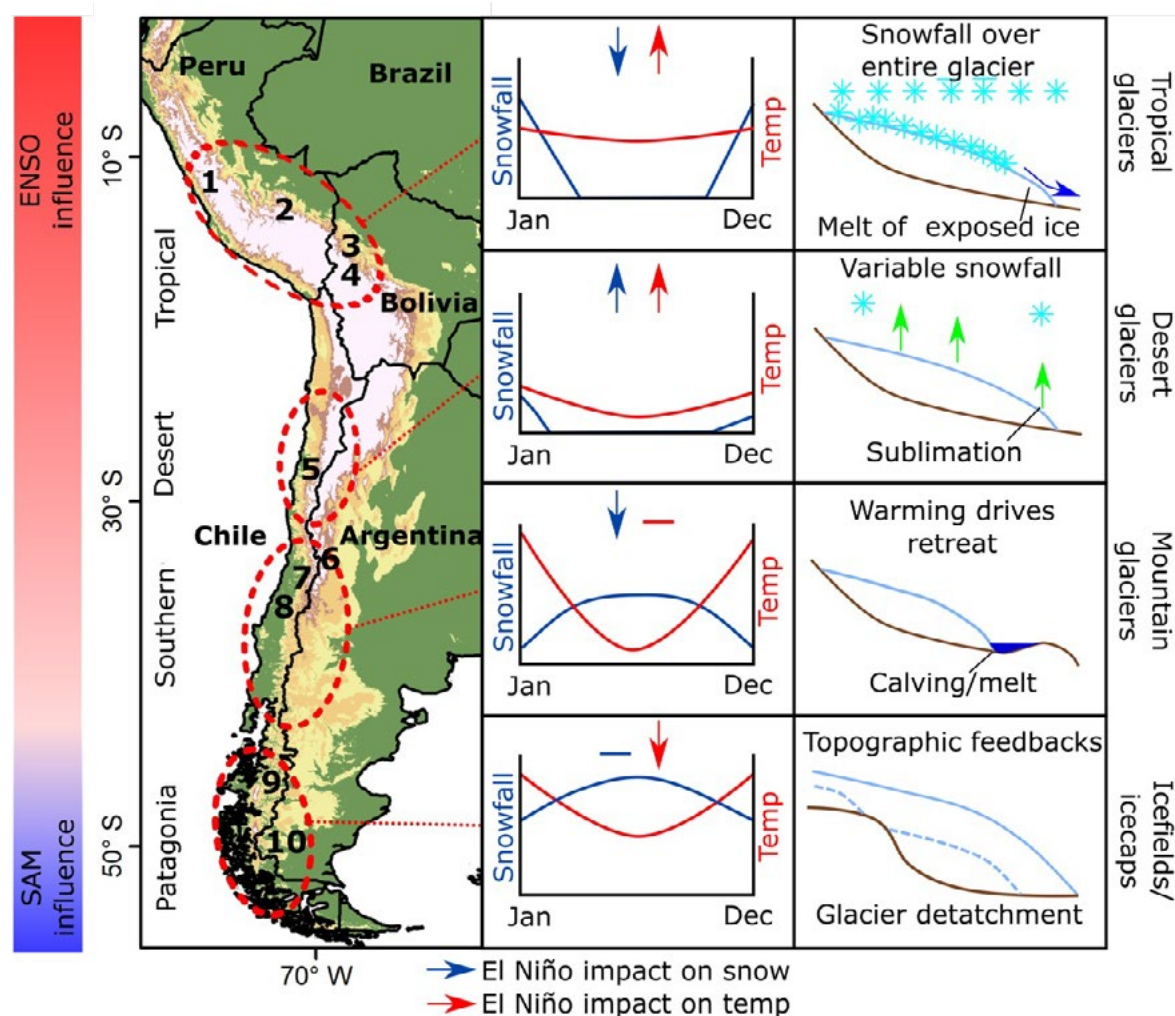


Figure 1. Location of the 10 study sites in Deplete and Retreat. Note the varying climate conditions and glacier processes that occur across the Andes. This includes sublimation (the transition from snow and ice into a gas) and calving (icebergs breaking off into lakes). ENSO – El Niño–Southern Oscillation; SAM – Southern Annular Mode.

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The glaciers in the Tropical Andes of Peru and Bolivia have been the most affected, losing 56% of their area since the end of the Little Ice Age and the subsequent accelerated emission of fossil fuels.

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Monitoring snow and ice change

Mountains represent a climate observation blind spot, due to a lack of weather stations at high altitudes. This limits our understanding of mountain climates, our ability to test models of climate change in these regions, and in turn hampers attempts to project snow and glacier change. In the Deplete and Retreat project, we have installed four new weather stations in Peru, Bolivia and Chile. The weather stations are located at the altitude at which precipitation seasonally changes between snow and ice. The highest, in Bolivia, is located close to the snout of Laguna Glacier at 5350m altitude (Figure 2). Logistically, such stations are difficult to install and maintain. Yet, further installations are necessary to gain a better understanding of the conditions at or near glaciers.

An alternative means of observing mountain change is by interrogating the untapped archive that has

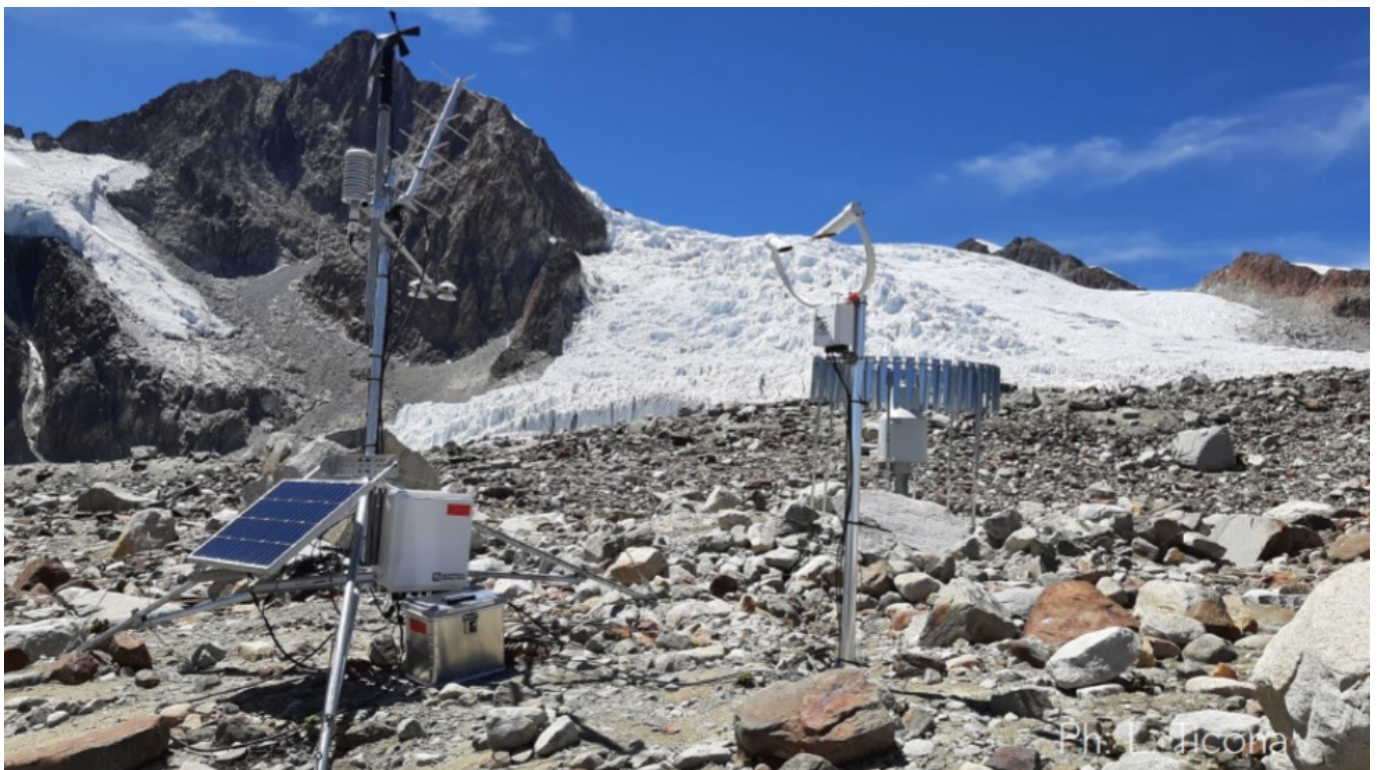


Figure 2. The Deplete and Retreat weather station at Laguna Glacier, Bolivia. Situated at 5365 m, the instruments record temperature, wind speed, radiation, humidity, precipitation amount and current conditions. Photo by Laura Ticona.

been obtained from above using declassified imagery from early satellites and aerial photography. This allows us to document variations in glacier change back to the 1960's. Such images show that glacier area has dramatically reduced in some regions (e.g. Figure 3). Beyond this two-dimensional view, we can also use these images to observe changes in three-dimensions. The height of glaciers can be measured through stereophotogrammetry, whereby the offset of two images of the same place allows the derivation of elevation data – a similar principle is used in 3D cinema. Using this approach, it is possible to measure both the area and volume change of glaciers across the Andes.

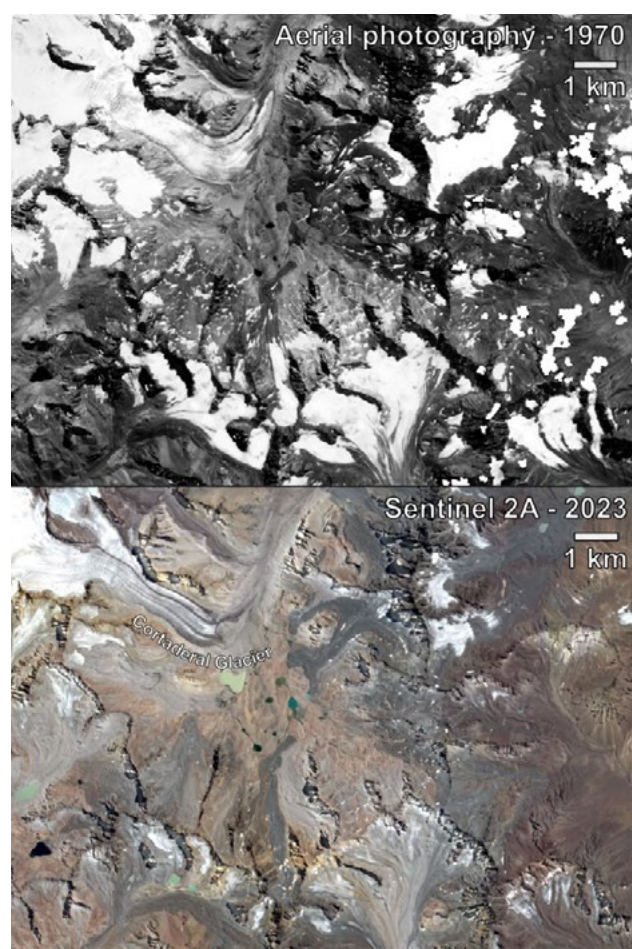


Figure 3. Birds-eye view of change over the Cortaderal Glacier region, Chile. Aerial photography from the 1970s (A) shows the greater extent of ice than recent satellite imagery (B).

Observations from satellite and aerial imagery allow us to obtain data on glacier change from the 1960's. To go back further, it is possible to use features in the landscape that record the previous extent of glaciers. During the Little Ice Age (approximately 1650-1850 CE in the Andes), glaciers were more extensive. Moraines, accumulations of sediment formed at the margins of glaciers, record the position of glacier termini during this phase. Mapping these moraines at more than 5,500 glaciers across the Andes, and comparison with directly observed ice extent, has shown that glacier area loss has accelerated (Carravick et al. 2024). The glaciers in the Tropical Andes of Peru and Bolivia have been the most affected, losing 56% of their area since the end of the Little Ice Age and the subsequent accelerated emission of fossil fuels.

Resolving the challenge of predicting of glacier and meltwater change

Without a time machine, we cannot observe the future. Thus, to project future change, scientists use models – representations of a physical system that capture aspects of their behaviour. Projections of future climate are based upon global-scale physics-based computer models. Due to this spatial scale, a typical grid-box used in a global climate model is around 100 km length and width. Whilst adequate for predicting the global trend and pattern of change, these global models lack the resolution required to capture the complex climatology of mountains required for quantifying water resource and glacier change. On Deplete and Retreat, we are using a regional climate model that refines global predictions to a scale of 4 km over the Andes. Such high-resolution simulations, though targeted to a specific region, are still computationally expensive to run. However, resolving the details of mountains topography is important for capturing the climatic change affecting glaciers and other stores of water in the Andean water towers.

The regional climate simulations produced by Deplete and Retreat inform us of the amount and type of precipitation falling over the Andes, as well as

temperature change. Although for a climate model these simulations are high-resolution, glacier models require yet finer resolutions (~100 m). This means that to isolate the changes to snow and ice, further models are required. A second step in our investigation of water resource change is to use two additional models. The first computes the accumulation and melt of snow and ice on the glacier surface, known as the glacier mass balance. Essentially, this model takes inputs of precipitation, temperature and radiation from our climate modelling, and computes the amount of energy within the upper layers of the glacier that results in glacier melt. The results from these calculations are input into a second glacier model. This simulates glacier flow – an important transportation process which compensates for the excess of mass that accumulates in the colder upper reaches of glaciers, and the loss of mass in the warmer lower portion of glaciers. These simulations will reveal the ongoing retreat of glaciers and potentially project their disappearance.

The final step in projecting water change is to simulate the streams, lakes and rivers resulting from glacier melt. This requires input from the previous three models – climate, snow and glacier models. From these, we can track where water from glaciers reaches within a river catchment. This will enable us to determine the areas most reliant upon glacier water, compared with, for instance, water sourced from rainfall and lakes. Though our projections resolve the different sources of water supply, it is also important to consider demand. In many South American cities downstream of glaciers, supply and demand are already near parity. The retreat of glaciers is meaning less water storage in the Andean water towers, and therefore lower supplies of glacier melt.

Quantifying the damage greenhouse gas emissions continue to inflict upon our water towers is of upmost importance. Planning for these changes, which are ongoing rather than a future possibility, requires regionally specific projections, which we aim to provide on Deplete and Retreat. As glaciers throughout the Andes retreat, the most effective way to preserve them and their role in regulating water release downstream is to reduce carbon emissions.

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Right: Wetlands and alpacas in front of the Quelccaya ice cap, Cordillera Vilcanota, Peru. ©Rike Becker



Will our mountains lose their snow and ice? And does it matter if they do?

Hamish Pritchard

British Antarctic Survey

Hamish Pritchard is a glaciologist at the British Antarctic Survey specialising in mapping, monitoring and understanding the cryosphere through remote sensing, field surveys and instrumentation. His research targets the two outstanding icy issues facing the world as the climate changes: sea level rise, and the fate of mountain water resources. He was a lead author on the IPCC Special Report on Oceans and Cryosphere and leads Bedmap3, re-mapping the hidden bed of the Antarctic ice sheets, and the Natural Environment Research Council project 'The Big Thaw', filling gaps in our knowledge of mountain snow and ice.

What have glaciers ever done for us?

Mountain ranges covering a third of the world's land are vital regional sources of fresh water. This is in part because mountains make their own wet weather by pushing humid winds to higher, colder altitudes, where clouds condense and rain down onto the slopes below. But mountains become particularly important where they are cold enough for snow to gather. Mountain snowpacks are natural reservoirs within the water cycle, storing the winter's precipitation and releasing meltwater through summer. This service is particularly valuable for those living downstream because it boosts water supply just as demand – and often water stress – is at its highest: through the summer crop-growing season. Complex and intensive farming regimes have developed over centuries to take advantage of this water supply such that today, it is an extraordinary generator of wealth and wellbeing in rich and poor countries. A third of the world's irrigated lowlands depend heavily on mountain runoff, which helps sustain a sixth of the global population and a quarter of global GDP (Barnett, Adam et al. 2005).

While a seasonal mountain snowpack shifts a winter's precipitation to the following summer, glaciers go further by smoothing out fluctuations between wet and dry years. Where snow falls on the coldest mountain slopes and survives the summer warmth, glaciers form. New snow compacts into glacier ice and joins the slow glacial flow downhill, replacing ice accumulated years ago that finally reaches the glacier snout and melts off. When a drought strikes, with little snow or rain for several seasons, this persistent glacier meltwater can keep rivers flowing throughout the period of regional water stress, when the risk of social instability, sudden population migration and even conflict surge (Pritchard, 2019).

The value of this drought-buffering service is particularly significant for about 800 million people living downstream of High Mountain Asia, with the world's greatest mountain ranges and 95,000 glaciers (Figure 1). Here, the annual glacier meltwater flux is sufficient for the basic needs of 221 ± 59 million people, or most of the annual municipal and industrial requirements of Pakistan, Afghanistan,

Tajikistan, Turkmenistan, Uzbekistan and the Kyrgyz Republic. And when the summer monsoons fail, glacier meltwater becomes the dominant water input to the upper Indus, Aral and Chu/Issyk-Kul river basins. Competition for these shared water resources is intense, though: Afghanistan, India, Pakistan, Turkmenistan and Uzbekistan rely on cross-border river flows for 29–97% of their water. Furthermore, Pakistan, Afghanistan, the Kyrgyz Republic and Nepal are classed as ‘ethnically fractionalised’, putting them at particularly high risk of conflict when resources are scarce (Pritchard, 2019). Asia’s glaciers, therefore, play a key role in protecting this region from the worst effects of water stress.

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The region is water-stressed. Water may be emerging as a weapon of war.

Arif Rafiq, Middle East Institute, 2019.

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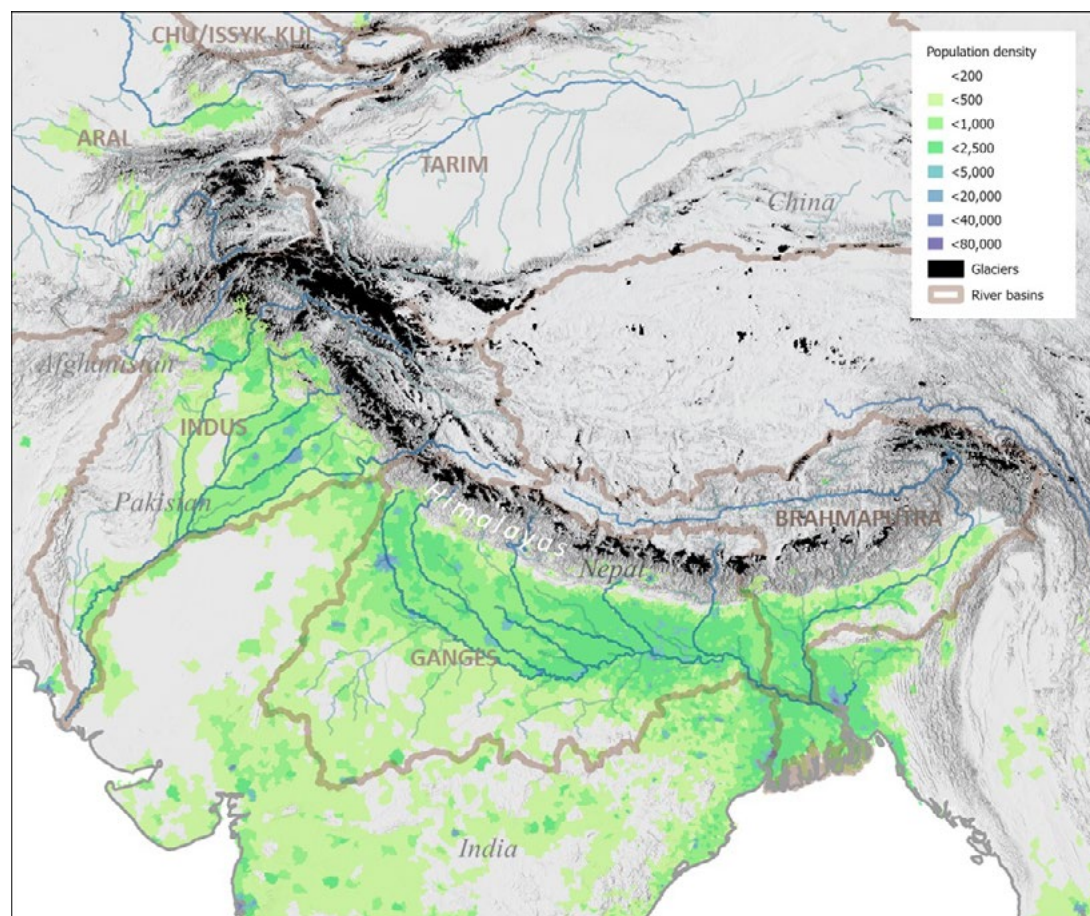


Figure 1. Population density (people per km²) distributed around High Mountain Asia, highlighting the strong connection between mountains, glaciers, the river network and people in some of the world’s most heavily populated river basins. (Map: Pritchard)

But the value of Asia's mountain water resources is not restricted to those living downstream. Through international food exports, much of the rest of the world indirectly consumes Himalayan snow. In this way, Pakistan is the largest snowmelt exporter (26% of global export), with China (14%) and India (10%) also major exporters, largely through rice and wheat sold to the USA, China, Germany, the UK and Japan (Qin, Hong et al. 2022).

The Big Thaw

As well as being valuable, mountain water resources are among the most sensitive of all major ecosystem-services to climate change. Warming has already skewed the balance between new snow falling annually onto Asia's glaciers and the meltwater flux from their snouts, now at 1.6 times the sustainable rate (Pritchard 2019). Glacier retreat has been accelerating since at least the 1960s and Asia is living through a glut of meltwater that cannot last. Over the next 30 years, the European Alps, Western North America, the Himalayas, and Andes will lose 10–40% of their snow, hundreds of cubic kilometres of summer water supply. In one lifespan mountain glaciers will lose 20–60% of their ice (IPCC 2019).

The coming decline in the mountain cryosphere threatens increasing water stress and increasing volatility in supply, with the potential for extreme and destabilising water shocks. This implies a decline in security of water, food, energy, and livelihood for hundreds of millions of people in Asia and beyond. We need to start adapting to the shifting seasonality and reliability of the mountain water supply, but how much water the mountain cryosphere provides, and how its role will change, remain remarkably uncertain. This matters because the potential replacement costs to society for lost meltwater (with dams, for example) are so large. Just the uncertainty itself, in the expected rate and scale of the loss, imposes additional financing costs for water replacement schemes on the order of trillions of dollars per mountain region (Sturm,

Goldstein et al. 2017). Good measurements are critical for predicting the future of mountain water resources; at present these are lacking. The mountain cryosphere is so large, varied, inhospitable and changeable that we must rely on models of snowfall, the seasonal snowpack, glacier mass balance and runoff to map and manage these water resources. Models, built upon the physics of real-world processes, of complex cause and effect, are vital in predicting how they will evolve. But our understanding of these processes is limited by the scarcity and low quality of key mountain observations required for testing and developing the models: they are simply too sparse, small-scale, poorly distributed, inaccurate, infrequent, or short-lived to constrain the models adequately.

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Most precipitation measurements, for example, come from a global array of long-running weather stations, well designed to measure rain but suffering snow ‘undercatch’ biases due to turbulence around the rain gauge. Spatial sampling is also biased: each gauge is as small as a dinner plate, far smaller than the kilometre scale of model grid cells. Furthermore, of the global rain gauge array, 26% lie in the cryosphere but only 6% in the mountain cryosphere, and mostly in valley settlements (Pritchard 2021). Strikingly, the 566,000 km² combined Himalayan headwaters of the major river basins Brahmaputra, Indus, and Ganges host only one such long-term rain gauge (Menne, Durre et al. 2012). Similarly, these three basins hold 41,000 glaciers but only six have ice thickness surveys, totalling only 10 km in length, so the size of the regional ice reserve is not known. Modelled global estimates of ice distribution conventionally use inverse methods constrained by observed velocities but this involves largely unknown model parameters, and recent measurements in

Nepal revealed model biases of -77% to +31%. These and similar global data gaps and biases imply that sophisticated weather and water models fly almost blind in the mountain cryosphere. Indeed, studies show that mountain water resources are systematically underestimated by 50-100% in all the world’s major mountain ranges (Figure 2) (Pritchard 2021).

Several UK research initiatives now seek to address this challenge. The Big Thaw project funded by UK Research and Innovation, for example, is working to fill four of the key observation gaps in i) Snowfall, ii) Glacier Thickness, iii) Runoff, and iv) Extreme Weather, using carefully targeted field campaigns designed and scaled not to provide blanket coverage of the mountain cryosphere but to test and improve model skill. Importantly, through accurate calibration and refinement of relevant model processes at these target sites, it aims to eliminate gross biases in model outputs, that can then apply across all model scales, past, present, and future.

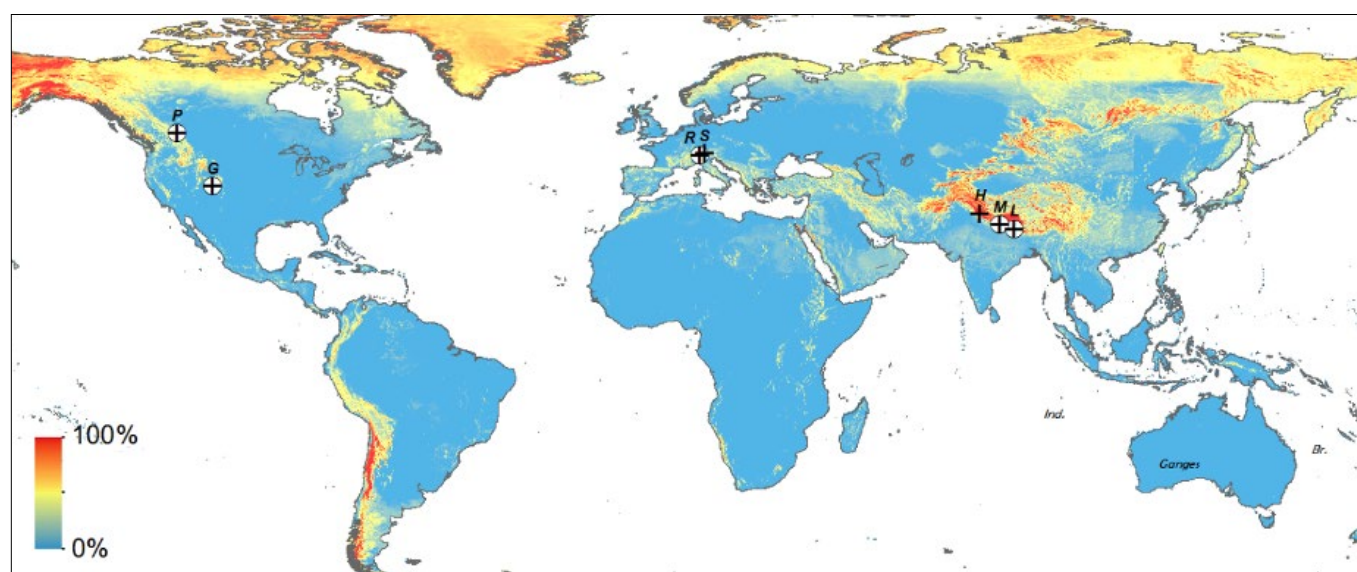


Figure 2. The disagreement between estimated annual precipitation (WorldClim v2) and annual river runoff (red to blue scale). Blue shows a good agreement (no bias) and red shows a precipitation estimate of as little as half of that needed to explain the river runoff (i.e., a 100% low bias, after Beck et al., 2020). Mountain ranges have a near-universal low bias in estimated precipitation. The Big Thaw snowfall measurement sites (P,G,R,S,L,H,M) are shown in the Rockies, Alps, and Himalayas. (Map: Pritchard)

i) Snowfall. To measure this parameter, The Big Thaw employs a new advance in snowfall sensing (Pritchard, Farinotti et al. 2021) to make unbiased, autonomous, and uniquely large-area observations at targeted sites in the Alps, Himalayas, and Rockies (Figures 2 & 3). Following from Archimedes, these use time series of water pressure in lakes through the winter to directly measure the mass (i.e., water content) of snow falling on the lake. This approach suffers no turbulence around the sensor and inherently senses the whole lake surface, an area of thousands to billions of square metres. So, for the first time this method can eliminate the two main sources of snowfall measurement bias, from ‘undercatch’ and from scaling up to the size of model grid cells. Indeed, each of the 14 mountain lakes The Big Thaw is monitoring has an area larger than that of all the world’s existing rain gauges combined, which would cover about half of a football pitch. These new measurements are being used to precipitation-optimize the UK Met Office Unified Model (MetUM) by varying the modelled processes of cloud microphysics, and the newly optimised model will then project mountain precipitation for the 21st century.

ii) Ice Thickness. Using a purpose-built, new low-frequency helicopter-mounted radar, glacier thickness profiles covering 200 km of Himalayan glaciers in the Solu Khumbu basin around Everest, have been recently surveyed (Figure 3b). This radar was adapted for high mountain airborne use from the British Antarctic Survey’s ice-sheet system. The data have provided the first opportunity, through the Big Thaw, to calibrate Himalayan glacier thickness models systematically for optimal dynamic parameters. Following calibration with these much more extensive new survey measurements, the model is being employed to estimate glacier thicknesses throughout the Himalayas to reveal the size of the region’s remaining ice reserve, which is key to predicting how long this resource will last.

iii) Runoff. With improved weather and glacier models, this project will forecast daily snow and ice meltwater contributions to river runoff at the study sites over the coming century, further tested against new and improved measurements of runoff: lidar is being used to monitor river levels, cameras are tracking river flow, and isotope analysis is revealing how much of this flow came from snow



Figure 3. A novel, ‘Big Thaw’ lake sensor set up to monitor snowfall in the Alps. b) The new helicopter radar system surveying glacier ice thickness over the Khumbu Ice Fall in the Western Cwm of Everest, Nepal. (Photos: Pritchard).

and ice. These measures assist in overcoming biases in conventional river gauges based on simple stage-discharge relationships that are often poorly calibrated in energetic mountain rivers with changeable channel morphometry, and know nothing of the water's recent history.

iv) Extreme Weather. Finally, to study how frequently extreme wet and dry years strike the central Himalayas, The Big Thaw is collecting new sediment cores from remote mountain lakes, undisturbed by centuries of land-use change downstream. The team is using a range of state-of-the-art analytical sedimentology techniques to reconstruct precipitation extremes and extend South Asia's ~100-year historical instrumental record by centuries. This is valuable because extreme weather events are rare and so their frequency and underlying climatic drivers are poorly known, and their future remains even more uncertain. By relating this new record of extreme events to the frequency of extremes from several state-of-the-art coupled atmosphere-ocean climate model simulations, The Big Thaw will examine what climate factors cause such extreme events and, by projecting these drivers over the 21st century, will show how extreme events are likely to evolve.

With more and better measurements such as those described here, we are starting to understand and to make predictable the future of the mountain cryosphere and its vital water supply, helping policymakers, investors and downstream communities to make well-informed decisions for a sustainable water future.

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Surveillance Techniques

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Tracking the Decline of Glaciers from Space

Noel Gourmelen and Livia Jakob

University of Edinburgh and Earthwave Ltd

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Monitoring ice loss from the planet's mountain glaciers over the last six decades

Owen King

Newcastle University

Tracking the Decline of Glaciers from Space

Noel Gourmelen and Livia Jakob

University of Edinburgh
and Earthwave Ltd

Noel Gourmelen is Professor in Earth Observation at the University of Edinburgh, UK, specializing in remote sensing and cryosphere studies. His research focuses on using satellite observations to understand glacier dynamics and ice sheet changes. With a keen interest in radar altimetry, he has contributed significantly to innovation and applications based on CryoSat-2, and to the development of the upcoming CRISTAL mission. His work plays a crucial role in assessing global sea level rise. An advocate for collaborative science, he actively participates in international initiatives like GlambIE to advance the accuracy of glacier monitoring techniques.

Livia Jakob is Chief Science Officer and Co-Founder of Earthwave, a satellite data science company based in Edinburgh, UK, facilitating cutting-edge research on climate change and its effects on our planet. Growing up in Switzerland and spending time in the mountains, she witnessed glacier loss firsthand, an experience that sparked her interest in understanding changes in the Cryosphere. She now focuses mainly on researching and monitoring glaciers, ice shelves and ice sheets with satellite technology – radar altimetry in particular.

Introduction

Glaciers are icons of climate change; their melting highlights the ongoing atmospheric and oceanic warming, and impacts global sea level and water resources. Understanding how much ice is stored in glaciers worldwide, and at what pace it is being lost with rising temperatures, are two fundamental questions. Yet these are very difficult questions to answer. There are over 270,000 glaciers distributed across the globe, from the poles to the tropics. They are often located in remote areas with harsh conditions, making field measurements extremely difficult and time-consuming, resulting in only a few hundred glaciers being routinely monitored in-situ. Glacier mass change remains one of the least constrained components of the global water cycle and was identified as a critical research gap in the 2019 Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC, 2019).

Observation from space is the only viable option for mapping glaciers at the global scale, but this remains a complex and challenging task (Berthier et al., 2023). The last two decades have seen several innovations in our ability to map changes in the volume and mass of glaciers from space. These rely on Digital Elevation Models (DEMs) from stereo-photogrammetry or radar interferometry, elevation point clouds from radar and laser altimetry, or on tracking changes in the Earth's gravity field (Figure 1). The fifth IPCC assessment (AR5) in 2014 was the first to base its estimate of glaciers' mass loss and sea level contribution on satellite measurements. By the time of the last IPCC report, AR6 in 2021, the number of global studies had increased from one to three with significant differences between them. Ahead of the next IPCC report, a number of initiatives are taking shape. These will increase the number of independent estimates significantly, thus improving the next assessment of glaciers' contribution to sea level rise and river run-off.

Global glacier monitoring from CryoSat-2 radar altimetry

a. Background

Radar altimetry is a spaceborne technique for measuring surface topography of planets by sending microwave pulses and capturing their echoes. Its advantages include high spatial and temporal resolution, and the ability to measure in all weather. It has been used onboard the Pioneer spacecraft in the late 1970s to derive the surface topography of Venus, and has been a staple in Earth observation since the 1990s, tracking the elevation of the Earth's oceans and the Greenland and Antarctic ice sheets. However, the large ground footprint of radar altimeters – several kilometers – poses challenges in areas with complex topography, like glaciers. This changed with the 2010 launch of the CryoSat-2 radar altimeter by the European Space Agency (Wingham et al., 2006), which, with innovative techniques, started monitoring glaciers beyond the two ice sheets. CryoSat-2 improved upon previous altimetry missions by attaining greater spatial resolution, nearly complete polar coverage, greater accuracy in locating measurements in space, and increased measurement density. The success of CryoSat-2 has inspired the CRISTAL mission under the Copernicus Space Programme, set to be a flagship mission in glacier monitoring in the decades to come.

b. Summary of findings and remaining challenges

A recent study by Jakob and Gourmelen (2023), capitalising on the strength of CryoSat-2 and previous demonstrations of the capabilities over selected study sites, applied CryoSat-2 for the first time at a global scale to measure glacier changes and their respective contribution to sea level rise. They found that glaciers have lost a combined 2,720 Gigatonnes of ice between 2010 and 2020 – equivalent to an ice cube that would surpass the height of the world's tallest mountain peaks (Figure 2). This means that ice being lost from glaciers is contributing nearly one third of global sea level rise, exceeding the contribution of either the Greenland or Antarctic ice sheet. The study provides a detailed picture of the glacier loss across the globe, with Alaskan glaciers contributing nearly 30%. The research also unveiled the drivers for glaciers' melting: 89% of the ice loss has been due to a warming atmosphere. The remaining 11% is due to increased ice discharge, meaning that glaciers are speeding up and flowing faster into the ocean, where the glacier front erodes in the warmer and saltier water.

To serve both glacier modellers and hydrologists, future work should deliver finer spatial and temporal resolution – capturing glacier-scale mass balance and seasonal to long-term mass fluxes.

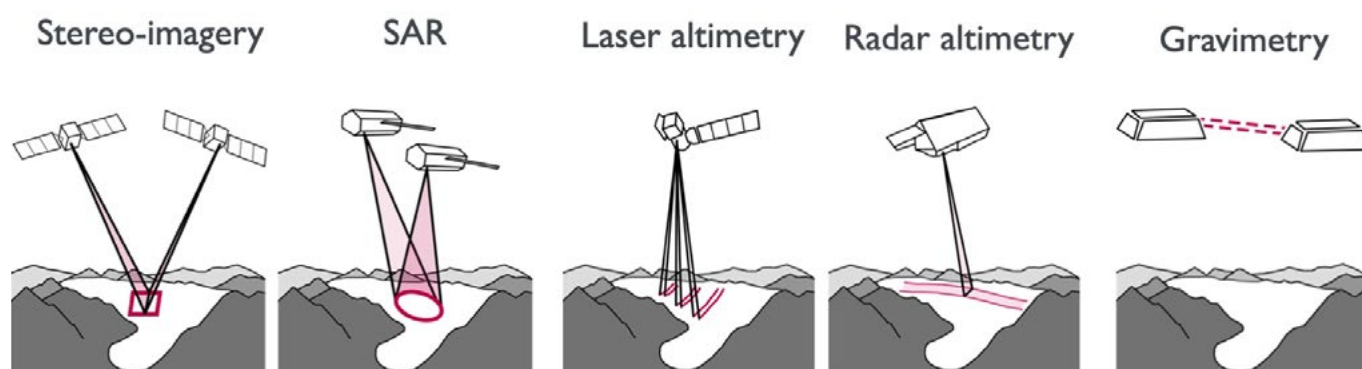


Figure 1. Techniques for measuring glacier mass change from space (adapted from The GlaMBIE Team, 2025).

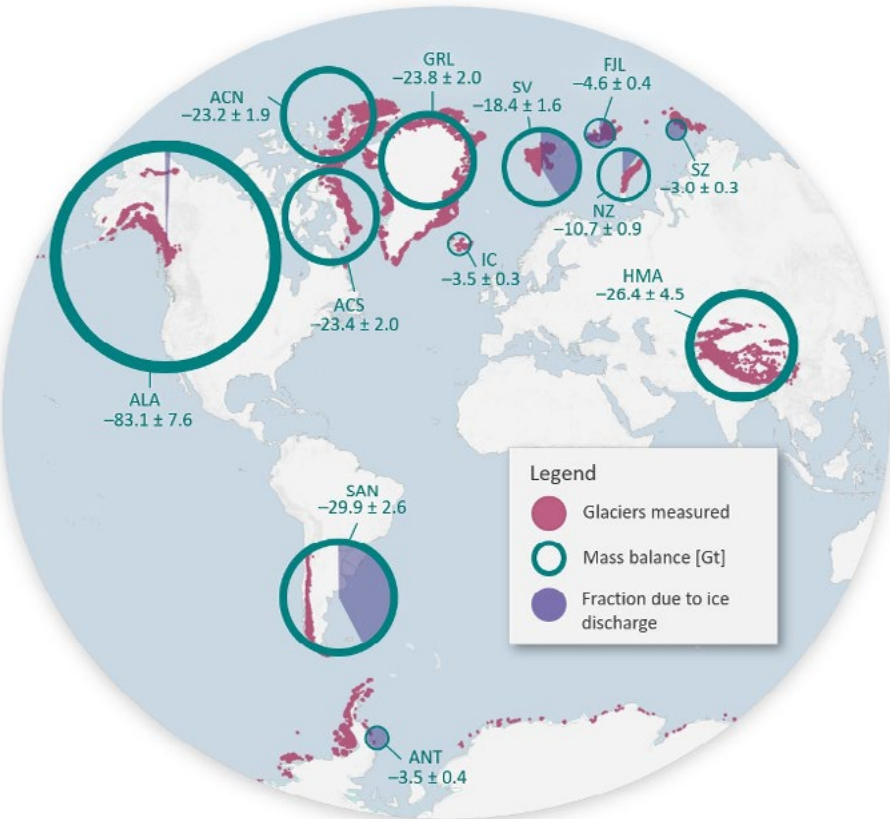


Figure 2. Top, a decade of glacier volume change represented as a cube with the French Alps in the background; Left, Glacier mass changes between August 2010 and August 2020. The size of the circles is proportional to the mass loss, with line thickness representing the uncertainty. The inner circle slice (purple shading) displays the proportion of mass loss due to increased ice discharge into the sea, the remaining mass loss being from surface mass balance. The numbers display mass change in Gigatonnes per year (Gt yr⁻¹). Glacier location based on the Randolph Glacier Inventory 6.0 masks are indicated in red (Jakob and Goumelen, 2023).

Glacier Mass Balance Intercomparison Exercise (GlaMBIE)

c. Background

The various techniques used to measuring glacier mass change from space have individual strengths and weaknesses, often leading to differing estimates. No single method offers the perfect combination of spatial and temporal resolution, spatial coverage, and accuracy. For instance, while DEM differencing provides high spatial resolution and coverage, its

temporal frequency is limited. Conversely, altimetry and gravimetry have high temporal resolution but relatively coarse spatial resolution. Methods based on measuring elevation (DEM differencing, Altimetry) rely on simplistic assumptions for volume to mass conversion, while Gravimetry methods rely on models to disentangle mass signals from glaciers, hydrology

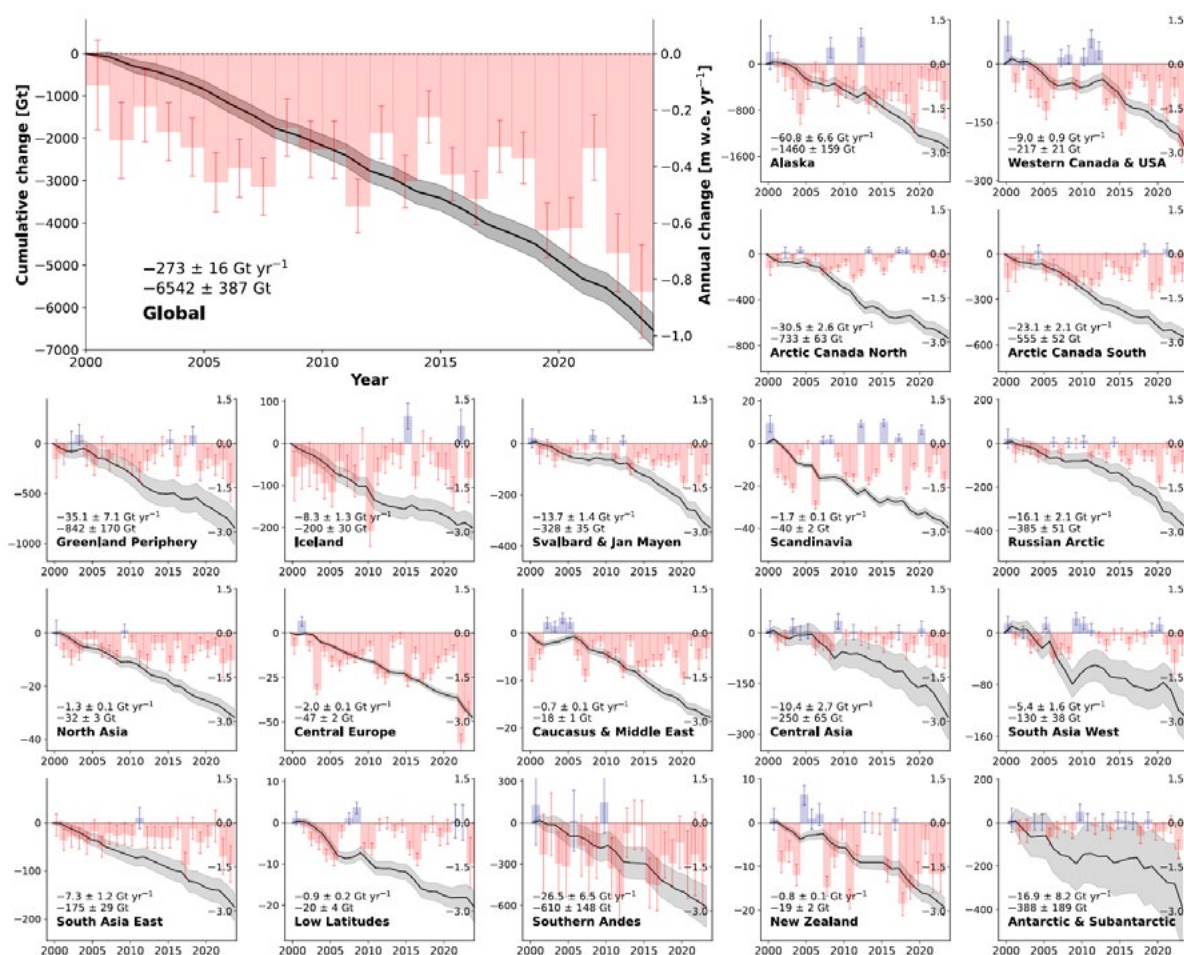


Figure 3. Cumulative and annual glacier mass changes since 2000 for the 19 glacier regions and aggregated to global sums. Cumulative mass changes (left y-axis, Gigatonnes) are shown as black curves with values for mean annual change rate (Gigatonnes per year) and cumulative change (Gigatonnes) for the entire period given at the bottom left. Annual mass changes (right y-axis, meter water equivalent per year) are coloured in blue and red for years with positive and negative mass changes, respectively. Note that the left y-axis differs for each subplot while the right y-axis is the same for all regions (The GlaMBIE Team, 2025).



Monitoring glacier change is fundamental to climate research and the development of effective mitigation policies.



and solid earth fluxes. Despite these limitations, the methods are complementary, and when used together, have the potential to offer a more accurate picture of glacier loss. The ad-hoc and somewhat uncoordinated nature of the various space missions available means that synchronous measurements are the exception rather than the norm, highlighting the need for a dedicated experiment to produce a community estimate of regional and global glacier mass loss.

d. Summary of findings and remaining challenges

The Glacier Mass Balance Intercomparison Exercise (GlaMBIE) is a community initiative aimed at harmonizing global glacier mass change estimates of the past twenty years using different techniques and methodologies. This extensive exercise collected 233 estimates from 35 international research teams, encompassing all 19 glacierised regions worldwide (Figure 3). The GlaMBIE team then assessed each dataset and devised an algorithm to integrate the estimates, capitalising on the strengths of each observational technique in terms of spatial and temporal resolution. Altimetry, gravimetry and field measurements were employed to capture annual variability, while longer-term trends were derived through altimetry, gravimetry and DEM differencing.

GlaMBIE has produced the first all-encompassing estimate of global and regional glacier change in the 21st century, establishing a critical new observational baseline for future studies. These findings are set to play a pivotal role in the next IPCC assessment, highlighting GlaMBIE's significance in climate science.

The results confirm previous individual estimates; since 2,000 glaciers have lost 6,542 billion tons of ice – more than 5% of their overall mass, with a 36% increase in loss from the first half of the record (2000–2011) to the second (2012–2023). The extent of loss varies significantly by region, reflecting the varying impacts of climate change on glaciers worldwide. Regions at lower latitudes, such as the

Caucasus, Middle East and Central Europe, have lost up to 40% of their glacier mass, while Arctic regions have seen a reduction of 3 to 7 %.

The GlaMBIE study not only offers a comprehensive estimate of glacier mass loss but also uncovers systematic differences between measurement methods. For instance, DEM differencing consistently measures higher glacier loss compared with altimetry across most regions, pointing to potential biases that require further investigation. Resolving these discrepancies will be essential for improving the accuracy of future glacier change estimates. The GlaMBIE project sets a benchmark for collaborative science, emphasizing the need for continued refinement of observational techniques and algorithms to reduce uncertainties in glacier mass balance studies.

Conclusion

Monitoring glacier change is fundamental to climate research and the development of effective mitigation policies. Over the past decade, breakthroughs in satellite technology and monitoring have greatly enhanced our understanding of glacier decline. However, planning satellite missions is a lengthy process – often taking years or decades – and many missions currently used for the GlaMBIE assessment lack planned successors (Zemp et al., 2025.). It is therefore vital to secure future satellite observation capabilities to i) continue improving knowledge of glacier loss, ii) support more accurate projections of future glacier evolution and iii) ultimately inform climate policy decisions in support of glacier preservation.

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Monitoring ice loss from the planet's mountain glaciers over the last six decades

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Owen King is Postdoctoral Research Fellow, Newcastle University whose research focuses on the behaviour of the planet's mountain glaciers over the last 60 years. He combines observations from modern satellite sensors with information from older imagery, such as archived aerial photography or declassified spy satellite images, to generate records of changes in glacier extent and volume. He also combines satellite observations with field data, to study small scale processes operating on glacier surfaces which, when occurring over broad areas, are capable of amplifying glacier melt. His work aims to refine predictions of freshwater availability in coming decades.

Introduction – why we need to quantify glacier ice loss

There are more than 274,000 glaciers covering >700,000 km² of the planet's surface which are separate to the Polar Ice Sheets, the majority of which are receding at a rate which has increased over the last few decades (Zemp et al., 2019). Whilst societies' largest population centres are situated far from the planet's high mountain regions, glacier meltwater makes up an important component of the total flow of rivers on which millions of people heavily depend for their daily needs. For example, the Ganges, Indus and Brahmaputra rivers have their source in the Himalaya, and cities situated along the arc of this mountain range rely directly on glacier meltwater for power generation, crop irrigation, consumption and cooking. The dependence of communities on glacier meltwater reaches a peak during periods of drought, when rainfall is scarce, but glacier meltwater flux remains constant, however. The stores of ice in the high mountains are finite, and this flux of freshwater is likely to soon diminish if it has not already begun to reduce (Huss and Hock, 2018). Water security is, therefore, linked directly to glacier survival, which is the primary driver of research undertaken by the cryospheric community.

To manage water resources now and over the coming decades, robust modelling of both the evolution of glaciers under different scenarios of climate change and downstream river flow are vital. Glacier models are calibrated with observations of recent glacier behaviour, namely measurements of glacier area and ice volume change which have occurred over past decades in response to changes in temperature and precipitation. Measurements of glacier change over broad (mountain range) scales are most efficiently undertaken using satellite data and is the focus of this article.

Measuring glacier change from space

The size and optically distinct nature of glaciers when compared to their surroundings allows precise monitoring of their behaviour using satellites orbiting the planet several hundred kilometres above. Glacier recession results both in reductions in their size (area)

and in their thickness, both of which can be quantified by mapping glacier extent from satellite images acquired at different points in time, and through measuring their surface elevation repeatedly. We have developed a detailed picture of glacier behaviour over the period since the millennium using these methods – the period when satellite data coverage became comprehensive (Hugonnet et al., 2021).

Recent methodological advances mean that it is now possible to examine glacier behaviour using archived images and even declassified spy satellite imagery, extending the period over which we can quantify glacier change – back as far as the 1960s. These datasets are invaluable for the robust calibration of aforementioned glacier and hydrological models as they provide information on glacier behaviour over a broad range of climate conditions, improving our ability to predict future glacier recession and meltwater yield.

Quantifying glacier recession in the planet's highest mountain ranges

Two of the planet's most important glacier water towers are High Mountain Asia and the South American Andes (Immerzeel et al., 2020) and these regions have been a focus of research by both the British and global cryosphere community in recent years.

Himalayan Glaciers

Using a combination of contemporary satellite imagery (2000 onwards) and declassified spy satellite images (1974-1984), King et al. (2019) examined the behaviour of glaciers in the Himalaya to establish whether they are losing mass at a greater rate now than the period prior to the millennium. The rate of ice loss over the period 2000-2015 was on average 56% greater than between 1974 and 2000, with the rate in

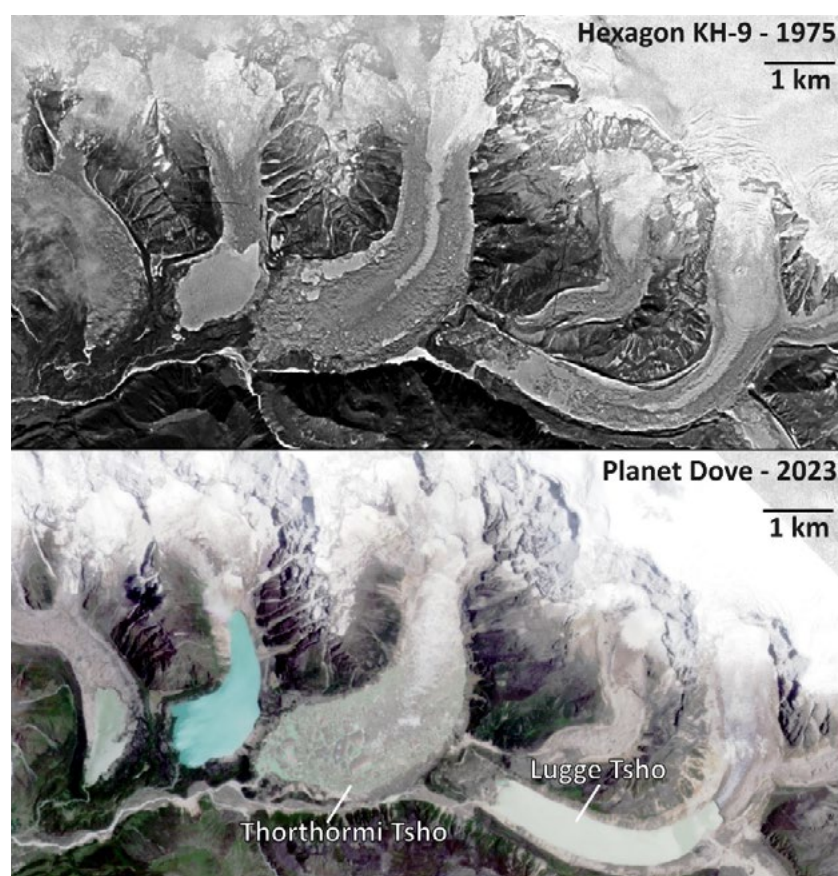


Figure 1. Glacier recession and glacial lake (Tsho) growth in Bhutan between 1975 (top panel) and 2023 (bottom panel), captured in declassified Hexagon KH-9 spy satellite and Planet Dove images.

sub-regions ranging from 28-114%. Furthermore, the growth of glacial lakes is likely driving this increased ice loss rate. Glacial lakes form immediately in front of receding glaciers (Figure 1), occupying the space created by their retreat, where meltwater collects readily. Despite accounting for a minor (~10%) but increasing portion of the glacier population, lake-terminating glaciers are now responsible for one-third of the ice mass loss in the region. Since there are now more than 5,000 glacial lakes in the Himalaya (Zhang et al., 2023), their expansion will likely drive a greater loss of ice in the region in coming decades.

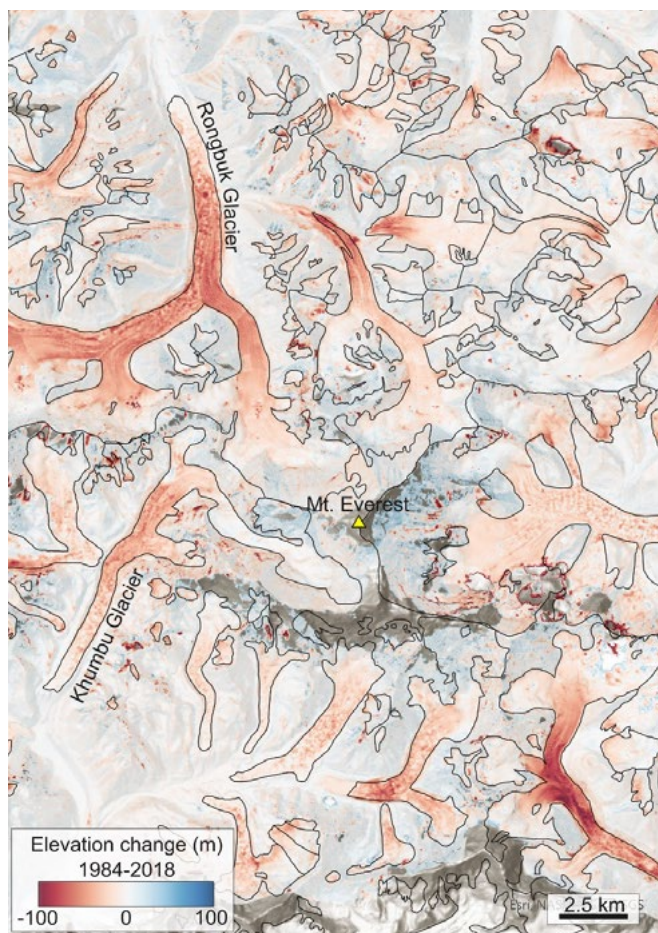


Figure 2. Elevation change around Mt. Everest between 1984 and 2018. Glacier thinning, and associated negative elevation change (red), are shown clearly over glacier surfaces (black outlines). Some glaciers in the region thinned by more than 100 m over this period.

Focussing specifically on glaciers around Mt. Everest, King et al. (2020) quantified the rate of ice loss from the planet's highest glaciers over the period 1962–2019, again using a variety of declassified spy satellite imagery, aerial photography collected during the 1980s and 1990s to support mountaineering expeditions to the region, and contemporary satellite imagery. In this work it was found there has been a 65% increase in the rate at which these glaciers are losing ice mass, when comparing ice loss rates from the 1960s to recent years (2009–2018). We documented glacier thinning even at extreme elevations (>6000 m a.s.l.) and measured reductions in ice thickness of more than 100 m over some of the area's largest glaciers (Figure 2). This magnitude of ice loss is unsustainable and problematic to both mountain communities in the Himalayan foothills and larger settlements further downstream. Up to 65% of the water used by local communities within the Khumbu valley is of glacial origin, and as many as 230 million people live alongside rivers who have their source in the Himalaya. Given predictions of sustained temperature increases in this region over coming decades, water stress is likely only to increase in the Himalaya as the supply of glacial meltwater from the high mountains dwindles.

Andean Glaciers

Observations of glacier change prior to the modern satellite era (pre-2000) are particularly sparse in the South American Andes. Whilst other high mountain regions such as the Himalaya were visited by numerous early expeditions which carried out pioneering surveys that have been repurposed to quantify glacier change, isolated regions of the Andes remain sparsely studied to the present day. Using the same techniques employed in the Himalaya, we are aiming to address this gap in our knowledge of long-term cryospheric changes along the planet's longest mountain range. As part of the Natural Environment Research Council (NERC) funded project 'Deplete and Retreat' (<https://www.antarcticglaciers.org/andes-water-towers/>), we aim to reconstruct glacier area and volume changes as far back as 1850, using both evidence from the landscape of past glacier extent

and observations from the full extent of the satellite archive. Akin to regions of High Mountain Asia, our results suggest the loss of up to 60% of glacier area over the last 150 years, with glaciers in tropical regions displaying particularly pronounced recession. Once again, this loss of ice threatens the water security of mountain settlements and larger population centres downstream such as Lima, Cusco and La Paz.

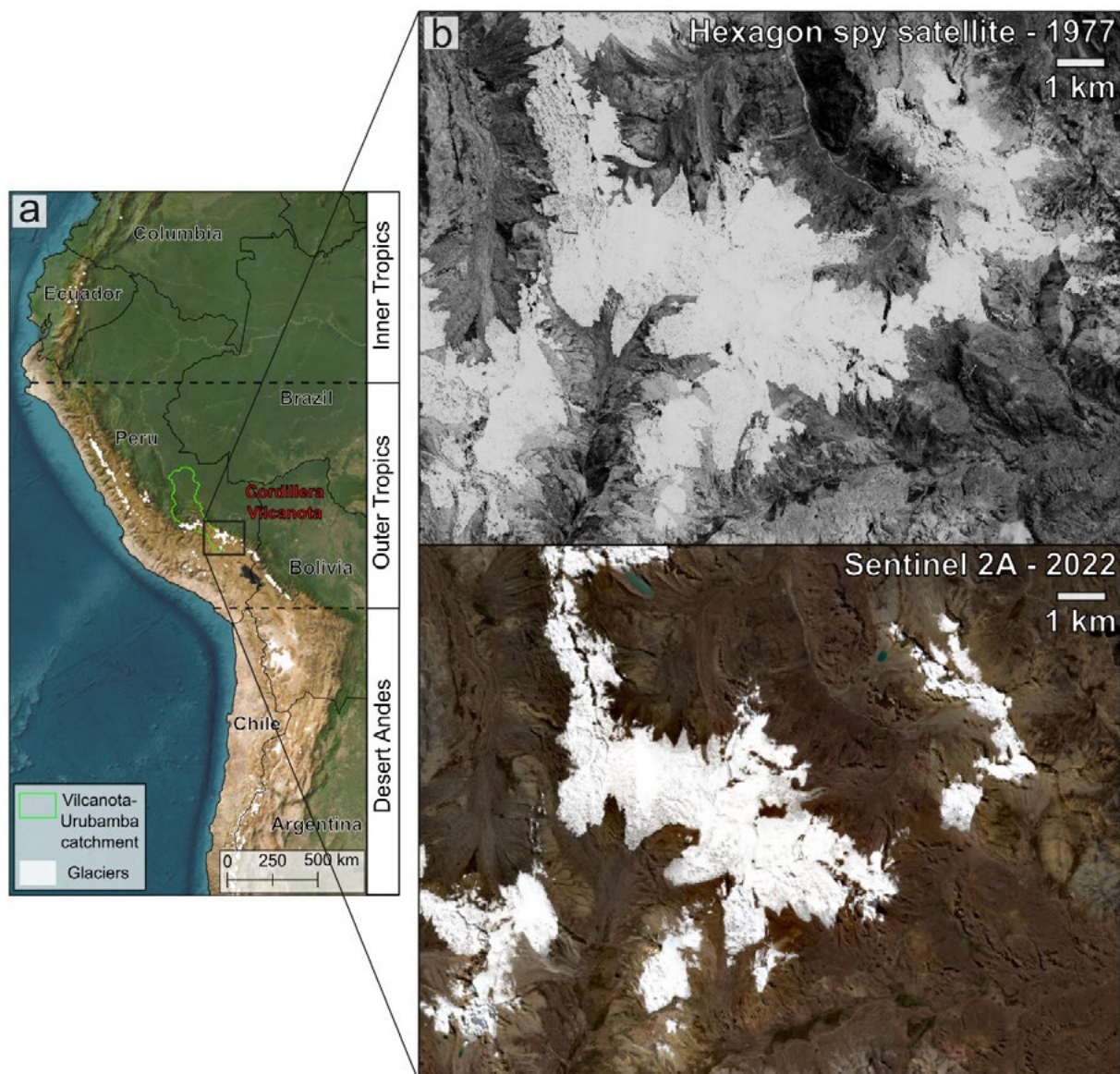


Figure 3. Recession of glaciers in the Cordillera Vilcanota (Peru) between 1977 (top) and 2022 (bottom), captured in declassified Hexagon KH-9 spy satellite and Sentinel 2A satellite images.

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Mountain Glaciers

5

Adapting to climate change in glacierized river basins

Wouter Buytaert

Imperial College London

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Shrinking of mountain glaciers, and
their downstream impacts: current knowledge
and future research directions

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Alaska's top-heavy glaciers are approaching
an irreversible tipping point

Bethan Davies

Newcastle University

Adapting to climate change in glacierized river basins

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Wouter Buytaert is Professor of Hydrology and Water Resources, Civil and Environmental Engineering, Imperial College London and works at the interface between hydrological process understanding, water resources management, and global development. He focuses in particular on studying the impact of environmental change on the terrestrial water cycle, and its consequences for managing water resources and flood and drought risk. He applies and develops advanced methods for data collection, computer simulation, and knowledge transfer to support environmental decision making and development policies. He is working extensively in the Global South, with a particular interest in mountain regions such as the Andes and the Himalayas.

Introduction

Water security in glacier-fed river basins is increasingly at risk from climate change. Mountain communities often rely on surface water sources, as groundwater is scarce and difficult to extract. Steep terrain limits the transport of water, while high elevations make pumping impractical. This leaves small streams and surface water bodies as primary water sources, but these are highly sensitive to degradation.

Unlike lowlands, where deep soils and aquifers often provide hydrological buffering, mountains have steep slopes, shallow soils, and low-permeability bedrock, limiting groundwater storage. Instead, hydrological features such as lakes, wetlands, snow, and glaciers play critical roles in buffering seasonal water supplies.

Glaciers and snowcaps act as natural reservoirs, converting irregular precipitation into steady meltwater contributions to rivers. Snowmelt in temperate mountains like the Alps and Rockies peaks in spring when temperatures rise above freezing, and seasonal buffering is therefore limited. Glacier melt continues through the summer, aligning with higher temperatures, low rainfall, and increased evaporation, making it crucial for the supply of water to the Ganges basin in northern India and Nepal, where the summer monsoon overlaps with the northern hemisphere's summer.

In tropical mountains, minimal temperature variation results in more consistent year-round meltwater contributions, influenced by solar radiation and humidity. In areas with prolonged dry seasons, such as the Peruvian Andes, glacier melt becomes vital during dry months (Figure 1).

Meltwater also buffers against interannual variability. Unlike rainfall-dependent sources, glacier melt often increases during droughts due to higher temperatures, increased sunshine, and lower humidity. This makes glaciers important for sustaining water supplies in a changing climate.

Impacts of climate change on water availability

Climate change is altering water resources worldwide through various pathways. One primary effect is the warming of the atmosphere, which increases the evaporation of water from the Earth's surface. This process reduces the amount of precipitation that runs off into rivers, streams, and underground aquifers.

In addition to influencing evaporation, climate change may alter precipitation patterns. The worst-case scenario arises where higher evaporation rates coincide with reduced precipitation, reinforcing water scarcity. More commonly, however, climate change intensifies seasonal variations, making wet seasons wetter and dry seasons drier. This heightened

seasonality reduces water availability during critical periods and exacerbates the frequency and severity of droughts.

While these trends are global, their impacts are particularly pronounced in mountain regions, where river basins have low buffering capacity. These effects are further intensified by the shrinkage of glaciers and snowpacks.

Although the reduction in snow and ice has a limited long-term impact on total water availability – since snow and ice contribute less water vapor to the atmosphere compared to other land surfaces – their short-term effects are significant. As glaciers lose mass, streamflow initially increases, reaching a point known as “peak water,” after which meltwater

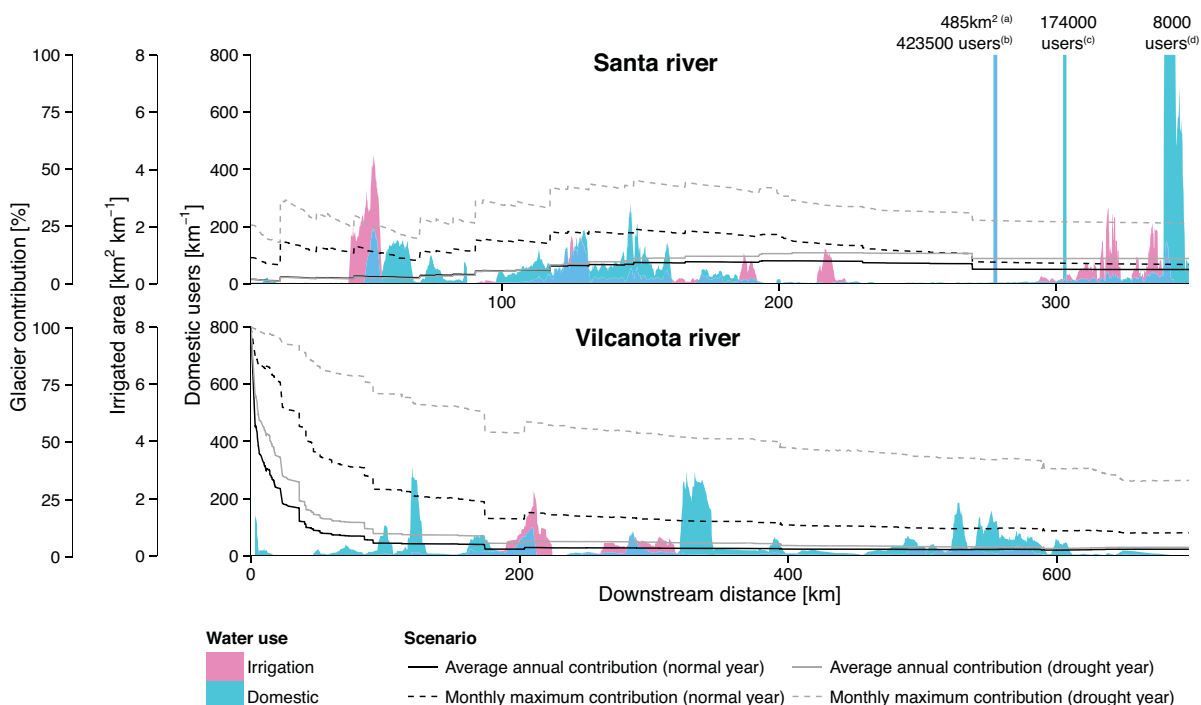


Figure 1. Glacier meltwater contribution to streamflow at varying downstream distance from the glacier, for two river basins in Peru. The Santa river (top) has a very sustained contribution because of a lack of lateral inflow from the non-glaciated part of the basin. In the Vilcanota basin, the meltwater signal dilutes much more quickly because of non-glacier runoff. Different scenarios (mean and monthly maximum for both normal and dry years) are used to show the temporal variation of the contribution. Main downstream water usages (irrigation and domestic use) are shown respectively in pink and blue colours. From Buytaert et al. (2017).

contributions decline rapidly. The timing of peak water varies based on glacier characteristics and has already been observed in regions such as the Peruvian Andes.

Beyond peak water, the loss of snow and ice primarily affects the temporal partitioning of streamflow, particularly during dry seasons. This effect varies by location, depending on the current meltwater contribution and the projected changes under future climate scenarios. Its influence also diminishes with downstream distance from glaciers, as meltwater mixes with runoff from non-glaciated areas (Buytaert et al., 2017).

The hydrology of non-glaciated areas is also subject to climate change, driven by rising temperatures, shifting precipitation patterns, and indirect effects such as changes in soils and vegetation. Assessing the overall impacts on water resources requires an integrated, catchment-scale approach to account for these interconnected processes and their spatial and temporal dynamics.

Lastly, glacier shrinkage affects not only water quantity but also quality. Glacier-fed streams sustain delicate hydroecological systems that can be disrupted by changes in flow volume, temperature, and biogeochemical properties. Additionally, newly exposed rock formations from retreating glaciers may release heavy metals and acidic drainage into streams due to accelerated erosion and oxidation, further degrading water quality (e.g., Santofimia et al., 2017).

Risks for water security

Water security is a multifaceted concept that expresses a society's ability to provide clean and safe water to support human livelihoods and sustain the broader environment. While water availability and quality are key determinants, water security is also affected by factors such as exposure to water-related risks, the current and future extent of water scarcity, vulnerability to shocks, and adaptive capacity.

Global assessments have attempted to evaluate the vulnerability of mountain water resources to climate change (e.g., Immerzeel et al., 2020). However,

the complex interplay between natural and human factors means that water security and vulnerability often exhibit highly localised and idiosyncratic characteristics.

In most mountain river basins, glacier shrinkage or disappearance alone is unlikely to result in severe physical water scarcity. This is because most water usage occurs downstream, where the contribution of glacier melt is significantly diluted, and reductions in glacier input typically have only a marginal effect on overall streamflow. Exceptions, however, include basins in arid regions such as parts of the Karakoram, as well as the western slopes and highland areas of the Central Andes. For instance, in Peru's Santa River basin, the arid nature of the region means that meltwater contributions remain significant all the way to the Pacific Ocean (Figure 1). Additionally, nearly all water is consumed due to extensive irrigation systems in the coastal region. This dependence makes the basin highly vulnerable to future streamflow reductions, particularly during the extended dry season or in drought years.

These vulnerabilities are often exacerbated by rising water demand. For example, approximately 30% of Lima's water supply depends on the Rimac River, which is fed by small glaciers. While glacier melt contributes less than 1% of the streamflow at Lima's water intake, the city's high and growing demand places extreme stress on the water system, rendering it susceptible to disruption. Lima has addressed these challenges through infrastructure projects such as reservoirs and inter-basin transfers from the wetter Amazonian side of the mountains. But the city is also exploring innovative approaches to enhance water security, including nature-based solutions.

For high mountain communities, the challenges are different. Although these areas benefit from lower population densities, which generally means higher per capita water availability, they are more vulnerable to periods of low flow and drought. Many of these communities have adapted to the increased water availability during peak water periods, leaving them more exposed to eventual streamflow reductions. Unlike urban centres such as Lima, these communities

often lack the financial resources to invest in adaptive infrastructure, such as reservoirs, or to transition to less water-intensive agricultural practices.

Adapting to climate change

Given the complex interplay between natural and human processes, effective and sustainable solutions must be tailored to the local context. From a technical standpoint, the loss of the hydrological buffering capacity provided by glaciers can be addressed by constructing artificial storage. However, such measures are costly and present their own challenges, including risks of outburst floods caused by landslides, rockfalls, or icefalls. Large infrastructure such as reservoir storage also lacks adaptability in the face of uncertain climate change – there is little utility in building reservoirs if future reductions in streamflow prevent them from filling.

As a result, policymakers are increasingly turning to more flexible alternatives. For instance, Lima's water utility company, SEDAPAL, is exploring nature-based solutions to enhance water availability. These solutions leverage natural processes, such as soil water retention and infiltration, and encompass a wide range of interventions, including soil conservation, enhanced recharge techniques, and revegetation of degraded areas.

One approach gaining particular interest in Lima is the use of amunas, a traditional water management practice that has been in use for centuries (Ochoa et al.,

2019). Amunas consist of small canals that divert water from mountain streams to hillslopes, where it infiltrates into the soil (Figure 2). The water then gradually migrates through the hill slope soil, eventually feeding small reservoirs and pools. This time-delay mechanism allows water captured during the wet season to resurface during the dry season, making amunas an efficient and cost-effective water storage method. Moreover, they can be flexibly expanded or modified as water needs and availability change over time.

However, amunas have limitations. The residence time of water in hillslopes is often insufficient to sustain water supply throughout the entire dry season (Figure 3). Consequently, they are not a direct substitute for reservoir storage but can complement it by reducing water withdrawals early in the dry season, thus conserving stored water for later use.

Amunas are part of a broader set of “water sowing and harvesting” practices found over the world, such as the careos in Spain and qanats in the Middle East. Together with other nature-based solutions, these practices expand the toolbox available to river basin managers, enabling better locally tailoring of solutions. This is particularly relevant as nature-based solutions often provide co-benefits, such as enhanced biodiversity, soil conservation, and improved water quality.

Despite their potential, several significant challenges remain. The natural processes underpinning nature-based solutions are not yet fully understood or quantified, complicating the prediction of their impacts and raising the risk of unmet expectations.



Figure 2. Conceptual representation of the amuna practice. 1. Flow diversion point; 2 & 3: diversion canal; 4. Infiltration in the hillslope; 5. Subsurface flow; 6. Delayed resurfacing of the water.

Moreover, nature-based solutions alone are unlikely to suffice; they typically need to be integrated with traditional “hard” engineering approaches into so-called blended solutions. Designing, maintaining, and optimizing such hybrid systems is inherently complex and demands innovative approaches to multi-objective optimisation, risk analysis, and benefit assessment – areas where existing tools and methodologies remain underdeveloped.

Furthermore, while it may be technically feasible to offset the loss of glacial hydrological buffering, this may not always be the most desirable solution. Trade-offs,

such as the economic and social impacts of converting farmland into reservoir storage, must be carefully considered. In some contexts, the effects of climate change on water resources may be overshadowed by issues like water quality degradation from inadequate urban and industrial wastewater treatment or agricultural runoff. In other cases, reducing exposure and vulnerability to water scarcity might be more effective, such as by promoting water-efficient irrigation systems or cultivating less water-intensive crops (Drenkhan et al., 2022).

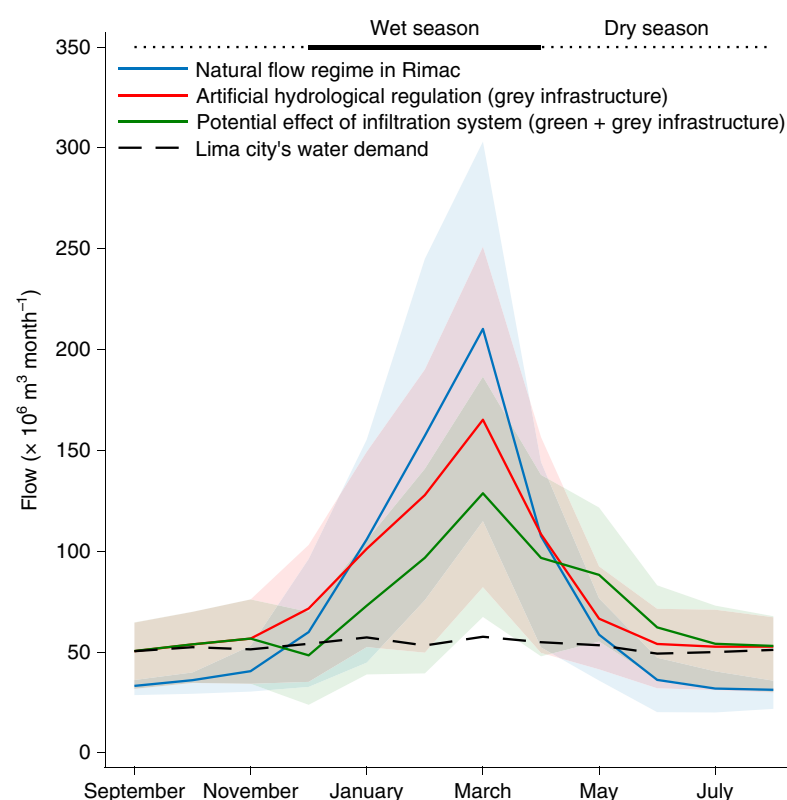


Figure 3. Potential for amunas to delay the seasonal flow in the Rimac basin, Peru. The natural flow regime (blue line) is already strongly buffered by traditional “grey” infrastructure¹ (red line). Implementation of amunas can delay the flow further (green line), thus making the grey infrastructure more effective (from Ochoa et al., 2019).

¹ “grey” infrastructure refers to such structures as dams, retaining walls, roads, pipes, water treatment plants etc.

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Shrinking of mountain glaciers, and their downstream impacts: current knowledge and future research directions

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Introduction

Due to our warming climate, glaciers are shrinking rapidly, freshwater biodiversity and ecosystems are at risk, water sources are dwindling for millions of people living downstream, and water-related risks are being created (e.g., potentially catastrophic glacial lake outburst floods or GLOFs). Given the extremely remote locations, real time monitoring of glacier systems and associated early warning systems (EWS) for mitigating risks are limited. EWSs are essential for improving communities' preparedness, response and recovery.

Recent significant advances in environmental data collection and analysis have opened new horizons to develop a holistic understanding of causes and impacts of glacier shrinkage. Nonetheless, our knowledge of glacier preservation (i.e., efforts and actions taken to protect and maintain glaciers in a warming world) remains partial. In this context, this perspective shares thoughts on the current state of glacier shrinkage, their downstream impacts on livelihoods and ecosystem services, and ways forward for achieving UNESCO's goals set in the International Year of Glaciers' Preservation (IYGP) 2025.

Shrinking glaciers: state-of-the-art knowledge

Globally, ice sheets and glaciers are the main freshwater resources as they cover ~10% of the global land surface but contain ~70% of the world's freshwater (Milner et al., 2017). Based on the latest Randolph glacier inventory, the distribution of world's glaciers (excluding ice sheets) is shown in the Figure 1.

The scale of glacier shrinkage across the globe is unprecedented; but it is nonuniform, varying by region due to differences in climate, watershed and glacier characteristics. For instance, the Himalayan glaciers are retreating at an average rate of 10–60 metres per year, with an approximate annual ice mass

loss of 8 billion tonnes (Bolch et al., 2019). This can be compared with an average retreat rate of 20–30 metres per year for Alpine glaciers, as the European Alps have lost 50% of their total ice volume since the 1850s (Zemp et al., 2015). Tropical glaciers in the Andes have experienced an annual ice loss of 1.2%, approximately 60 metres of frontal retreat per year (Rabatel et al., 2013). Future projections indicate that glaciers across the globe could lose between $26 \pm 6\%$ of their mass by 2100 under a global increase of 1.5°C in air temperature, leading to $49 \pm 9\%$ to $83 \pm 7\%$ of world glaciers to be disappeared (Rounce et al., 2023). This includes the 'extinction' of glaciers from one third of the UNESCO World Heritage Sites by 2050.

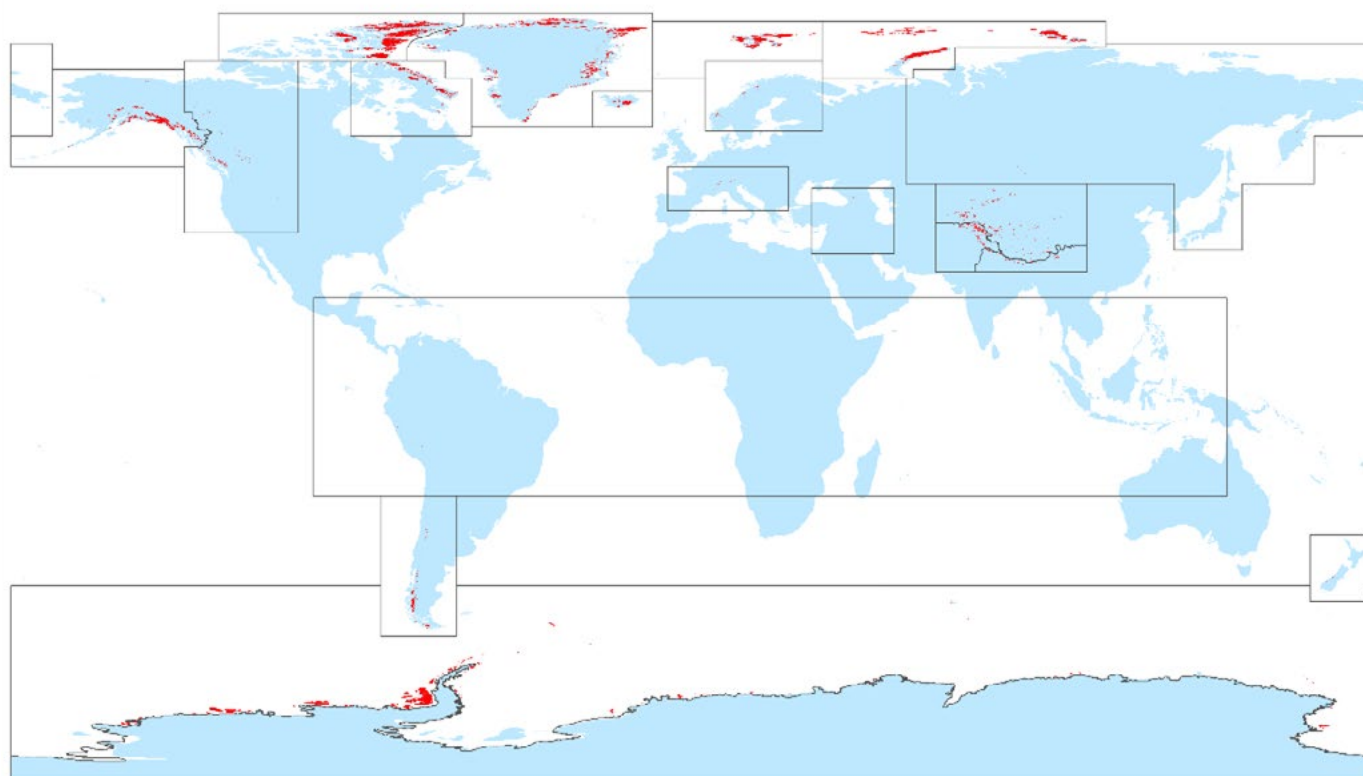


Figure 1. Global distribution of glacier coverage (Data source: Randolph Glacier Inventory, version 7, 2023). This database shows the maximum glacier area is in the Greenland periphery (13250 km^2), followed by Asia (10574 km^2), North America (7186 km^2), South America (1466 km^2), Europe (855 km^2), and New Zealand in Oceania (104 km^2).

Downstream impacts on environment and people

With rapid glacier shrinkage, river flow regimes lose the steady 'annual compensation effect' (summer meltwater cycle) leading to more variable (precipitation dominated) river flow patterns with greater potential of ecological disturbance and biodiversity threats. For example, cold-water fish populations are declining rapidly, and ~50% of alpine streams fed by glacier meltwater are at risk of drying up in late summer by 2100 (Milner et al., 2017).

The supply of water is under severe stress from glacier-fed rivers in transboundary basins, and this often generates up-downstream water conflicts across political borders. Glacier shrinkage leads to exposure of new terrain in the proglacial/ downstream zone, which creates opportunities for the constructions of new dams (Milner et al., 2017) adversely affecting the aquatic and terrestrial ecosystems.

Besides the environment, glacier shrinkage has significant impacts on national economies as the meltwater supply from glaciers is used for hydropower generations. According to the International Energy Agency (IEA), hydropower contributes ~16% of total electricity globally but for many countries those are heavily dependent on the glaciers. In the Alps, Himalayas and Andes, the production of electricity from hydropower may significantly reduce under the changing climate and induced rapid shrinking of glaciers. The International Hydropower Association (IHA) estimates that the cost involved in adapting hydropower infrastructure could be between \$50-100 billion globally by 2050 to diversify energy sources and build reservoirs to counteract the reduced glacial meltwater storage.

Glacier shrinkages not only impact terrestrial ecosystem, and freshwater resources, but create associated hazard cascades downstream such as the GLOFs. Between 1990-2020, the formation of new lakes increased by 53% across the globe (Shugar et al., 2020). This include ~1,000 new lakes in the Himalayas (i.e., 50% increase) ~1,200 lakes in the Alps, and ~700

in the Andes. These hazards often cause widespread disruptions in the mountains including fatalities, infrastructural damages and ecological disturbances. Approximately, 15 million people are exposed to the potential risks of GLOFs, with 9.3 million in the High Mountain Asia alone (Taylor et al., 2023).

Future research challenges and opportunities

Glacier shrinkage is a visible and powerful indicator of the impacts of climate change. Scientific advances have deepened our understanding of this phenomenon; and its potentially devastating effects on the natural environment and society. The need to take action has never been more urgent. As reviewed above, glaciers act as valuable freshwater resources, provide ecosystem services with socio-economic benefits, and create water-related hazards. Therefore, preserving glaciers is crucially important to maintain the benefits and mitigate the risks. However, this requires concerted global efforts addressing the root causes of climate change and development of resilient, sustainable strategies.

Several challenges are involved in doing so because glaciers are located in mountainous and highly inaccessible terrains and consequently areas with poorest observational data. Long-term observations are unavailable for majority of world's glaciers and glacierized basins; the earliest instrumental records began in early 20th century. The advancement in remote sensing technique over the past decades has expanded the horizon for glacier monitoring.

New ground observations have the potential to provide more detailed information and robust understanding. In addition to satellite imagery, drone-based aerial mapping has provided significant breakthroughs in glacier observation to detect changes at much higher spatio-temporal resolutions. Novel low-cost (wireless) sensor networks offer potential for finer space-time data provision from automatic rain gauges, river water level sensors, river discharge estimation

systems, lake water pressure sensors, and motion cameras. Initiatives such as developing citizen science programmes have proven an effective way to enrich environmental data archives alongside expert inputs and harnessing of indigenous knowledge. These help to inform local decision-making. Besides, monitoring the current states of glaciers, understanding how glaciers have retreated in the past can improve models for accurate projections of future glacier shrinkage. Past glacier variations can be reconstructed using environmental proxies and tracers such as stable isotopes from ice cores, lake sediments, tree rings, glacier moraines etc. Such data-led studies provide a better evidence base for improved glacier preservation strategies and their implementation.

Several geoengineering techniques have been promoted for glacier preservation. These include draining or freezing glacier beds, altering surface albedo to reduce glacier melt rates, creating obstacles to retain ice, local cloud seeding to cool glacier surfaces etc (Lockley et al., 2020). Other techniques have also been shown effective in reducing the potential risks of GLOFs by draining glacial lakes through siphoning techniques (Wake, 2014). In the glacier forefields, preserving glacial meltwater by creating artificial glaciers, known as ‘ice stupas’ is deemed a significant intervention for freshwater resource management (Palmer, 2022). Ice-stupas can make contributions to meet the demand for drinking and agriculture, especially during dry summer months. These geoengineering approaches need further scientific exploration to test their benefits and potential unintended consequences.

In addition to advancing our scientific knowledge and technological innovation, it is critically important to raise the awareness of wider society and local communities. Often, the latter have significant indigenous knowledge to share. Public awareness is one of the key objectives of the IYGP 2025 as well as a priority area in the ninth phase of UNESCO’s Intergovernmental Hydrological Programme. This can be achieved through several initiatives, including educating wider society about the importance of

glaciers and training them to act as citizen scientists. Any actions for the best practices in glacier monitoring, preservation and risks mitigation measures (e.g., early warning systems, timely glacier inventories) should be promoted through knowledge-exchange and transboundary cooperations for water sharing.

Strengthening policy frameworks at different sectoral and governance levels from local to national to international is needed for robust policy-making and implementations for sustainable water management. Such action will facilitate water accessibility for all stakeholders, reducing potential water conflicts. Notably, ensuring financial support for research programmes on glacier monitoring, impact assessments and climate change adaptation through collaborations among international partner organisations such as Canada-Inuit Nunangat-United Kingdom (CINUK) are paramount for achieving the glacier preservation goal. Such cooperations can help to improve holistic understanding of complex cryosphere-hydrosphere interactions and their impacts on aquatic-terrestrial ecosystems. It is also essential to strengthen financial support (e.g., loss and damage funds) to the most vulnerable communities exposed to shrinking water resources and glacial hazards.

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Glacier shrinkages not only impact terrestrial ecosystem, and freshwater resources, but create associated hazard cascades downstream such as the glacial lake outburst floods.

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Conclusion

Given the current trend of warming climate and need to restrict warming to within the IPCC limit of 1.5°C above pre-industrial levels, it is difficult to preserve most glaciers from shrinkage. Nonetheless, given the importance of these water towers for ecosystems and society, it is essential that glacier preservation efforts are focused and purposeful to slow the current pace of change (related to greenhouse gas emissions) and build adaptation capacity and resilience. For this,

we need to broaden our horizon to look beyond glaciers, by examining the glacierized catchment as an integrated system. Establishing a holistic catchment monitoring network is needed (as illustrated in Figure 2) to inform models and decision-making. This science can help to develop an effective integrated river basin management system for securing longer-term mountain freshwater availability and an early warning system for mitigating hazards and risks.

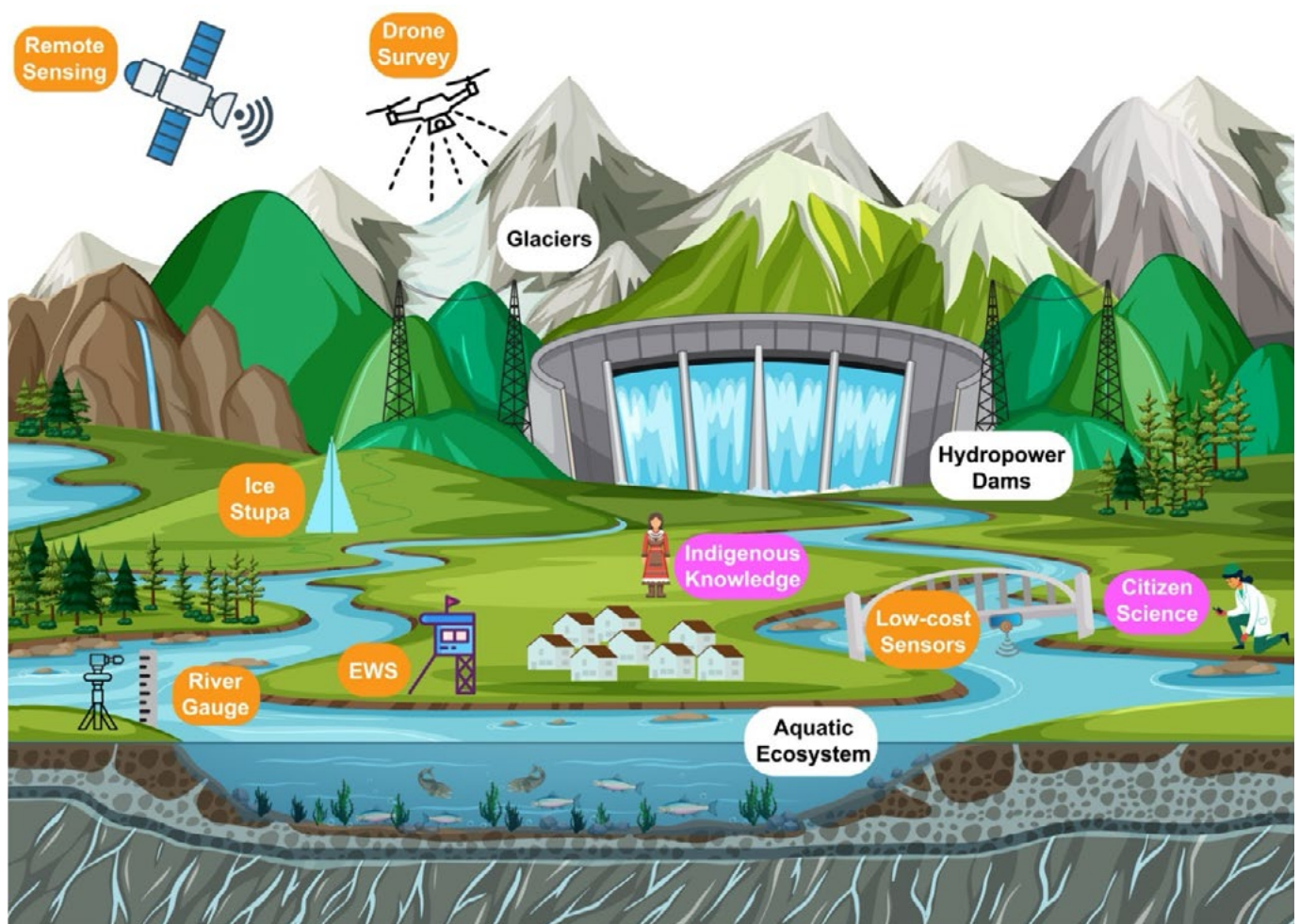


Figure 2. Illustration of an integrated catchment monitoring management system from upstream glaciers to downstream hydrology and impact. Technological and geoengineering solutions for glacier and hydrological monitoring are highlighted in orange, and human aspects are highlighted in pink.

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Accelerating glacier recession across the Andes

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Bethan Davies is Professor of Glaciology at Newcastle University. She specialises in the response of glaciers and ice sheets to climate change, with recent work focusing on the British-Irish Ice Sheet, Patagonia, Antarctica, the Andes, Alaska, Svalbard, and Austria. Her research has been recognised with awards from the Quaternary Research Association (Lewis Penny Medal, 2014) and British Society for Geomorphology (Gordon Warwick Medal, 2021), and her service to the community formally recognised by the International Glaciological Society (Richardson Medal, 2024) and the Scientific Committee for Antarctic Research (Medal for Antarctic Education and Communication, 2022). She is currently editor for *Quaternary Science Reviews*, chair of the UK Arctic-Antarctic Partnership and co-chair of Diversity in Polar Science Initiative.

The Andean Glaciers

The Andes contain numerous glaciers along its length (Figure 1). These glaciers range from the high-altitude tropical glaciers in the Peruvian and Bolivian mountains, the glaciers of the subtropics in the Central Andes, glaciers on volcanoes in the arid central Andes, and the temperate Patagonian glaciers in the southern Andes. The glaciers in the tropical and arid Andes are highly important as water resources, as they melt in the dry season, supporting water flow and buffering drought. The food and water security of 90 million people depends on the Andean Mountain water tower, which is at risk in several regions because climate change is altering the stores of water held in high altitude wetlands, lakes, snow and glacier ice.

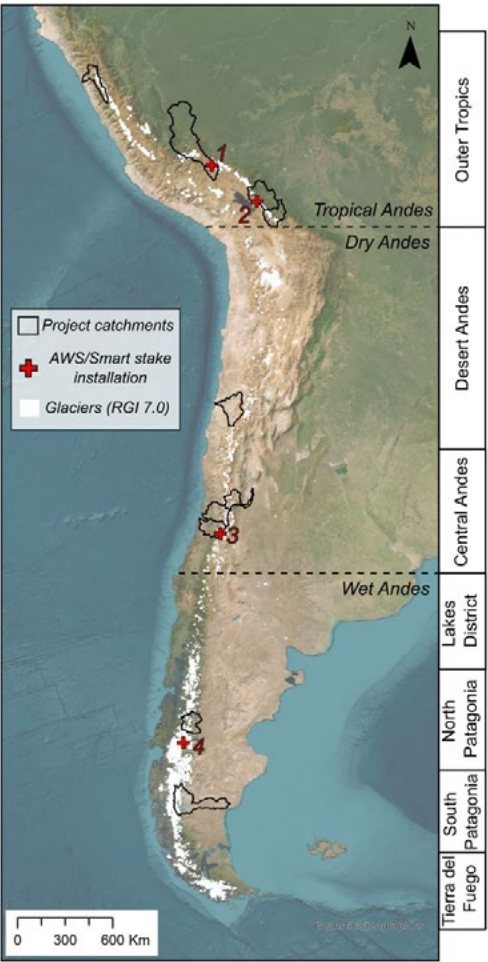


Figure 1. Glaciers and climatic zones of the Andes.

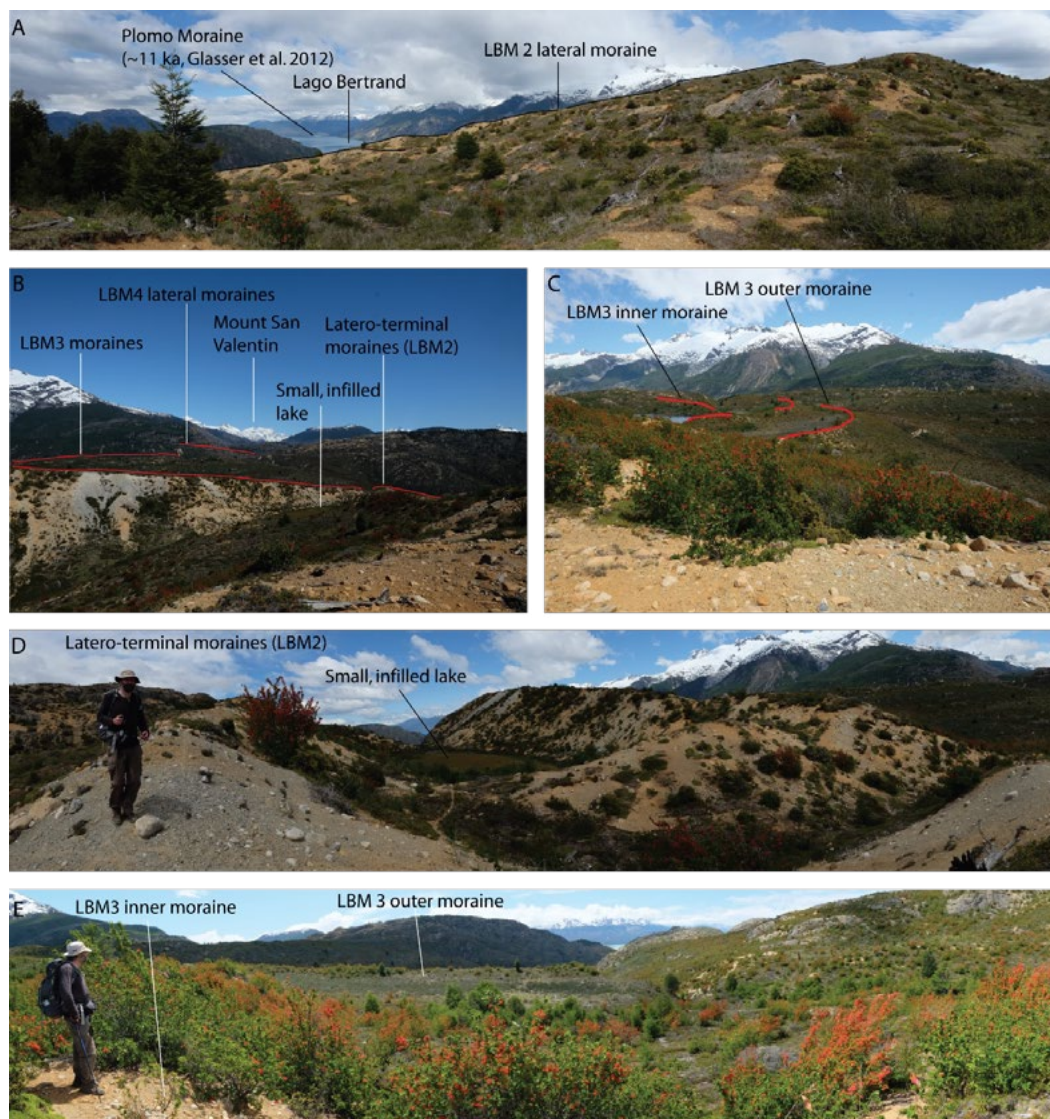


Figure 2. Examples of moraines from the former glacier extent in Patagonia.
From Davies et al. (2018). Photograph credit: Bethan Davies

Patagonia, between ~40°S to 56°S, is the most southerly part of the South American continent. The landscape of this region is one of contrasts. Dense temperate rainforests cover the western coast, whereas the eastern plains are flat, vast, and arid. Perhaps most striking, however, is the high, Patagonian Andes, rising steeply (up to around 4,000m asl) above deeply carved fjords and valleys, and home to the Patagonian Icefields.

Patagonia is one of the windiest and wettest places on Earth. The region has a temperate maritime climate, with a strong west-east precipitation gradient as a result of the year-round passage of westerly winds over the Patagonian Andes. On the west coast, annual precipitation reaches up to 7,500 mm year, whereas less than 1,500 mm a year falls east of the icefields.

The snowfall brought by the westerly winds is the main source of accumulation for the glaciers. The large volume of glacier ice here means that the Patagonian icefields are a significant contributor to global sea level rise from land ice.

Glacier change: 35,000-present

Glacier reconstructions from the pre-satellite era require careful analysis of glacial geology, using the landforms left by former glaciers to reconstruct their former extent and thickness (Martin et al., 2019; Cooper et al., 2021). The landforms include the substantial moraines deposited at the margins of the glaciers (e.g. Figure 2). Large moraines form when the glacier is in equilibrium with climate and therefore is neither

growing nor shrinking. As debris is transported along the glacier as it continues to flow down-valley under the force of gravity, moraines build up at the glacier edges and terminus. Detailed maps of these landforms are needed to reconstruct former glacier extent.

Glacially transported boulders on these moraines can be used to calculate the timing of moraine formation (‘cosmogenic nuclide exposure-age dating’, and the extent of glaciers can be fixed in time (e.g. Davies et al., 2018; Thorndycraft et al., 2019).

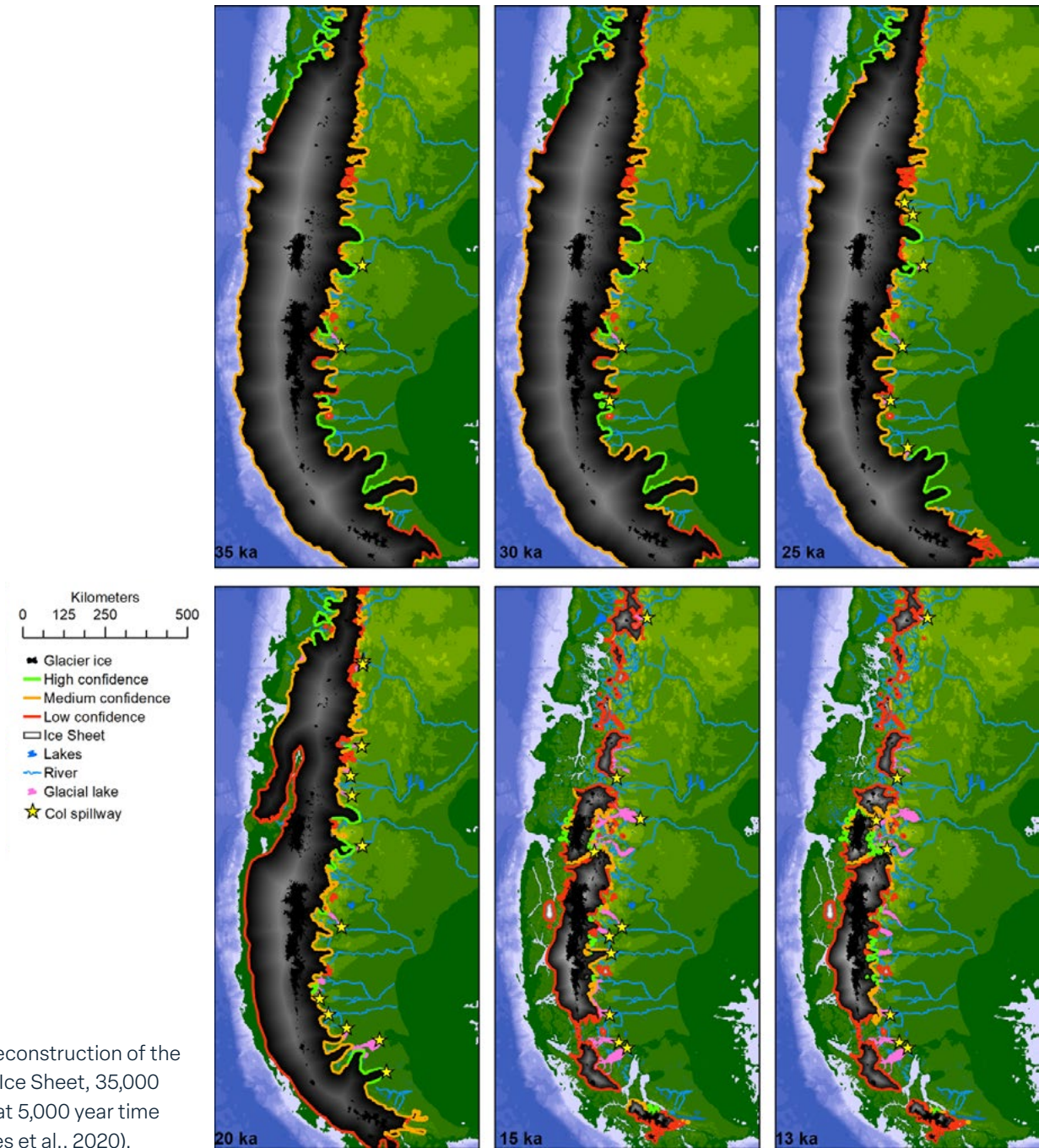
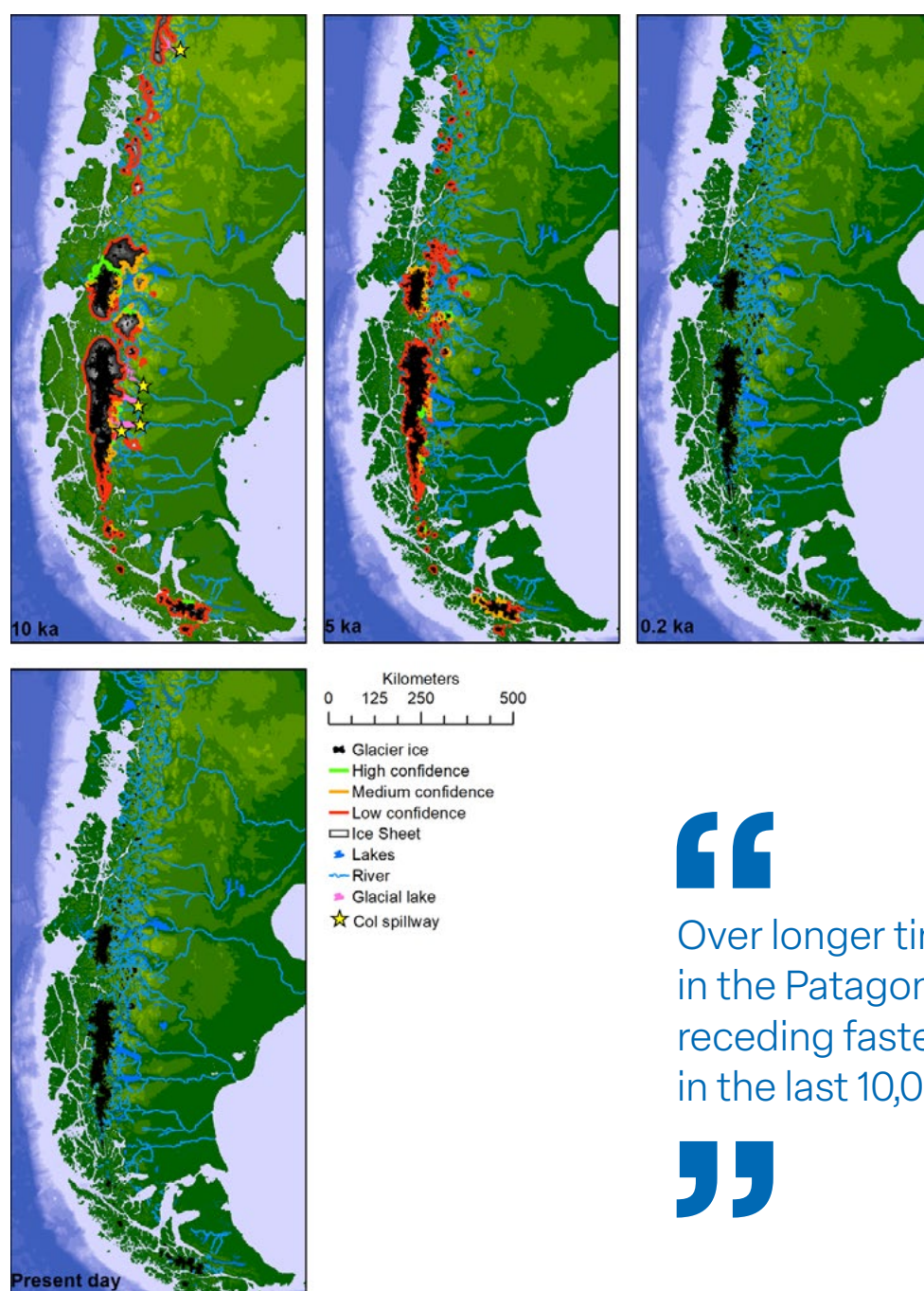


Figure 3. Reconstruction of the Patagonian Ice Sheet, 35,000 to present, at 5,000 year time slices (Davies et al., 2020).

Using these techniques, it is possible to reconstruct the extent and then shrinkage of the former Patagonian Ice Sheet over the last 35,000 years (Davies et al., 2020). Over longer timescales, glaciers in the Patagonian Andes are now receding faster than at any time in the last 10,000 years (Figure 3).

These datasets have been used extensively in model-data comparisons, in order to improve the projections of future behaviour of Andean glaciers, and have motivated widespread international attempts to better constrain past glacier behaviour.



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Over longer timescales, glaciers in the Patagonian Andes are now receding faster than at any time in the last 10,000 years.

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Glacier change: 1850 AD to present

Recent work has relied on detailed mapping of glacier moraines formed at the Neoglacial maximum, the Little Ice Age (LIA), across the Andes (Carrivick et al., 2024) (Figure 4). This was undertaken along the full length of the Andes, for >5,500 glaciers, and showed that glaciers shrank at a rate of $-36.5 \text{ km}^2 \text{ yr}^{-1}$ from the LIA to the year 2000. Overall, glaciers lost 25% of their ice coverage from the LIA to the year 2000.

Glacier change: recent decades

Over more recent timescales, satellite imagery can be used to constrain the shrinkage of glaciers in the Andes (Davies and Glasser, 2012). This work uses repeat satellite imagery to inventory glacier extent and to quantify rates of glacier shrinkage since the 1980s. This showed that across Patagonia, annual rates of glacier shrinkage accelerated rapidly after 2001. Comparison of recent inventories with the work

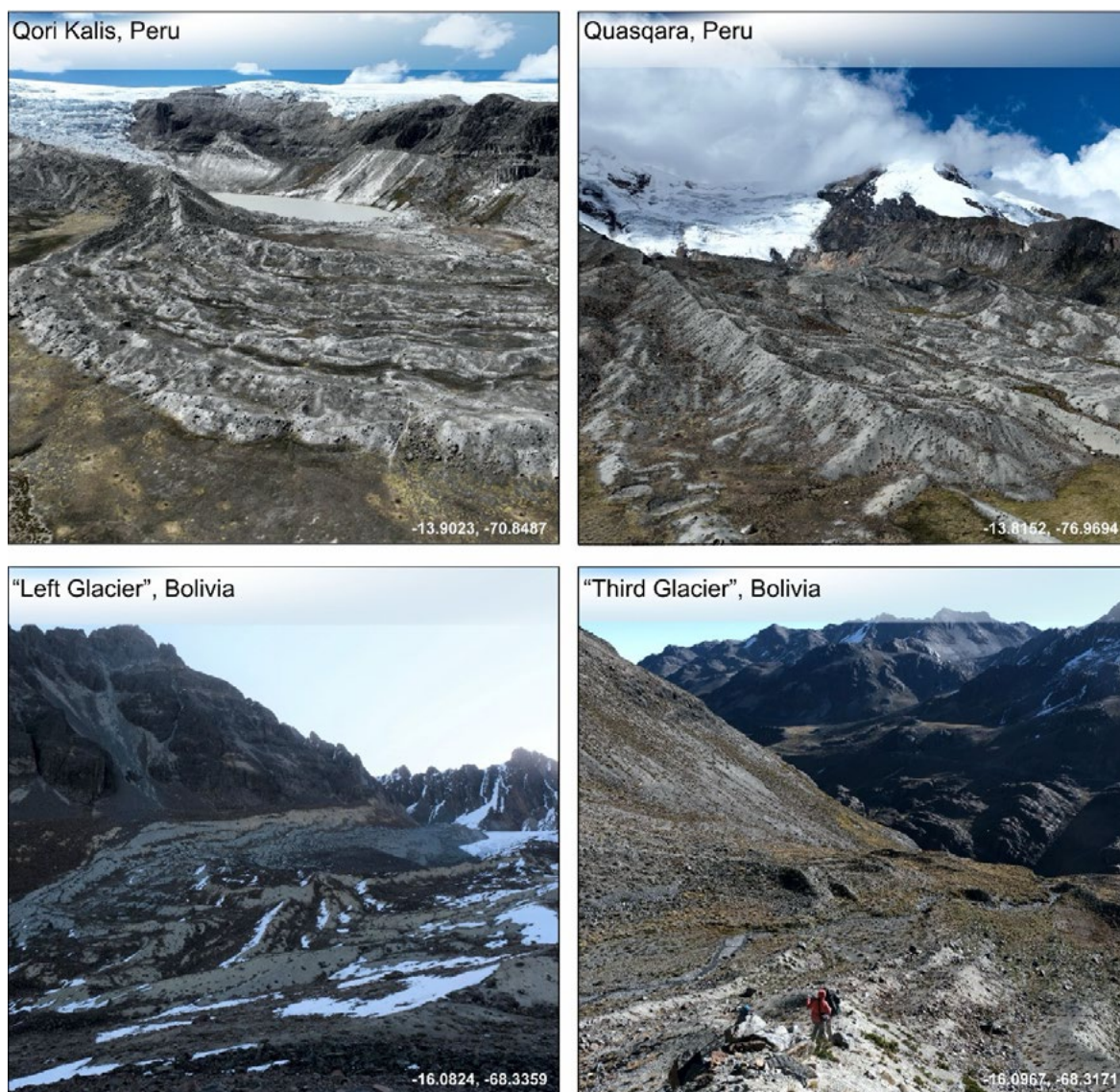
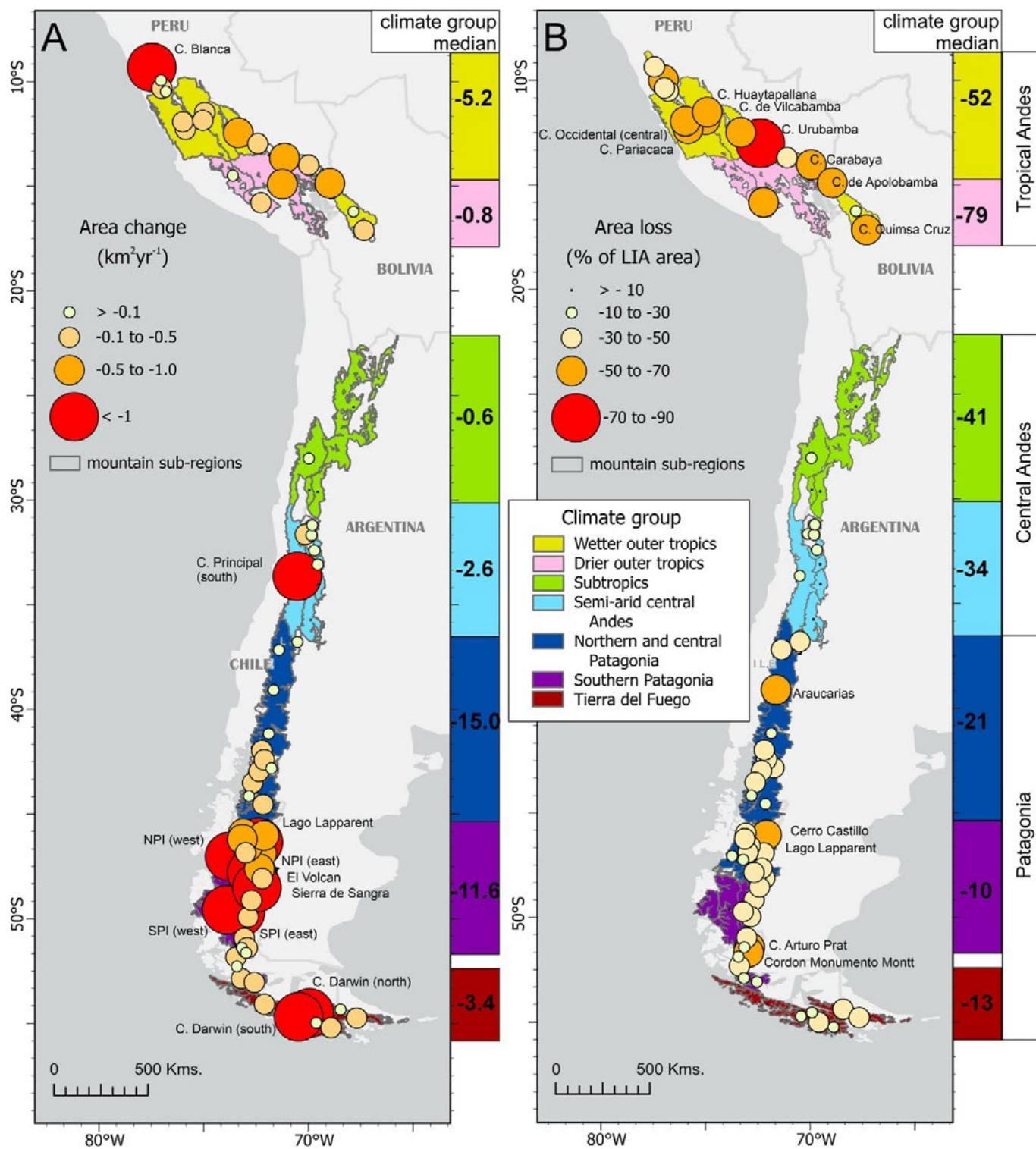


Figure 4. Moraines formed at the margins of tropical glaciers in Peru and Bolivia. From Carrivick et al. (2024).



reconstructing glaciers over longer periods indicates that glaciers in the tropics shrank 10 times faster after the year 2000 than the rate of shrinking, LIA-2000 AD.

High variability in glacier response to global warming indicates that local topography and climate is very important. The absolute rates of area loss are highest from those areas with the highest ice volumes, the Northern and Southern Patagonian icefields, Cordillera Darwin and Cordillera Blanca. The highest proportional rates of glacier area loss occurred in the wetter tropical Andes (Carrivick et al., 2024), demonstrating the strong sensitivity of these glaciers to air temperature. As this rises, it is affecting the phase of precipitation, reducing snowfall, and increasing melt rates through lowering regional albedo as less reflective glacier ice is exposed.

Overall, tropical glaciers have responded the fastest, with the greatest area loss proportionally. This is concerning, because these glaciers are particularly important for water resources. Such tropical glaciers are particularly threatened by warming, and are at risk of largely disappearing by the year 2100 AD.

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Beyond the ice: valuing glaciers in the Tropical Andes

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Sally Rangecroft**

Durham University and
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Caroline Clason is Associate Professor at Durham University, and a glaciologist specialising in glacier hydrology, with interests in both mountain and polar environments. Caroline has conducted research in multiple regions, from the Arctic to the Andes. Her recent research focuses on water resources in glacier-fed catchments, including leading the SIGMA: Peru project, and the transport of pollutants through glaciers and into downstream rivers. Her work applies an interdisciplinary approach to assess the impacts of changing glacier meltwater production for water security and environmental quality under shifting patterns of climate and land use.

Sally Rangecroft is Senior Lecturer at the University of Exeter and an interdisciplinary academic with a physical geography background and expertise in water security, hydrology and glacier retreat in the Andes. She has conducted research in Bolivia, Peru and Chile, investigating the impacts of climate change on the changing cryosphere and water security (e.g. droughts, water quality, food-water-energy nexus). She was the research fellow on the SIGMA: Peru project and led the Nuestro Rio project researching local perceptions of water quality to improve the co-production of knowledge, understanding and solutions for mountain communities in the Peruvian Andes.

Ice at its limits

The Tropical Andes are home to the vast majority of the glaciers within Earth's tropics (Figure 1) however they are already feeling the heat from continued climate change. In 2024, Venezuela was declared the first country to lose its glaciers in the modern era when the Humboldt (La Corona) glacier was reclassified as an ice patch. Numerous other glaciers, such as Chacaltaya glacier in Bolivia, have disappeared in recent years and decades, mirroring the situation in many of the world's mountain glacier regions. Most of the glaciers remaining in the Tropical Andes are restricted to high mountain settings, with the majority found in Peru which hosts ~70% of all Earth's tropical glaciers. But even here glaciers are fast dwindling, with a 56% reduction in Peruvian glacier area between 1962 and 2020 (INAIGEM, 2023). In Ecuador and Colombia only a handful of isolated glaciers remain, many on high elevation volcanic peaks.

In an average year ~2.3 million people in the Tropical Andes consume freshwater containing at least 25% glacier meltwater for one month or more, but during periods of extreme drought this rises to ~3.9 million (Buytaert et al., 2017). Glaciers and the freshwater they produce also provide wide-ranging and valuable ecosystem services, from supporting services such as nutrient cycling and species habitat to cultural services, important for indigenous identity and wellbeing (Figure 2. Clason et al., 2022). Freshwater supply is a crucial yet fragile cornerstone of resource security in the Tropical Andes, and changes to the water supplied by glacier melt intersect with pressures from population growth, hydro-climatological shifts, evolving land use practices, and risks to water quality. Combined with the dynamic nature of social and environmental systems in the region, from political unrest to natural hazards, a future without glaciers is a very real prospect for the Tropical Andes which brings with it a range of cascading challenges.

Frozen water, thawing reserves

Together with snow cover, the glaciers of the Andes and other high mountain regions act as water towers, supporting the downstream populations and ecosystems of multiple major river catchments. Additionally, the Tropical Andes is a region characterised by distinct wet and dry seasons, while also being susceptible to the hydrological extremes of both drought and flooding, with the potential for significant negative impacts on people and the environment alike. As well as being key sources of freshwater, glaciers and glacial landscapes are important buffers for these hydrological extremes. Andean glaciers have long been a source of streamflow, providing meltwater even during the dry

season and playing a particularly important role during periods of drought. While the contribution of glacial meltwater to the water supply of some Andean cities like Lima and Quito is relatively low, this contribution is more significant for other areas, especially highland rural populations in both Peru and Bolivia which are particularly vulnerable to water stress. For example, meltwater contributions vary between 15% to 86% for La Paz (Bolivia) and 19% to 91% for Huaraz (Peru) – two high elevation cities in close proximity to glaciers – under annual average or extreme drought conditions respectively (Buytaert et al., 2017). This contribution is important not only for domestic water supply, but also in supporting both subsistence and large-scale

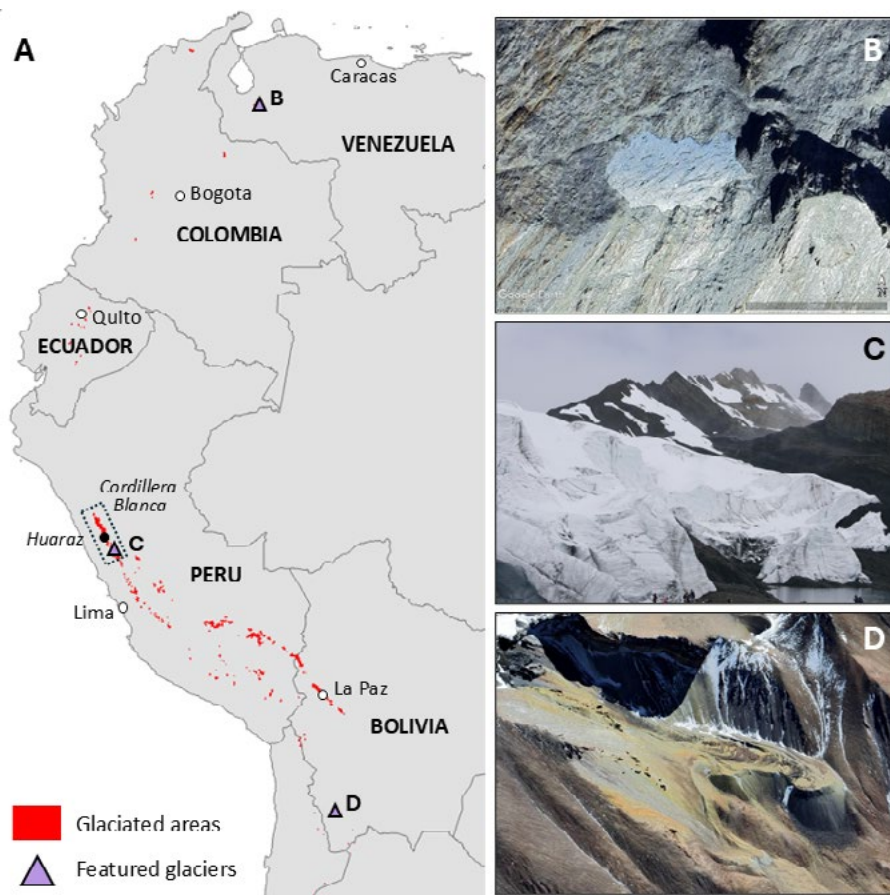


Figure 1. Glaciers of the Tropical Andes. A) Glacier cover based on data from the Randolph Glacier Inventory, with select glaciers illustrated: B) La Corona / Humboldt Glacier, Venezuela (Google © 2024 Airbus); C) Pastoruri Glacier in the Cordillera Blanca, Peru (photo by Sally Rangecroft); and D) Caquilla rock glacier in Bolivia (Google © 2024 Airbus).

agriculture, local industry, and hydropower production which forms an important component of the green transition in countries like Peru. The forelands of glaciers also play a crucial role in the natural management of freshwater resources, with high altitude wetlands (“bofedales” in the Andes) providing valuable water storage, while further acting to reduce flood risk downstream and regulating the cycling of nutrients, carbon and contaminants in glacier-fed systems.

However, many glacial catchments in the Tropical Andes have now reached, or will soon reach, peak water, a critical point in time where the runoff produced by glacier melt reaches a maximum under climate warming and associated glacier retreat.

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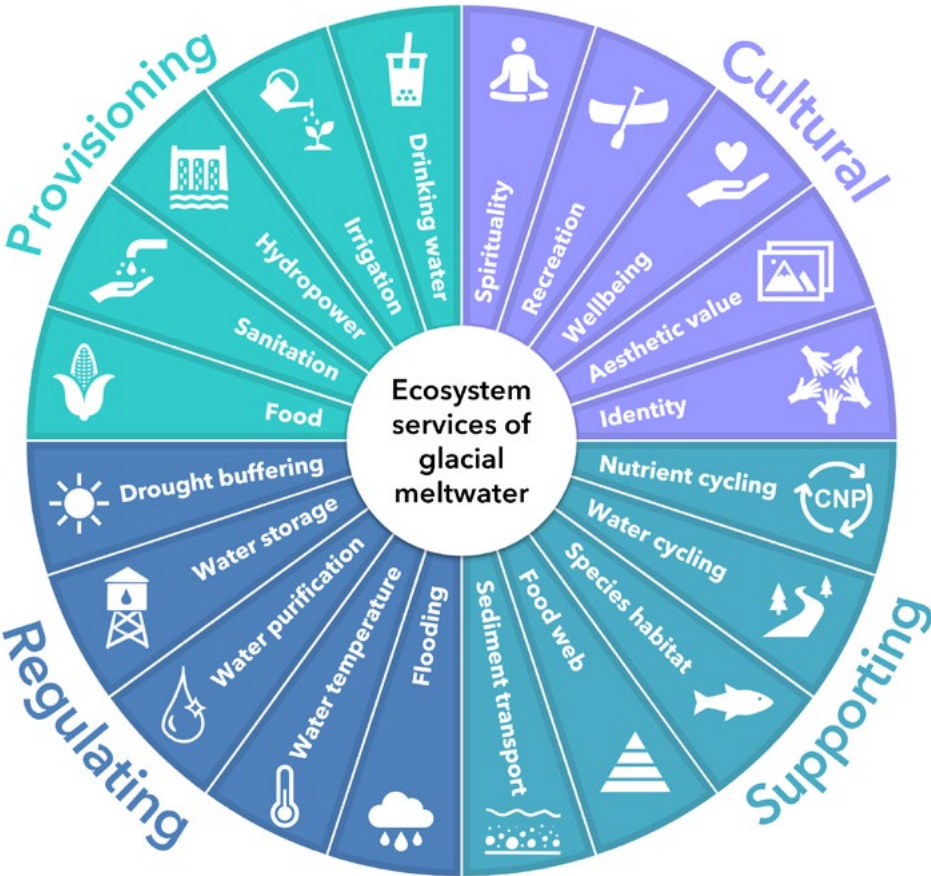


Figure 2. The multiple ecosystem services provided by glacial meltwater in regions such as the Tropical Andes (from Clason et al., 2022).

The proportion of river discharge originating from glaciers will thus decrease in the future as the meltwater produced by shrinking glaciers continues to decline (Figure 3). This will have inevitable consequences for downstream water supply in catchments where meltwater has historically been significant, particularly during the dry season. In addition to visible ice and snow, hidden ice can be found across the Tropical Andes in the form of rock glaciers, debris covered glaciers, and permafrost, which are particularly prevalent in drier regions such as Bolivia (Rangecroft et al., 2015). Rock glaciers typically contain ~40-70% ice, but a surficial layer up to ~5 m thick of rock debris acts as armour, protecting the ice within from rising atmospheric temperatures. This means that rock glaciers respond more slowly than ice glaciers to climate change, such that while

they are currently believed to play a modest role for freshwater supplies in the region, in the future their proportional contribution to river baseflow may be increasingly important. Rock glaciers have historically received considerably less focus than their ice glacier counterparts, so further research is required to assess their true significance in this region.

Not so crystal clear

Water security, the ability of a population to have sustainable access to water for wellbeing, livelihoods and socio-economic development, is not only about having a sufficient *quantity* of water, but access to water of acceptable *quality*. The water quality of glaciated catchments of the Tropical Andes is

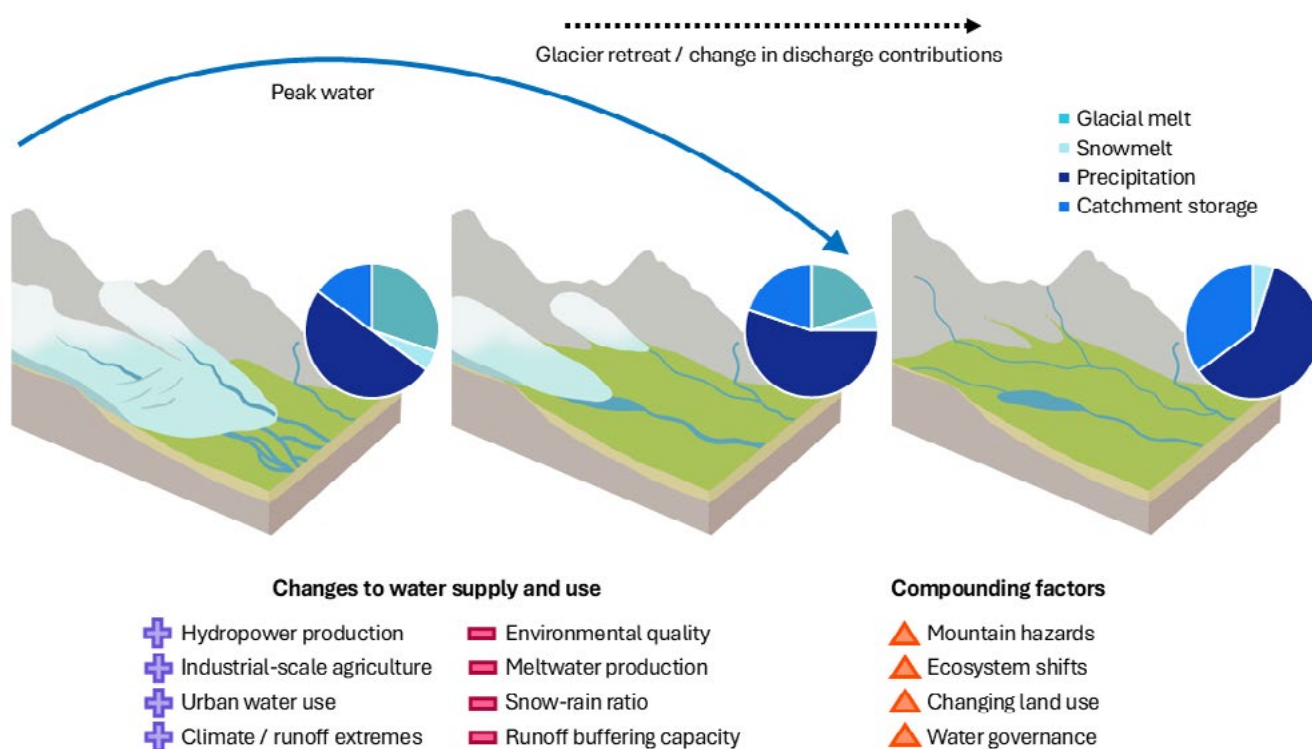


Figure 3. A conceptual model of changing contribution of glaciers to freshwater supply after peak water, and examples of the pressures on that supply from physical processes and human water use. Here catchment storage refers to groundwater, lakes, rock glaciers and other stores.

affected by natural factors such as erosion of rock rich in heavy metals, sedimentation, and mobilisation of contaminants during hydrological events, in addition to human factors such as lack of sanitation and water treatment, mining activities, and agricultural pollution. Much of the research conducted in mountain glacier catchments has focused on measuring changes in the quantity of water or the physical indicators of water quality such as pH, turbidity, and chemical composition. While these parameters provide a quantitative overview of water health, they cannot tell us about nuances in lived experience, nor how water quality affects water usage for those relying upon it. To understand the socio-environmental complexities of water quality, in our recent project *Nuestro Río* (Our River) we worked with local communities to understand the perceptions of and relationship between water users and water quality in Peru's Rio Santa, including glaciated sub-catchments of the Cordillera Blanca (Rangecroft et al., 2023; Figure 1).

Our interdisciplinary project investigated local experience and knowledge of water quality by using a smartphone app to capture images and associated perceptions in both rural and urban communities. Results identified hotspots of poor water quality as experienced by those directly using the water, and perceived drivers of these assessments of water quality. For many rural participants across the Rio Santa one of the commonly identified drivers was natural pollution related to local geology. This phenomenon, known as acid rock drainage, is associated with glacial and fluvial erosion and produces an orange staining and sour taste that means water is unusable for either domestic consumption or agriculture without treatment. In addition to providing understanding of experiences related to water quality across the region, our study assessed the value of using a citizen science approach to knowledge co-creation, highlighting the importance of direct involvement of local stakeholders and the value of traditional ecological knowledge. Potential solutions to these issues have also been explored through work conducted by our project partners INAIGEM and the Instituto de Montaña. This has

included working with rural communities affected by poor water quality to implement nature-based solutions such as bioremediation in wetlands using native flora. Co-developing approaches to local-scale adaptation is of crucial importance for communities who are already experiencing the impacts of changes in water quantity and quality under the intersecting challenges of glacier retreat and shifting land use practices.

After the ice

It is now unequivocal that the Earth will experience warming under all pathways for near-term greenhouse gas emissions, but this will not be felt evenly. Warming will be particularly pronounced in high mountain regions such as the Tropical Andes, where air temperatures are predicted to increase between 1°C to 5°C by 2100, and likely more at the higher elevations where many glaciers are situated (Vuille et al., 2018). There remains considerable uncertainty around future patterns of precipitation in the Tropical Andes, and predictions even differ on whether future changes will be positive or negative. But with a warming climate will come a shift from snowfall-dominant to rainfall-dominant precipitation, which has implications both for storage of water in the snowpack and glaciers and for the timing and variability of downstream runoff. Compounding future changes to annual and seasonal climate is a predicted increase in climatic extremes. Periods of drought are likely to worsen, placing further emphasis on the role of (declining) meltwater in buffering low streamflow, in a context of a future where demands on water will likely increase. Furthermore, flooding associated with both extreme precipitation and glacial lake outburst floods (GLOFs) poses challenges for the security of populations and key water and energy infrastructure. There is also the possibility that extreme El Niño events will increase in frequency under future warming. These events have been associated with increased suspended sediment yields in the Peruvian Andes, further compounding issues of water quality (Morera et al., 2017).

Such climate-related challenges add to the already pressured reliance on meltwater for a stable freshwater supply in the Tropical Andes, essential for water, food, and energy security. Transdisciplinary research which incorporates local expertise and lived experience will be necessary to navigate the challenge of balancing water supply and demand in a region where meltwater contributions are dwindling, patterns of food and energy production are shifting, and land use is evolving. Holistic water governance will be crucial for resource security under the reality of decreasing meltwater contributions post-peak water, yet there are multiple challenges for the implementation of policy and adaptation measures.

The inclusion of local stakeholders within decision-making processes and removal of social, political and technical bottlenecks will be key for successful water management which recognises the multidimensional nature of water, both social and ecological (Dextre et al., 2022). Furthermore, future climate adaptation and mitigation must consider the central role of glaciers – socially, culturally, and environmentally – within the lives of communities at the front line of this rapidly changing region. Researchers, practitioners and communities of the Tropical Andes will need to think not only *beyond the ice*, but also *after the ice*.

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Alaska's top-heavy glaciers are approaching an irreversible tipping point

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Introduction

The world's glaciers are in trouble. Rising temperatures (Climate Action Tracker, 2024) and end-of-summer snowlines (Larocca et al., 2024) are having a catastrophic impact, with several feedbacks accelerating melt. Climate-driven ice loss from glaciers and icefields has been shown to contribute to rising sea-levels, with Alaska expected to remain the largest regional contributor to this effect up to the year 2100 (Rounce et al., 2023). Once a threshold is passed, these feedbacks can accelerate melt and drive self-perpetuating loss of snow and ice. Juneau Icefield, straddling the Alaska-Canada border near the city of Juneau in Alaska (Figure 1), is an example of how feedbacks are accelerating glacier melt (Davies et al., 2022; Davies et al., 2024).

Juneau Icefield, Alaska has a smooth, flat plateau in its upper reaches (Figure 2A&B). Alaskan icefields like this are particularly vulnerable to changes in the climate because they are often top-heavy (with more area at a higher altitude) and located on plateaus. In addition, these factors make Alaskan glaciers more prone to threshold behaviour, in which exceeding a tipping point could result in an irreversible recession. Longer-term records of Alaskan glacier change are needed to understand how climate change impacts these glaciers.

Our research has shown that, as a result of rising end-of-summer snowlines, this flat plateau of Juneau Icefield is indeed now melting each summer, causing strong thinning across the icefield. The melting of these glaciers has, therefore, accelerated and could soon reach an irreversible tipping point.

Methods

To investigate the operation of these melt-accelerating feedbacks and their control on glacier shrinkage, ice loss was measured from the end of the last "Little Ice Age" (~1770 AD, about 250 years ago) to the present day.

Satellite records have traditionally been used to reconstruct past glacier behaviour, but this limits the record of observations to the last 50 years. To go back further, different methods are required. To reconstruct the extent of glaciers 250 years ago, we mapped the ridges of moraines (Davies et al., 2022) deposited at the glacier snout (Figure 2H), and places where glaciers have scoured and polished the bedrock from satellite imagery (Figure 2G). To check and build on our remotely sensed mapping, we spent two weeks on the icefield and two weeks working in the rainforest at the glacier margins.

To reconstruct the icefield in the 1940s and 1970s, in the era before readily available satellite imagery, we used aerial photographs (Figure 3). These are high-quality but flown before global positioning systems made it easy to locate them spatially. A number experienced some minor damage in the intervening years; some Sellotape, a tear, a thumb print. The consequence was similar to undertaking the world's hardest jigsaw puzzle; the individual images had to be stitched together to make a 3D picture of the whole icefield. We then used satellite imagery to reconstruct the ice extent and volume change from the 1990s to 2020.

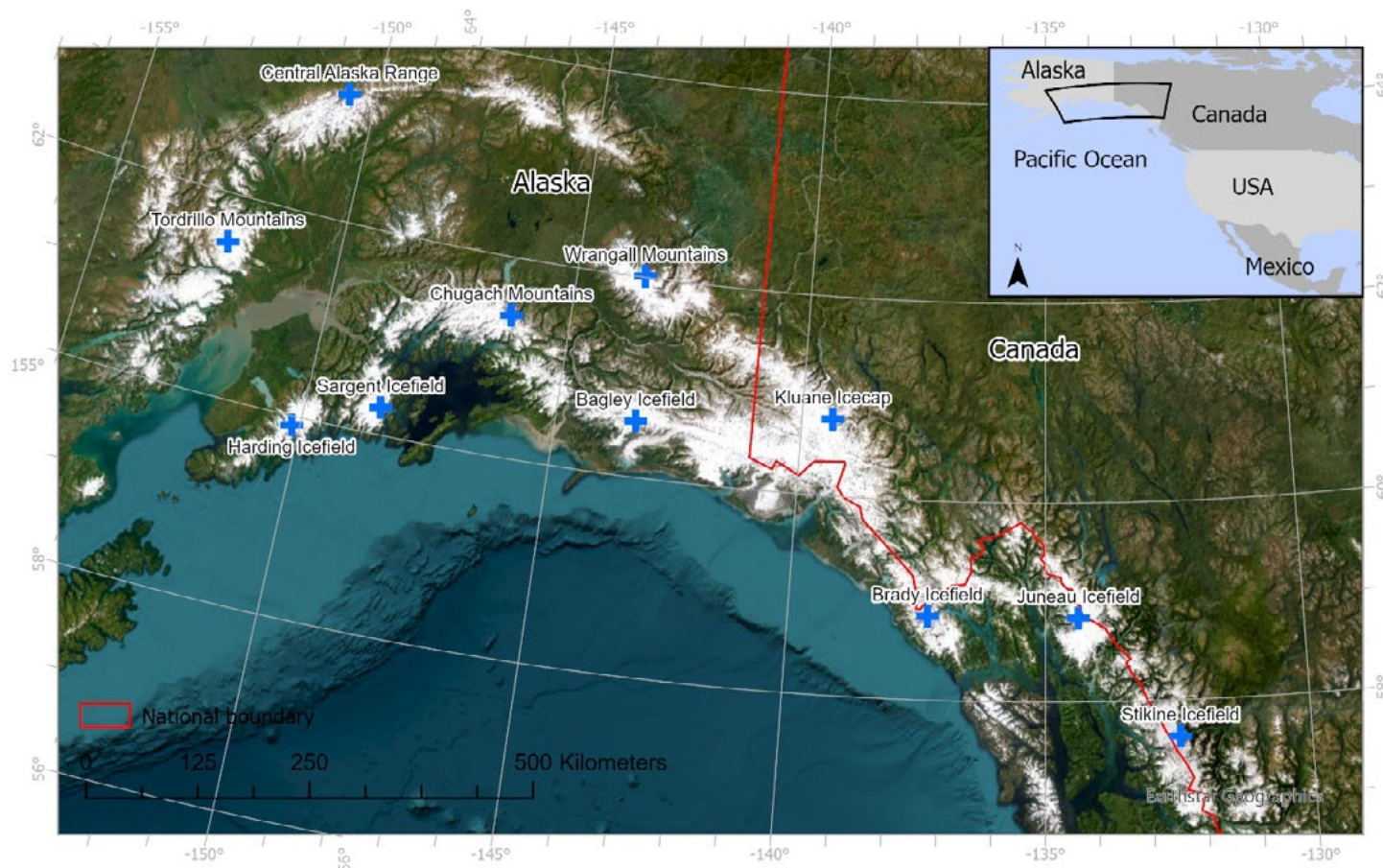


Figure 1. Glaciers and icefields in Alaska and Canada

Glaciers and Ice Sheets in a Warming World: Impacts and Outcomes

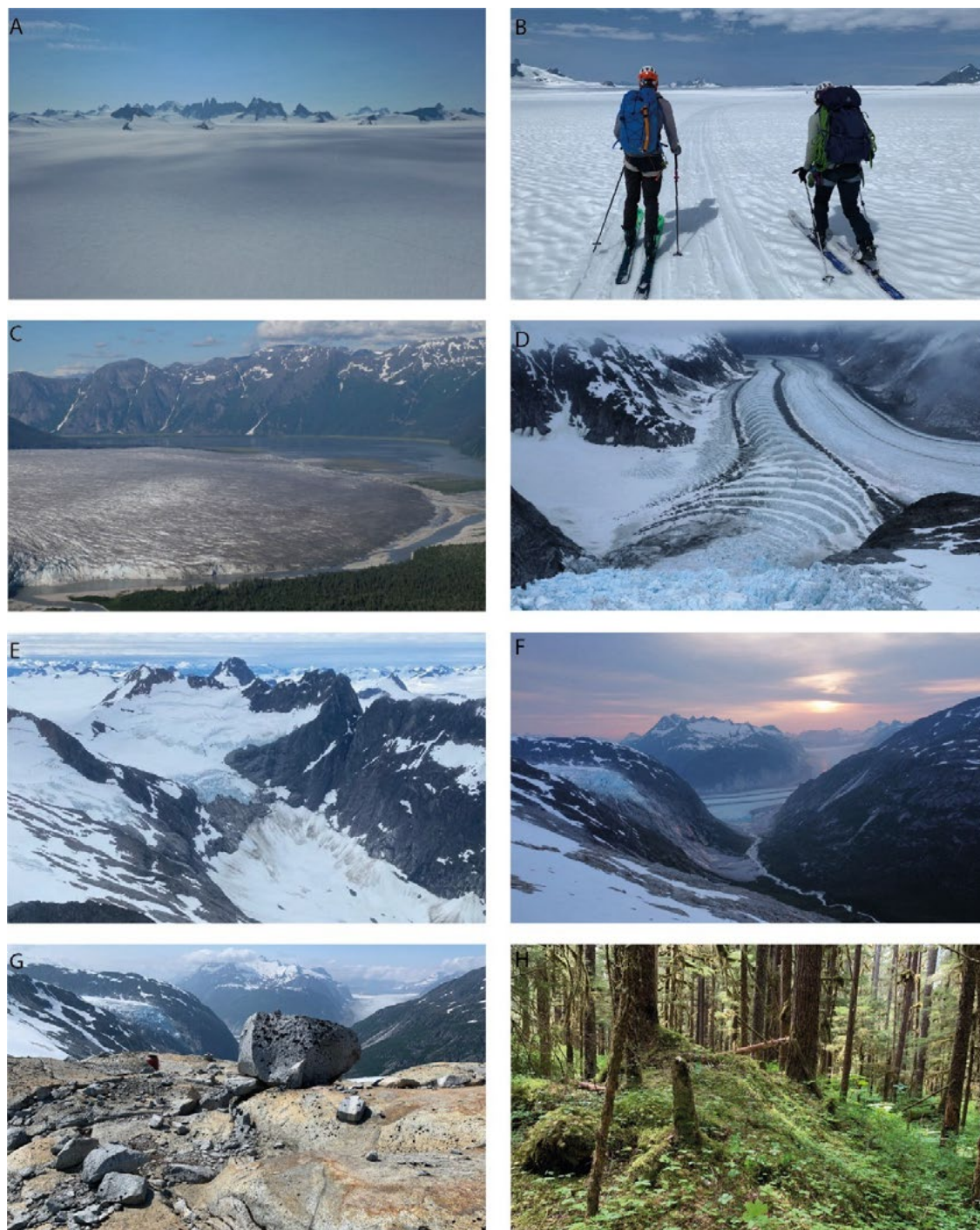


Figure 2. Field photographs from Juneau Icefield in 2022 (Davies et al.)

- A. The plateau accumulation area.
- B. Skiing across the plateau of Juneau Icefield with the Juneau Icefield Research Project.
- C. The lobate terminus of Taku Glacier.
- D. The Vaughan Lewis Icefall, Gilkey Glacier, Juneau Icefield.
- E. Fragmentating, disconnecting glaciers of Juneau Icefield.
- F. Avalanche Canyon, a glacially scoured valley, with Gilkey Glacier in the background.
- G. Ice-scoured bedrock and glacially transported boulders, above Avalanche Canyon. Gilkey Glacier is in the distance.
- H. Moraines in the rain forest at the terminus of the glaciers.

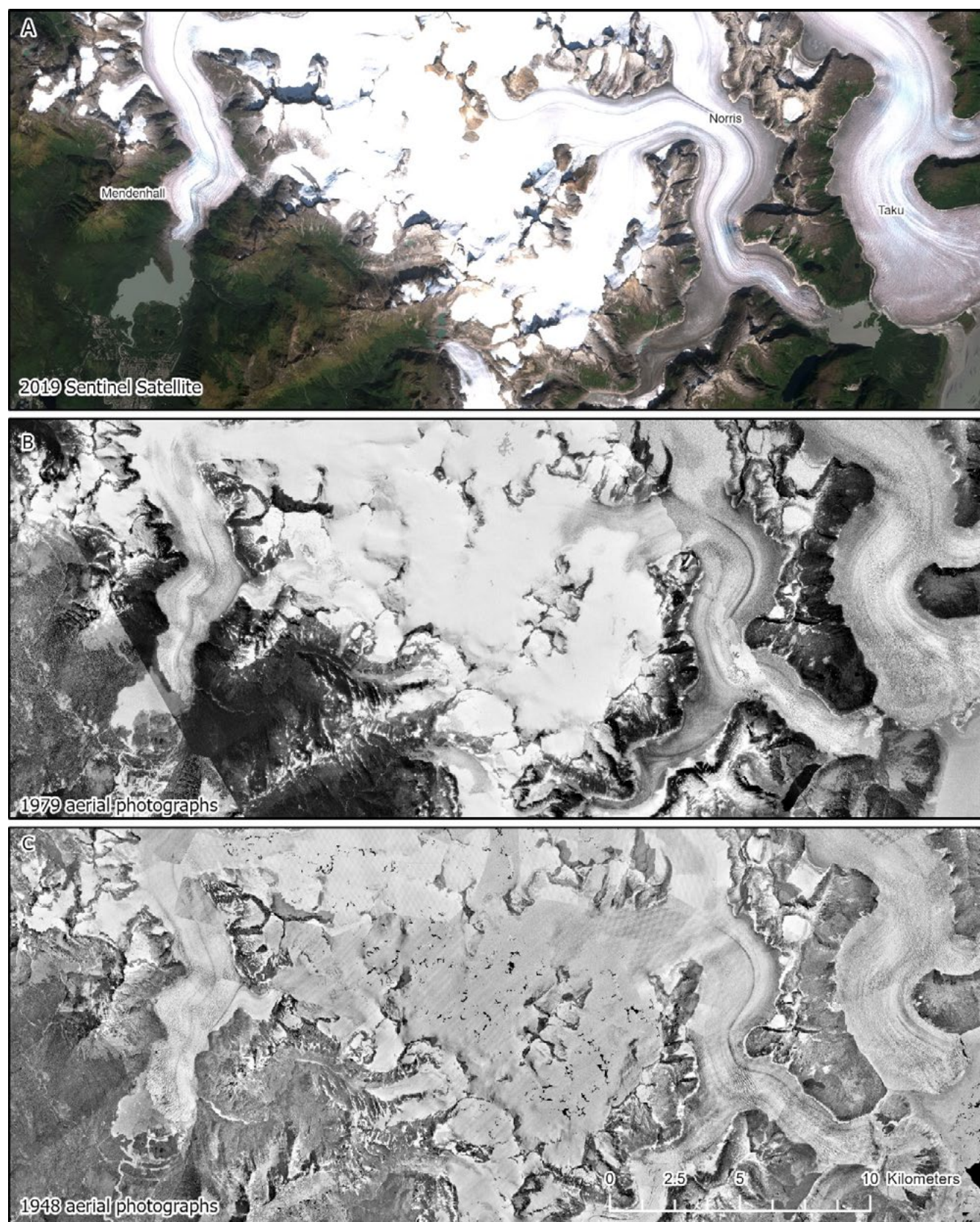
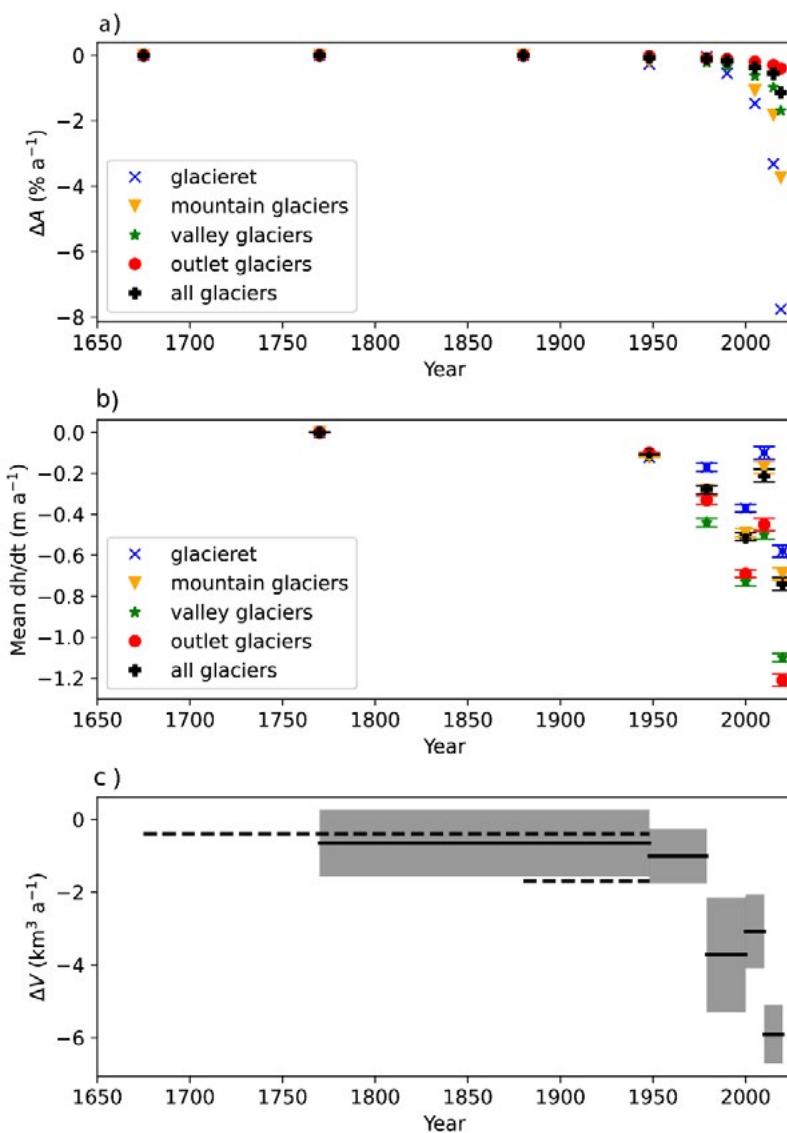


Figure 3. Image A (top) is a recent satellite image; images B and C (middle and bottom) are archival aerial photographs used to reconstruct Juneau Icefield in 1948 and 1979.

Results

We observed that the glaciers began shrinking after the “Little Ice Age”, which ended in about 1770 AD. The rate of ice loss remained constant until about 1979, when it accelerated. It accelerated again in 2010 AD, doubling the previous rate. Glaciers here shrank five times faster from 2015–2019 than from 1979 to 1990. We observed steady glacier volume loss at approximately 0.65 km³ per year between 1770–1979 (Figure 4). This rate

accelerated to approximately 3 km³ per year between 1970–2010 and then doubled to 5.9 km³ per year between 2010–2020. This ice loss acceleration between 2010–2020 was accompanied by a glacial thinning rate 1.9 times higher than that from 1979–2000 and increased icefield fragmentation. Overall, the icefield has been shrinking faster over the last 10 years than at any time in the last 250 years.



“

Glaciers here shrank five times faster from 2015–2019 than from 1979 to 1990.

”

Figure 4. a) Change in glacier area (percentage per annum) for different kinds of glaciers. b) Mean thinning (dh/dt) for each type of glacier through time. c) Glacier volume loss. Dashed lines indicate calculations for an earlier and later date of the Little Ice Age, respectively. Glacier types classified according to GLIMS (Glacier Land Ice Measurements from Space) protocols (Paul et al., 2010).

This thinning has set off a chain of different topographically controlled feedback processes, driving a non-linear acceleration in icefield shrinkage and volume loss across the plateau. A continuation of this trend could push glacial shrinkage beyond the brink of possible recovery.

Our data show that as the snow decreases and the summer melt season lengthens, the icefield is darkening. Fresh, white snow is very reflective, and more of the strong summer solar energy is reflected into space. However, the end-of-summer snowline is rising and is now occurring on the low-slope plateau of Juneau Icefield (Davies et al., 2024). The rising snowline means that older snow and glacier ice is exposed, resulting in a gradual darkening of the icefield. These

slightly darker surfaces absorb more energy, increasing snow and ice melt and driving thinning.

The rising snowlines and glacier equilibrium line altitudes are also responsible for the increased fragmentation of the icefield. As the snowlines rise they intersect areas of steep, heavily crevassed ice; these icefalls (Figure 2D) are common around the edge of the plateau accumulation area. Such icefalls are thin and form a point of vulnerability for the glaciers draining from the plateau. Thinning at these icefalls rapidly exposes bare rock within the glacier, resulting in an along-flow disconnection between the valley glacier and the accumulation area (Figure 2E). These disconnections are occurring increasingly rapidly as the snowline rises to intersect their mean altitude at the edge of the plateau (Figure 5).

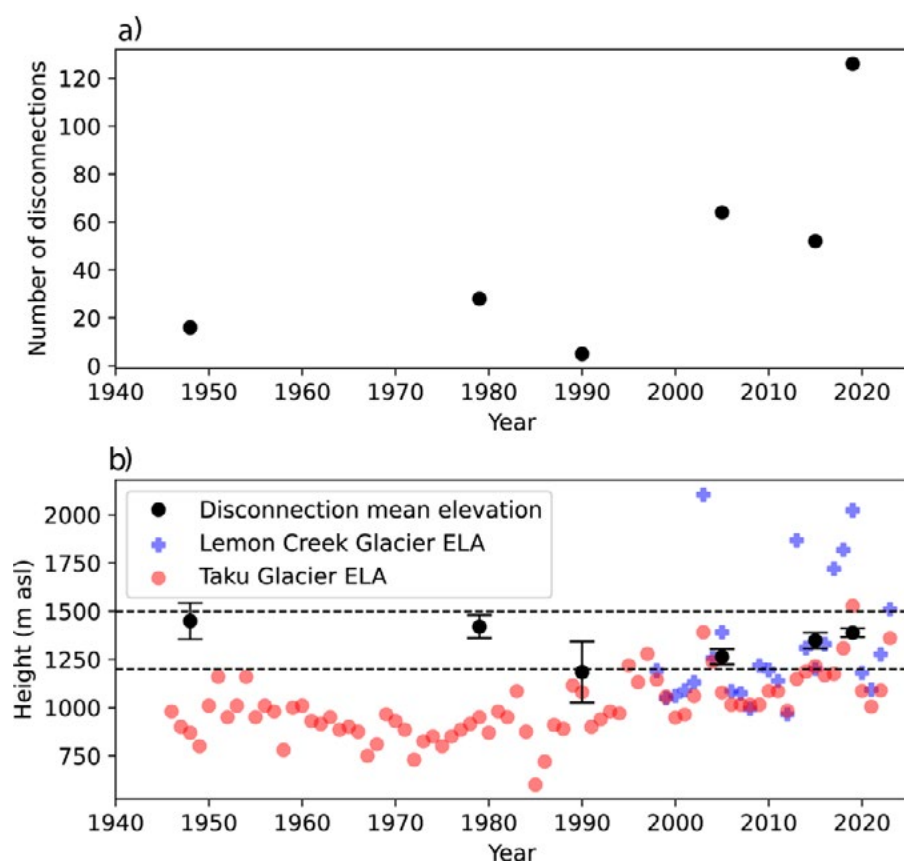


Figure 5. a) Rising numbers of glacier disconnections through time. b) Snowlines and glacier equilibrium line altitudes are rising across the icefield and increasingly intersecting the elevation of the plateau (dashed lines indicate lower and upper plateau, respectively).

The lowering surface elevation across the icefield makes it increasingly difficult for the recession to stabilise or even recover. As the plateau of the icefield thins and the ice surface lowers, ice and snow reserves at higher altitudes are lost. Warmer air temperatures at low elevations drive further melt, leading to an irreversible tipping point, even if warming stabilises. Longer-term datasets like this are critical to understand the variability in glacier behaviour, and the sensitivities, processes and tipping points that exist within individual glaciers. These complex processes make it difficult to predict the future of glacier behaviour.

The world's glaciers all together currently lose more mass than the Greenland or Antarctic ice sheets, and thinning rates of these glaciers worldwide has doubled over the last two decades (Hugonnet et al., 2021). Our longer time series shows how stark this acceleration is. Understanding how and where feedback processes are amplifying melt is essential to make better predictions of future glacier change in this important region.

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Front of the Ross Ice Shelf, Antarctica
(cliffs are 20-60m high). ©David Drewry

Ice Caps and Ice Sheets

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From ice sheet to ocean: local to global impacts
of Arctic iceberg hazards

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University of Liverpool

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to help constrain our uncertain future

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From ice sheet to ocean: local to global impacts of Arctic iceberg hazards

James M. Lea

University of Liverpool

James Lea is Professor and a glaciologist at the University of Liverpool, with 15 years' experience researching the past, present and future evolution of Arctic glaciers and ice sheets. His primary research interests are in understanding the dynamics of marine terminating glaciers and how their behaviour has environmental and social impacts at local to global scales. He has been a pioneer in the application of cloud computing approaches to large scale analysis of satellite imagery within glaciology, and in the development of tools to make these more accessible for the wider environmental science community.

Icebergs large and small can pose significant hazards. While the most famous example is the sinking of the Titanic in 1912, damaging iceberg collisions still occur with vessels of all sizes including small boats, commercial shipping and large tourist cruise liners.

However, icebergs are not only risks to boats and ships. They also pose hazards to people, static infrastructure, settlements and archaeological heritage, as they physically collide with and damage structures, erode coastline, and generate tsunamis of several meters as they capsize.

These hazards are set against a context of an increasingly busy and globally connected Arctic. The Northwest Passage and the Northern Sea Route are becoming more easily navigable to commercial shipping, Arctic cruise tour traffic is increasing, and the global demand for critical minerals from the Arctic region (particularly Greenland) in areas of ice-affected waters, is expanding.

To help understand and mitigate these risks our research has concentrated on icebergs calving from the Greenland Ice Sheet; specifically the controls of their formation, size, production rates, and trajectories. Such studies will enable us to anticipate how these factors may evolve into the future.

This work is of increasing importance as glaciers that produce icebergs are experiencing conditions and behaviour that have no modern analogue. One such area is around Greenland's largest port and capital city, Nuuk, where we have worked for nearly 15 years to understand iceberg calving processes and fjord ice conditions on timescales of days to centuries (Figure 1).

Significant changes in iceberg risks do occur

Over longer timescales (the last 1,000 years), our research has been able to reconstruct glacier and iceberg behaviour in this part of Greenland showing that calving behaviour has changed dramatically. This was achieved by combining evidence from satellites, historical photographs, diary entries of colonial settlers, landforms, sediments and even archaeology from the Greenland Norse (Pearce, Lea, et al., 2022).

This work has demonstrated dramatic changes in these iceberg producing systems. Their extent is such that parts of the fjord that are currently inaccessible by small boats were once navigable by the Norse 800–1,000 years ago, highlighting future changes in glacier behaviour will likely result in shifts in ice cover regimes in nearshore/fjord regions of Greenland and elsewhere in the Arctic.

Harnessing cloud computing for research and education

Closer to the present day where we can observe glacier change and fjord ice conditions from satellite imagery, we have pioneered the use of cloud-computing-driven analysis of glacier change, dramatically accelerating the rate at which data can be obtained (Lea, 2018). Alongside, we have evaluated different methods of measuring changes and demonstrated how researchers

may use different techniques depending on the scientific questions that they are asking.

These advances have allowed one of the first ice sheet-wide assessments of iceberg producing glacier change during the satellite era (Fahrner et al., 2021) and enabled detailed studies of glaciers along the southeast Greenland coastline (Brough et al., 2023). The datasets have subsequently set the standard format for an international community-led compilation of data that is now being widely used by glaciologists to address a range of scientific questions (Goliber et al., 2022).

The tools associated with these studies have demonstrated value beyond academia; they are now used extensively in the UK and international undergraduate environmental science teaching. The ease of use and speed of analysis they afford have helped to improve the accessibility of otherwise unwieldy underlying datasets, aiding the next



Figure 1. Icebergs at the glacier front of Narsap Sermia, SW Greenland, in May 2022. Narsap Sermia has a relatively shallow ice front (approximately 200m deep) and is medium-sized outlet of the Greenland Ice Sheet (measuring 4 km across). It currently produces icebergs up to 250m across that drift through the fjord towards Nuuk. [Credit: David Ashmore]

generation of researchers to have enormous volumes of data at their fingertips.

On the individual glacier scale, using cloud computing has allowed us to capture the finer details of the conditions that contribute towards iceberg formation. This has been achieved through novel use of extremely high spatial resolution satellite data (Fahrner et al., 2024), and application of new methods to understand how spatial patterns of glacier velocity and crevasse formation can change dramatically as a glacier begins to lose more ice through iceberg calving (Van Wyk De Vries et al., 2024). These studies have revealed the spatial scales over which computer models need to simulate processes in order to capture iceberg calving behaviour and allow future projections.

Assessing present day iceberg risks

These studies, however, deal only with the conditions leading up to iceberg formation rather than what happens to the icebergs themselves. To understand what occurs after iceberg calving, our group developed a new, automated approach to quantifying iceberg populations using many thousands of digital maps of iceberg heights above the waterline (Shiggins et al., 2023). This has been successful in generating a dataset of more than one million icebergs around Greenland that is currently being prepared for publication, providing a comprehensive “snapshot” of the size and distribution of icebergs around the ice sheet.

For the day-to-day evolution of fjord ice distribution that is most useful for those who frequently use the waters of Nuuk Fjord, we have recently developed a

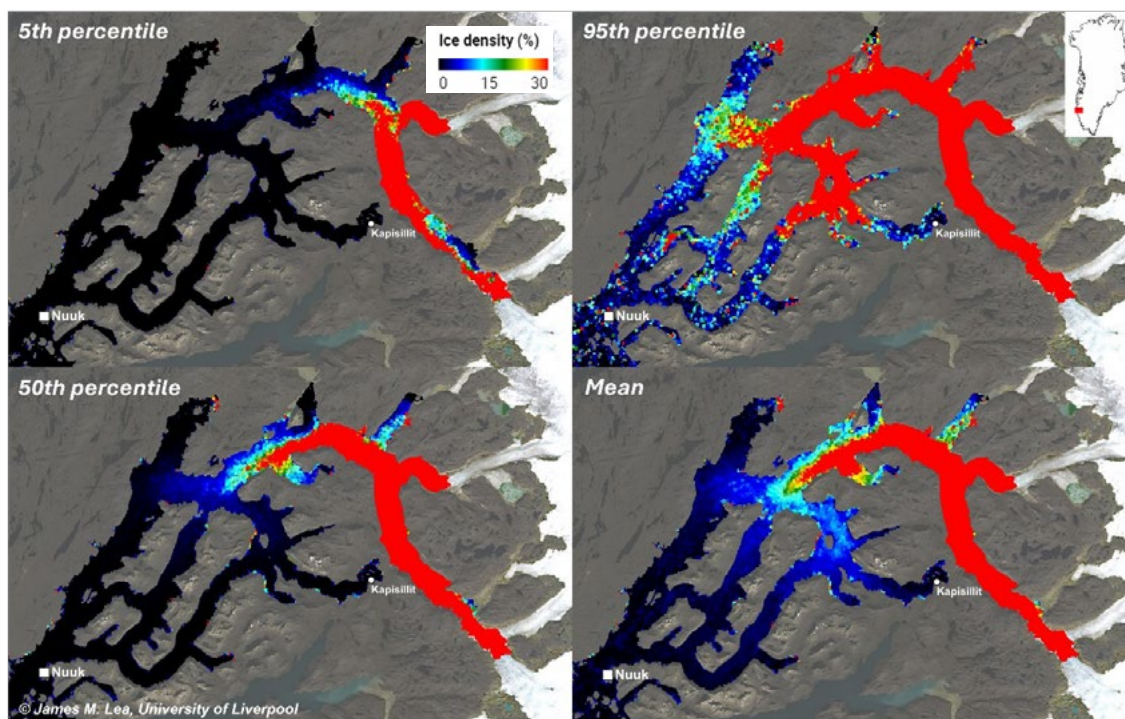


Figure 2. Maps showing different ice cover extents for Nuuk fjord for the month of July for 2016-2024 (colours ranging from 0% to >20%). These results are made up of 164 days of observations of the fjord from 223 satellite images. The whole record summarising monthly conditions from January to December comprises 1229 days of observations derived from 1515 satellite images. Similar maps of nearshore/fjord ice conditions are being created for the whole of Greenland and the wider Arctic.

proof-of-concept user interface that allows an internet connection to access the latest observations via mobile phones (<http://tiny.cc/nkicemobile>). Working alongside Greenland-based Asiaq Greenland Survey, the availability of this method is currently being extended to the entire Arctic, with the intention that seasonal ice maps at this scale will allow for improved long-term planning of activities in nearshore iceberg affected waters (Figure 2).

Outlook: the policy need to deal with iceberg risks

As the Arctic becomes increasingly busy, the need for these datasets and research is growing so that they can be linked to best practice shipping guidance and policy on infrastructure development. This is especially the case for coastal regions and fjords where many sea ice map products either do not have coverage or are resolved at spatial resolutions that are too coarse to be useful.

High impact events arising from iceberg hazards in Arctic waters, potentially with considerable loss of life or environmental damage, are not only possible but (arguably) probable. This arises because of the lack of adequate data and understanding of iceberg hazards. Despite the increase in global connectedness, many threatened areas remain geographically remote and have limited search and rescue or rapid disaster response capabilities.

Our work is focussed on the glaciological understanding of how and why these risks will evolve. Minimising risks, however, will require development and extension of policy, regulation and guidance at national and international level. We propose that this is needed, and would be willing to contribute our experience to ensure that future measures are informed by the best possible science.

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Subglacial Lakes at Isunnguata Sermia, west Greenland – Dynamics and Evolution (SLIDE)

Stephen Livingstone and Elizabeth Bagshaw

University of Sheffield and
University of Bristol

Stephen Livingstone is a professor and glaciologist at the University of Sheffield who uses remote sensing, geophysics and glacial geomorphology to investigate the drainage and storage of meltwater through past and contemporary ice sheets. He is Principal Investigator on the SLIDE project.

Elizabeth Bagshaw is at University of Bristol and has worked on hydrology and biogeochemistry in the polar regions for 20 years, understanding relationships between glacier melt and ecosystem processes and developing new sensors. She is a Co-Investigator on the SLIDE project.

Introduction

The SLIDE team is working in Greenland to investigate lakes that are hidden from sight beneath the ice sheet (also known as subglacial lakes). These lakes exist due to the pressure and insulating effect of ice from above, geothermal heat from below and drainage of a large volume of water from the surface to the bed through cracks in the ice (Livingstone et al., 2022).

There is mounting evidence to suggest that subglacial lakes that fill and drain are common and dynamic components of the hydrological system underneath the ice sheet (Bowling et al., 2019; Livingstone et al., 2022). Until recently, however, they have been largely ignored. Therefore, the key processes controlling how lakes under the ice sheet form and drain, and their impact on other components of the hydrological system (e.g. channels and cavities), and ice flow have yet to be identified. Thus, the current and future importance of subglacial lakes is unknown.

The SLIDE project addresses this research gap through a dedicated field campaign using geophysical sensors and remote sensing to characterise and monitor multiple subglacial lakes beneath Isunnguata Sermia. These results will be used to constrain a numerical model to determine their impact on the future mass balance of ice sheets.

Aims

Our investigation is focused on four subglacial lakes beneath Isunnguata Sermia, a large glacier in south-western Greenland. It drains a catchment of 16,000 km² extending to the centre of the ice sheet and is 400–800 metres thick, moving at a rate of about 120 metres per year in the region of investigation, close to where it terminates in a large valley (Figure 1).

The four lakes were serendipitously discovered from satellite imagery, which revealed regions of the ice surface ('bullseyes') about 1 km wide that were slowly uplifting over a number of years before subsiding rapidly by as much as 30 metres over a few weeks to form a surface depression (Livingstone et al., 2019) (Figure 2). We interpreted the uplift as a result of the

lakes slowly filling, pushing up the ice, as they capture water draining from the surface through cracks and from under the ice. The ice-surface collapses downwards when the lake drains rapidly resulting in a downstream flood and a subsequent flow of water from the front of the glacier.

We have chosen to focus on these lakes due to their location close to the ice margin, the availability of logistical support and airport, enabling a research programme of low risk and cost. Such access to multiple lakes beneath relatively thin ice (350-500m) provides an opportunity to characterise the system in detail.

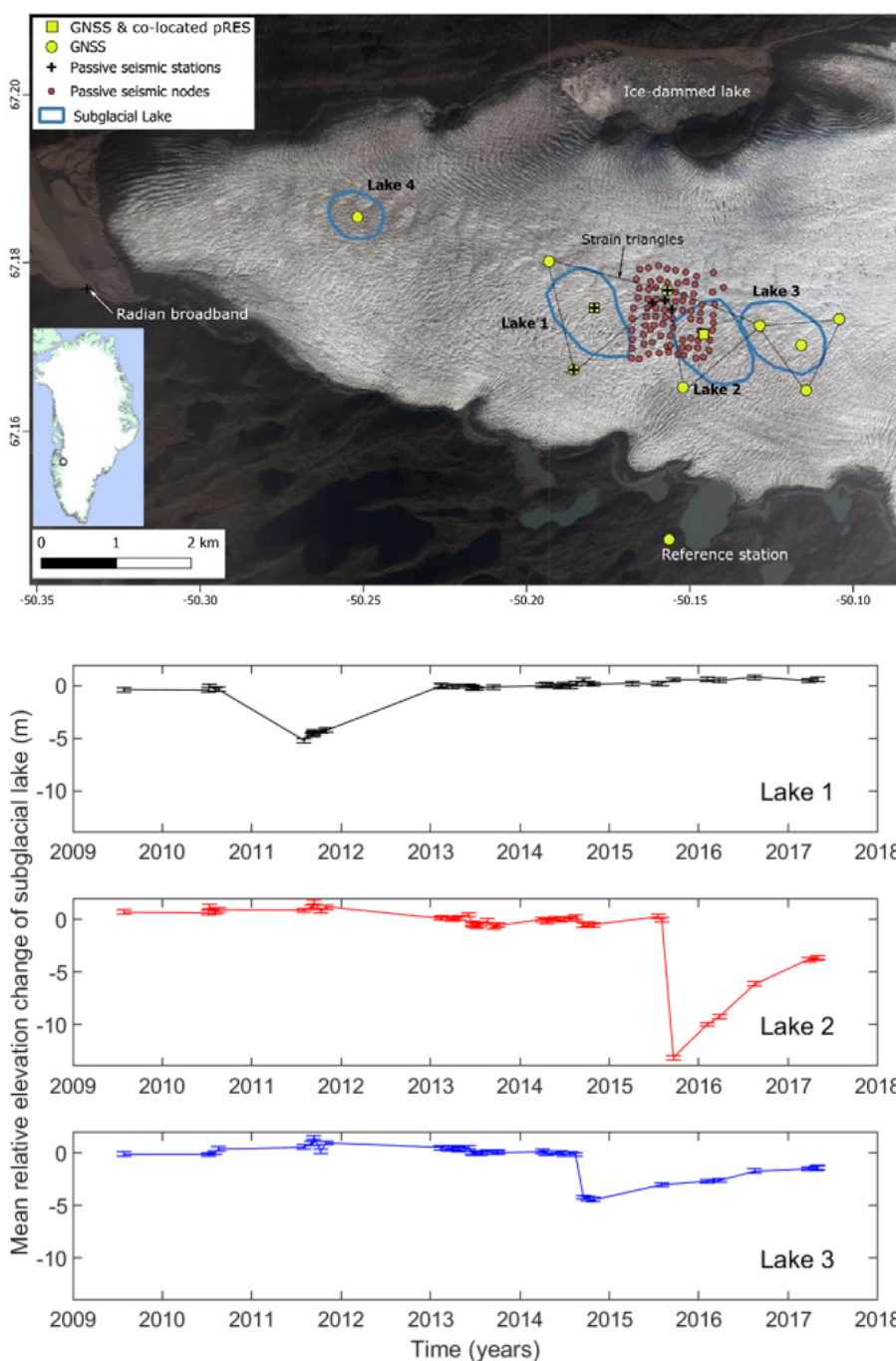


Figure 1. The location of Isunnguata Sermia on the west coast of Greenland, and the 2023 deployment of long-term monitoring equipment on top of and surrounding the subglacial lakes. This includes, i) Global Navigation Satellites (GNSS) to measure very precisely how the ice flows and is displaced up and down by the flow of water and filling and draining of lakes underneath, ii) passive seismic stations to listen to the sound of water flow under and exiting the front of the glacier. Radar and active seismics were used to image the bed and lakes under the ice, drone surveys carried out to repeatedly map the ice surface at centimetre scale resolution and wireless sensors (Cryoeggs) deployed down cracks in the ice to relay information about the lakes and water transport through the plumbing system.

Figure 2. Timeseries of ice-surface elevation change from 2009-2017 above three of the lakes (from Livingstone et al., 2019). The ice-surface rapidly drops and then slowly recovers above each lake (e.g., in 2015 for Lake 2), interpreted as recording lake drainage followed by refilling.

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Our investigation is focused on four subglacial lakes beneath Isunnguata Sermia, a large glacier in south-western Greenland.

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Figure 3. The SLIDE team installing and maintaining science equipment on Isunnguata Sermia. Credit: Scott Crady (Scott Crady Photography)

Objectives

1. Determine the physical properties of the subglacial lakes and their surroundings.
2. Quantify how the subglacial lakes evolve through time and how they interact with the surrounding hydrological system and overlying ice.
3. Constrain and test a catchment-scale subglacial hydrological model to apply to a realistic range of synthetic catchments.

Fieldwork

The SLIDE team have deployed over 200 scientific instruments on the glacier over three years (2023 to 2025), (Figure 3). This has involved a team of 30 UK and French scientists, with more than 700 person-days in the field.

Modelling

Once all the field data have been collected the information will be used to build up a picture of how water is moving and being stored under the ice and the influence it has on ice flow. To help do this a numerical model will be employed to assist understanding of the wider effect of the subglacial lakes and water flow. This will be accomplished by simulating a range of scenarios that might represent different areas of Greenland or a warming world – for example, by increasing the amount of melt or making the ice thicker or flatter – to evaluate their impacts.

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The effects of climate change across the Antarctic Ice Sheet: implications for global sea levels

**Robert G. Bingham and
Helen Ockenden**

University of Edinburgh

Robert Bingham is Professor of Glaciology and Geophysics at the University of Edinburgh. His principal research addresses the causes and pace of polar ice-sheet change, and the contributions of polar ice sheet to global sea levels. Recent research has included radioglaciological surveying of West Antarctica as part of the International Thwaites Glacier Collaboration, and leadership of AntArchitecture, an international project building a 3-D age-depth model of Antarctica's ice.

Helen Ockenden is a post-doctoral researcher at the Institut des Géosciences de l'Environnement in Grenoble, France. Her research focuses on improving boundary conditions for modelling the behaviour of Antarctic ice sheets. During her PhD at the University of Edinburgh, she worked on methods for mapping subglacial topography and geomorphology in the interior of Antarctica. Her current research explores ways to improve neural network emulators of sub-ice-shelf melting to facilitate more efficient coupling between ice sheets and oceans in global climate models.

Glaciologists at the University of Edinburgh are studying how climate change impacts the Antarctic Ice Sheet and the consequences for world sea levels. Our investigation techniques combine satellite remote sensing with airborne and ground-based geophysical techniques, notably radio-echo sounding. This article first explores how we have used satellite remote sensing to monitor the degree to which warming in the atmosphere and ocean is causing coastal ice around Antarctica to retreat. It then outlines how we have used radio-echo sounding and satellite measurements to constrain the shape of the bedrock upon which the Antarctic Ice Sheet sits, which represents vital knowledge for numerically modelling the ice sheet's future in the face of ongoing climate warming. The final part explains developing work that plans to use the internal structure of the ice as a further important constraint on how changes to the ice sheet in response to past and projected future climate change have impacted and will impact again upon sea-level rise.

Ice retreat around Antarctica's coast from satellite remote sensing

Satellite remote sensing has revolutionised our understanding of polar ice sheets and showed beyond doubt that major changes are taking place across the Antarctic ice sheet in response to climate change. The launch of the Landsat programme of optical satellites in the 1970s first gave glaciologists the data to begin appreciating how much change was taking place in this remote part of the planet, especially along the coastline and around the Antarctic Peninsula.

In the decades since, more sophisticated satellite programmes have allowed the quantitative and pan-continental mapping of ice flow and ice-flow acceleration, changes to ice-surface elevation (commonly surface lowering equating to ice loss, especially around West Antarctica's Pacific-facing coast) and widespread retreat of the grounding line. However, the radar and altimetry techniques that are largely relied upon today only commenced in the 1990s, when much of the change witnessed around Antarctica's coastline had already been initiated, so in recent years our group

has comprehensively revisited older optical satellite datasets, targeting our interests on how these data can help us to understand changes that were occurring in response to climate in earlier decades.

Christie et al. (2023) developed a technique to quantify the rate of grounding-line retreat from a combination of optical and active remote sensing data and used this to show that coastal changes along Antarctica's

Pacific-facing coastline, including at Pine Island and Thwaites Glaciers, remain heavily coupled to ocean and atmospheric conditions in the Pacific (Figure 1). A further investigation, focussed on changes to “pinning points” around the entire Antarctic Ice Sheet, is described in Chapter 13 of this volume: *‘Progressive un-anchoring of Antarctic ice shelves is increasing the rate of sea level rise.’*

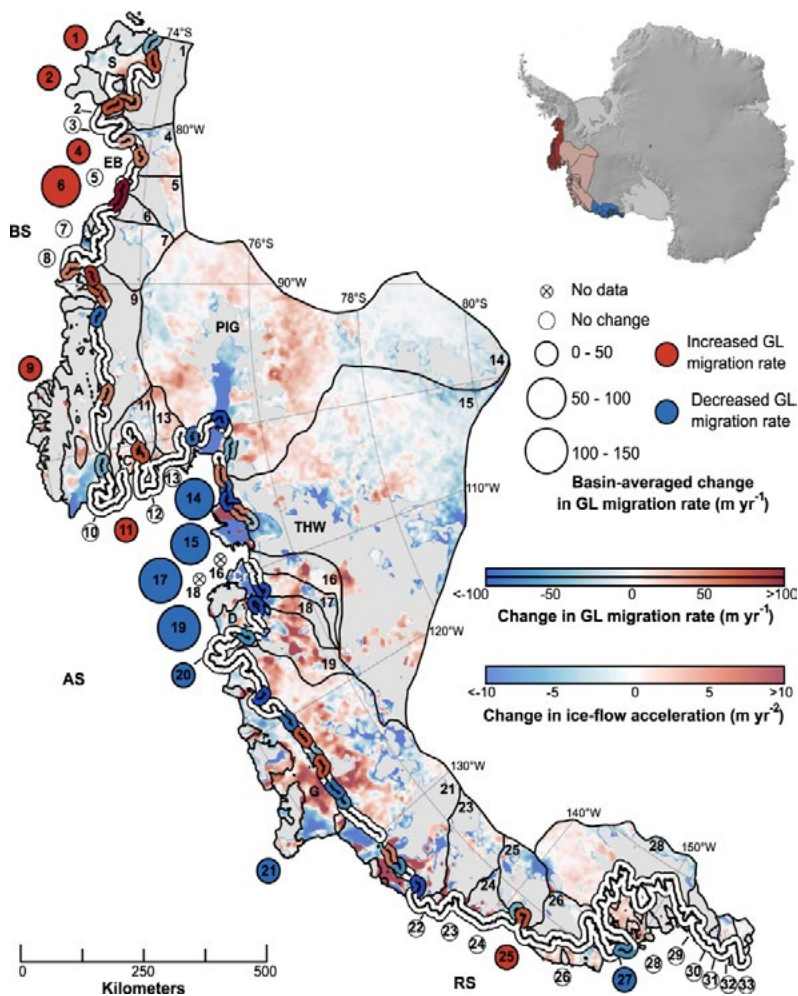


Figure 1. Glaciological change across West Antarctica's Pacific-facing margin, 2003–2015 (Christie et al., 2023). The thick curve bounding the coastline shows net change in grounding-line migration rate (m yr^{-1}) over the observational period (c. 2010–2015 minus c. 2003–2008), binned into 30 km segments along the grounding line. Also shown is catchment-averaged change in grounding-line migration rate for each glacial basin, along the coastline (numbered circles). Data are superimposed over near-contemporaneous change in ice-flow acceleration (m yr^{-2}). AS denotes Amundsen Sector, BS Bellingshausen Sector, RS Ross Sector, S Stange Ice Shelf, EB Eltanin Bay, V Venable Ice Shelf, A Abbot Ice Shelf, C Cosgrove Ice Shelf, PIG Pine Island Glacier, THW Thwaites Glacier; Cr Crosson Ice Shelf, D Dotson Ice Shelf and G Getz Ice Shelf. The glacial basins shown are from MEaSUREs but for ease of reference we have numbered them 1–33 from east to west. Inset shows the location of the study domain, partitioned into the Bellingshausen (red), Amundsen (pink) and Ross Sea sectors (blue).

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Recently, we have gathered further radio-echo sounding data from Thwaites Glacier alongside deploying seismic surveys so that we can resolve not only the effect of topography, but also changes in subglacial hydrology and subglacial geology, on the coupling between ice and the underlying substrate.

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Basal properties of ice sheets: impact on ice flow and ice-sheet response

Our studies above, complementing more recent decades of satellite altimetry and evidence in the recent geological record, offer copious evidence that the Antarctic Ice Sheet has been thinning around its margins for at least the last several decades, and there are suggestions that parts of the ice sheet may be in “runaway” retreat. Airborne radio-echo sounding (RES) across the continent (Pritchard et al., 2025) has demonstrated that the ice sheet contains a volume of ice equivalent to a global sea-level rise of 60m, but the rate at which this loss may occur over the coming centuries is unknown and resolving this represents one of the grand science challenges of contemporary glaciology.

To project how rapidly the ice sheet may retreat and contribute to rising global sea levels in the coming decades to centuries, the numerical models that are now supported by state-of-the-art physics must also be informed by the best possible boundary conditions. Decades of glaciological research have shown the primary importance of characterising the shape and condition of glacier and ice-sheet beds for determining the speed with which ice flows, yet obtaining data on these properties at the resolution required remains a tough proposition. We have addressed this task in two critical ways:

First, in collaboration with the British Antarctic Survey, and as part of substantial NERC-funded programmes, we have used low-frequency ground-penetrating RES to survey regions of the ice sheet broadly the size of cities at sub-km resolution. Figure 2 shows some examples from West Antarctica’s Pine Island Glacier. These data are being used to understand the three-dimensional shape of the basal topography at the sub-km scale that theories show controls basal sliding and/or subglacial sediment deformation (Bingham et al., 2017). Recently, we have gathered further radio-echo sounding data from Thwaites Glacier alongside deploying seismic surveys so that we can resolve not only the effect of topography, but also changes in subglacial hydrology and subglacial geology, on the coupling between ice and the underlying substrate.

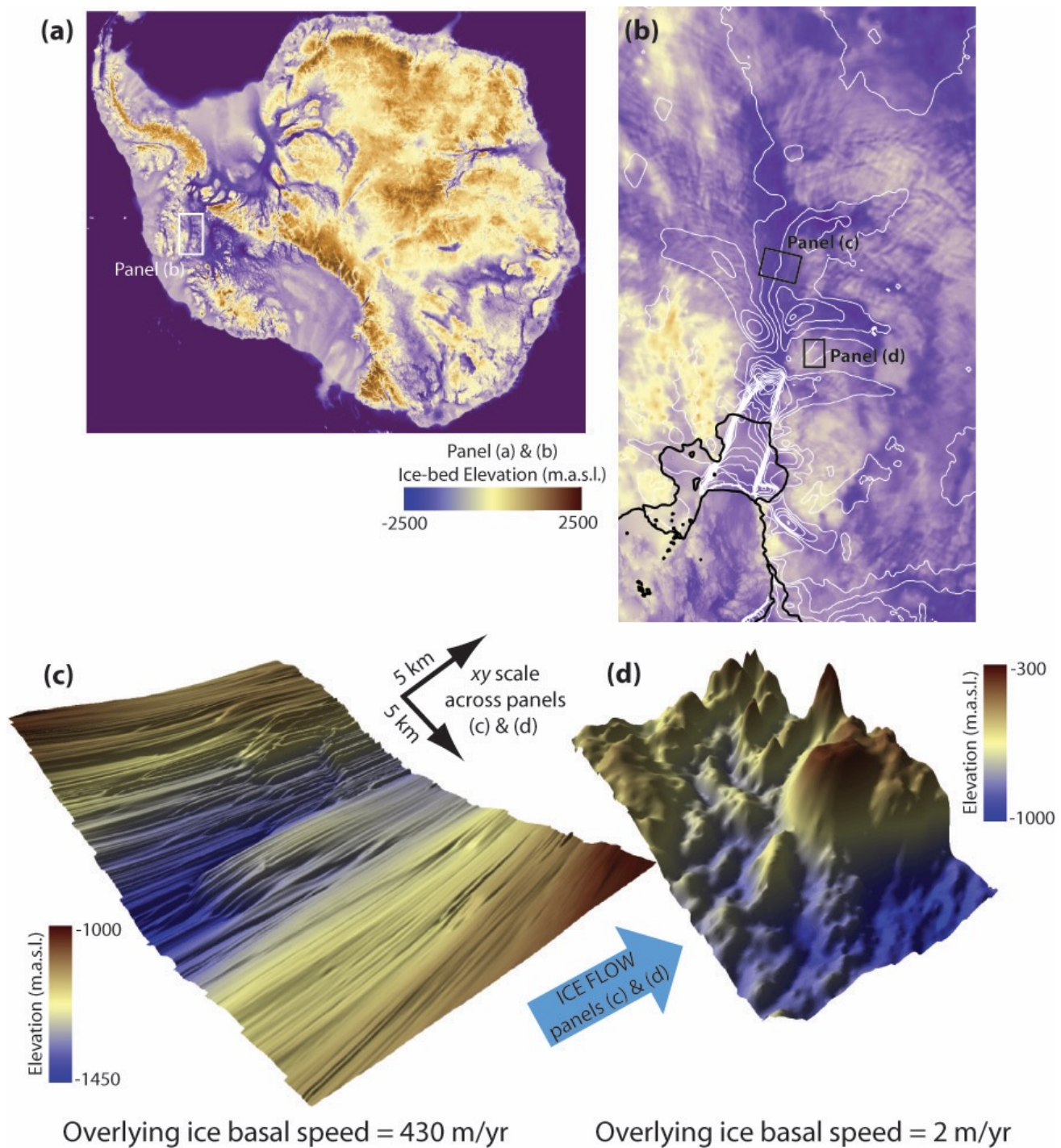


Figure 2. High-resolution images of the bed of Pine Island Glacier, from Bingham et al. (2017). (a) Location and context marked on a map of Antarctic ice-bed elevation. (b) Inset location map of Pine Island Glacier, with colourmap showing regional bed topography, black curve outlining Pine Island Ice Shelf and grounding line, and black rectangles showing locations of high-resolution survey patches shown in (c) and (d).

Second, taking advantage of the unparalleled availability of modern high-resolution digital elevation models of the Antarctic Ice Sheet surface, we have revisited and developed surface-to-bed-topography inversion techniques to produce new maps of Antarctic Ice Sheet bed topography in areas sparsely surveyed by ice-penetrating RES (Figure 3). The

inversion technique, which we have termed Ice Flow Perturbation Analysis, is described in Ockenden et al. (2023), and represents a major advance over previous interpolations between RES profiles because the textural information on the bed topography is spatially invariant and unaffected by the density of RES surveys over Antarctica.

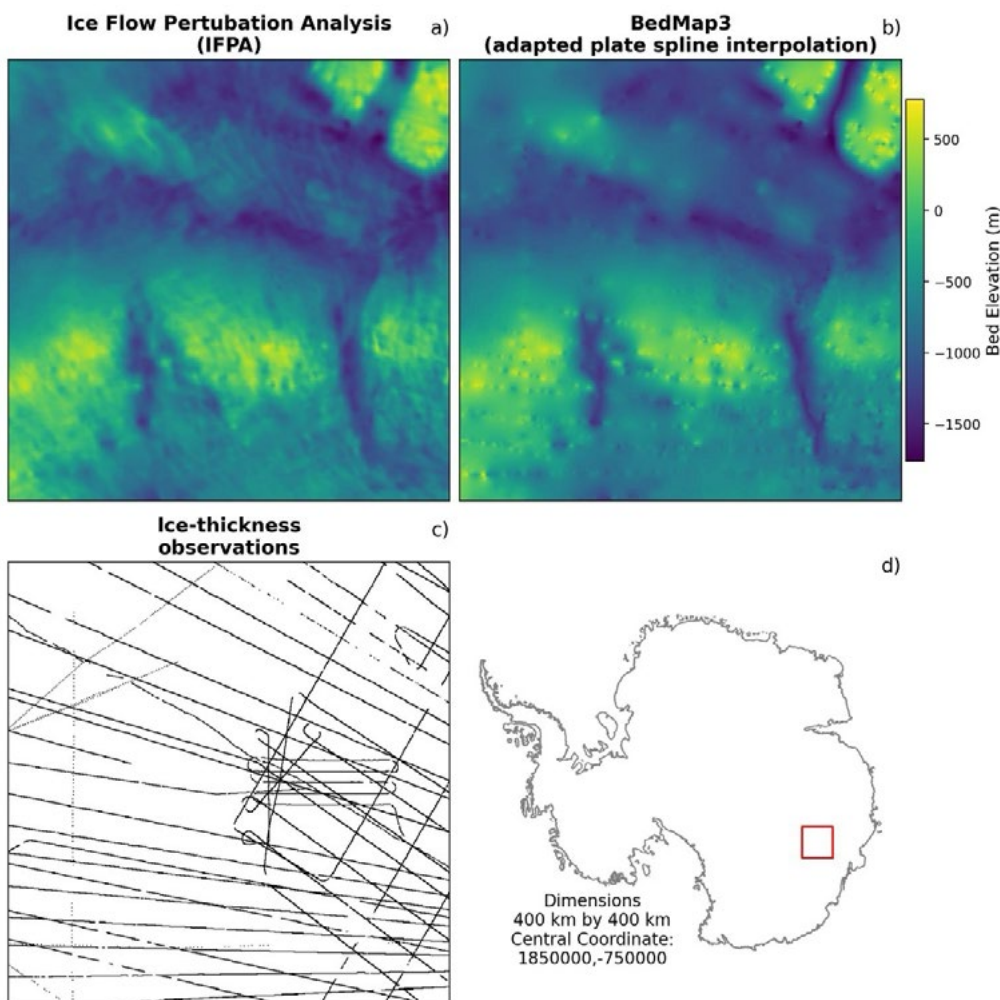


Figure 3. Insights into high resolution bed topography beneath the Antarctic Ice Sheet inverted from high-resolution surface ice elevation, as introduced in Ockenden et al. (2023). The example is taken from a 350 x 350 km region spanning Highland B, East Antarctica. (a) shows bed topography inverted from Ice Flow Perturbation Analysis, hence inverted from ice-surface elevation. (b) shows bed topography interpolated from existing but widely-spaced ice-penetrating RES measurements across the regions (from Pritchard et al., 2025); (c) shows the radar-profile locations from which (b) has been interpolated; (d) location map. Note in (b) that, at this resolution and with wide radar-profile spacing, artefacts around the radar profiles are clearly seen; an effect which is removed with the use of Ice-Flow Perturbation Analysis in (a).

Internal properties of ice sheets: a 3-D record of past climate change

RES has also revealed an “internal architecture” within Antarctica’s ice that records its depositional, deformational, and melting histories. Crucially, spatially-widespread RES-imaged internal-reflecting horizons, tied to ice-core age-depth profiles at notable locations such as the West Antarctic Ice Sheet Divide and Dome C, can be treated as isochrones that record the age-depth structure across the Antarctic Ice Sheet.

These isochrones, which can be used as “internal contours” for reconstructing variations in snowfall and changes to ice-flow dynamics in response to past climate change, are gradually being traced through the Antarctic Ice Sheet by an international consortium of scientists named AntArchitecture, coordinated through the Scientific Committee for Antarctic Research. Steadily, the group is developing a data-informed 3-D age-depth model of the Antarctic Ice Sheet, in which the 3-D surfaces are dated at intersections with deep ice cores. These datasets are now being used as calibration points for ice-sheet models reconstructing the past geometry of the Antarctic Ice Sheet. Progress to date is summarised comprehensively in Bingham et al. (2025) and an illustration of internal layers traced across West Antarctica’s Pine Island Glacier is given in Figure 4 below:

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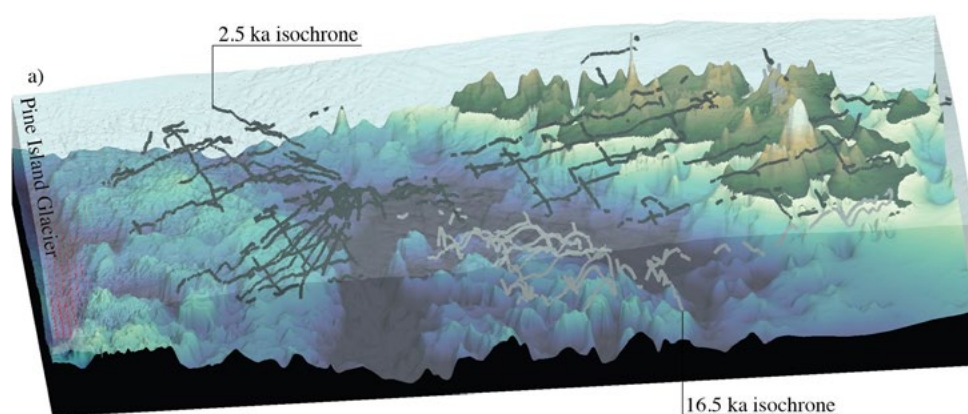


Figure 4. 3-D visualisation of selected traced and dated isochrones across West Antarctica’s Pine Island Glacier. Depicted are isochrones dated by intersection with the West Antarctic Ice Sheet Divide ice core to 2.5 ka (black lines) and 16.5 ka (grey lines). Modified after Bingham et al. (2025)

Progressive un-anchoring of Antarctic ice shelves is increasing the rate of sea level rise

Bertie Miles

University of Edinburgh

Bertie Miles is a Chancellor's Fellow in Climate and Environmental Sustainability at the University of Edinburgh. He investigates the changing dynamics of the Antarctic Ice Sheet, with a particular interest in ice shelves. His research explores how ice shelves respond to various environmental factors, including changes in sea ice and ocean conditions. Through his work, he has examined the long-term thinning of ice shelves, instances of ice shelf collapse, and variations in glacier flow. These studies contribute to a better understanding of the ongoing evolution of the Antarctic Ice Sheet.

Ice shelves 'buttress' the Antarctic Ice sheet

The Antarctic Ice Sheet is almost completely encircled by floating ice shelves, which are extensions of glaciers that flow from the ice sheet's interior towards the coast (Figure 1). Ice shelves are important because they buttress, or reinforce, the ice sheet by anchoring onto topographic highs on the seafloor. Without the back stress provided by these ice shelves anchoring onto topographic highs, known as "pinning points," ice from the ice sheet's interior would flow much more quickly into the ocean, increasing global sea levels. Since ice shelves are floating, they are very sensitive to even small changes in ocean temperature. We show that warm ocean currents have progressively melted the undersides of floating ice shelves over the past five decades, causing them to detach from topographic highs, reducing the back stress provided to the ice sheet's interior, and leading to ice sheet mass loss (Miles, Bingham, 2024).

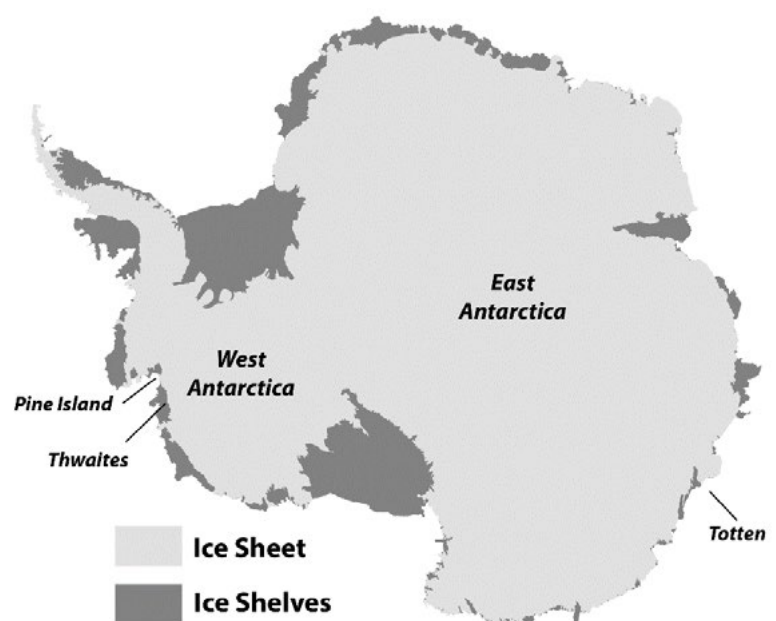


Figure 1. The Antarctic Ice Sheet and its fringing floating ice shelves

Five decades of progressive un-anchoring

We know from modern satellites that can directly measure elevation change, that some ice shelves in Antarctica have been thinning since at least the mid-1990s. This record is short, however; very little information was available on ice shelf thickness (Adusumilli, Fricker, Medley et al., 2020) changes prior to the mid-1990s. We use a novel method that relies on optical satellite imagery (i.e. photos), to track changes in ice shelf thickness. Because ice shelves are floating, they typically have very smooth upper surfaces, but when they make contact with topographic highs on the ocean floor, clear bumps are visible from satellite imagery. If these bumps get smaller through time, it is a clear indication of the ice shelf lifting off or un-anchoring from the topographic high beneath (Figure 2). Therefore, tracking the changes in these bumps provides a proxy for ice shelf thickness change. The advantage of this method is that because it relies on optical imagery, we can utilize the full historic Landsat satellite imagery archive back to 1973. We geo-correct

the old satellite imagery from 1973 and 1989 where there is good coverage of Antarctica, along with existing mosaics from 2000 and 2023 to map decadal change in pinning points.

The results are striking. In each subsequent decade a greater proportion of pinning points are getting smaller or vanishing, 15% were shrinking (Figure 3) between 1973 and 1989, 25% from 1989-2000 and 37% between 2000 and 2022. A very small number of ice shelves show a thickening trend.

In the 1970s and 1980s, there were only small, isolated pockets of ice shelf thinning concentrated around the glaciers that are losing the greatest amount of mass today: Pine Island, Thwaites, and Totten. By the 1990s, thinning had become much more widespread in West Antarctica. By 2000-2022, virtually all pinning points along a 3,000 km coastline spanning the western Antarctic Peninsula and West Antarctica were reducing in size, and some had vanished completely.

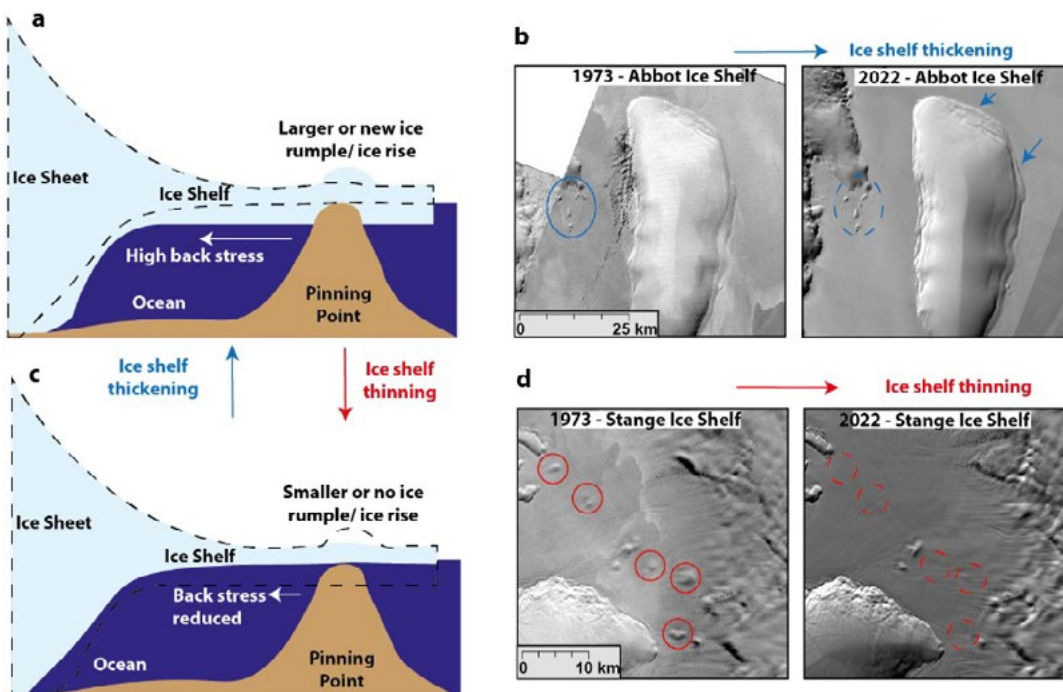


Figure 2. Changes in ice shelf thickness cause a change in the size of pinning points visible on the surface of ice shelves from satellite imagery.

There is a lag between the onset of ice shelf thinning and the largest changes in ice discharge into the ocean, as it takes time for the ice shelves to thin sufficiently to reduce contact with the topographic highs underneath. Therefore, it makes sense that the glaciers losing the most mass today (Pine Island, Thwaites, and Totten) are also the ice shelves that have been thinning for the longest period. The concern is that many glaciers feeding the ice shelves that started thinning more recently are only just beginning to show signs of acceleration, and greater mass loss can be expected in the near future.

Climate change is driving these changes

We have shown that progressively more Antarctic ice shelves are thinning and losing their pinning points. The culprit driving these changes is the ocean, specifically increased intrusions of warm modified Circumpolar Deep Water (mCDW) which is melting the base of the ice shelves. This type of warm and dense water mass is found in the open ocean, but under favourable wind conditions it can upwell and extend onto the continental shelf and be funnelled towards the Antarctic Ice Sheet. There is strong evidence that

the band of westerly winds that encircle Antarctica has both intensified and migrated poleward in response to increased greenhouse gas emissions. It is these anthropogenically driven trends that have been linked to the melting of ice shelves and the subsequent mass loss of the ice sheet (Holland, Bracegirdle, Dutrieux, et al., 2019).

What does this mean for the future?

The future for the ice shelves fringing the Antarctic Ice Sheet is bleak. The winds encircling Antarctica are projected to continue intensifying and migrating poleward, pushing more warm water toward ice shelves. By the end of the 21st century, summer temperatures in coastal Antarctica may be warm enough to generate significant surface melt, meaning ice shelves could be exposed to melting both from below, due to the ocean, and from above, due to the atmosphere. Long-term, vigorous ice shelf thinning has already resulted in the near-complete detachment of the Thwaites Ice Shelf from pinning points; however, substantial parts of the ice sheet are still impounded by ice shelves.

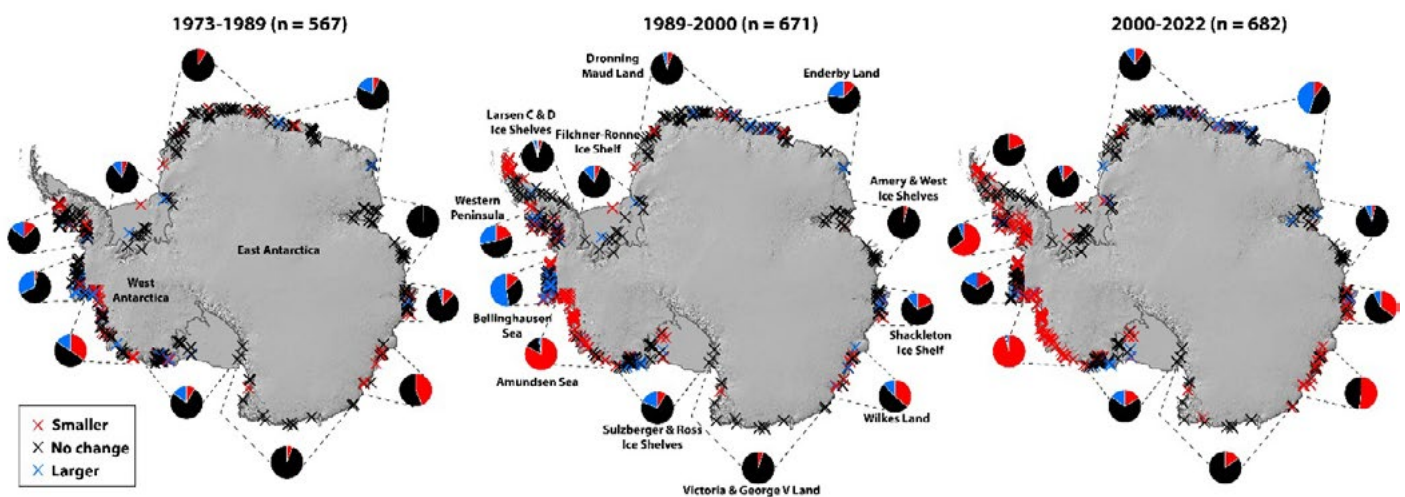


Figure 3. Pinning point change in Antarctica. Each cross represents a pinning point, and is colour coded for change. The increase in red crossed through time is showing the progressive un-anchoring of ice shelves.

Numerical modelling simulations show that the mitigation of greenhouse gas emissions may not be enough to prevent the collapse of the West Antarctic Ice Sheet, but there are large uncertainties about the rates of sea level rise resulting from any collapse (Naughten, Holland & De Rydt, 2023).

The story is very different for the much larger East Antarctic Ice Sheet, which is currently in balance and not contributing to sea level rise, with ice shelf thinning presently concentrated only in the Wilkes Land sector. If global warming is limited to below 2 degrees Celsius, substantial mass loss of the East Antarctic Ice Sheet could be averted. Sustained warming above the two-degree threshold, however, could lead to significant contributions to sea level rise from the marine basins of East Antarctica (Stokes, Abram, Bentley et al., 2022).

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Flow Response of Antarctic Glaciers to Meltwater (FRAM)

Andrew Sole

University of Sheffield

Andrew Sole is a glaciologist at the University of Sheffield who specialises in combining field observations and satellite remote sensing to investigate contemporary glaciological processes. His research has improved our understanding of how glacial meltwater beneath glaciers affects ice motion, and elucidated links between glacial meltwater runoff, submarine ice melt and iceberg calving from marine-terminating glaciers. His current research focuses on quantifying the relationship between glacier melt and dynamics of Antarctic Peninsula glaciers, investigating the role of subglacial lakes in the basal hydrological system of the Greenland Ice Sheet, and monitoring meltwater runoff from the Greenland Ice Sheet using passive seismology.

Introduction

Surface melting and ponding of meltwater is widespread around Antarctica and is predicted to increase substantially as the climate warms. On mountain glaciers, ice caps and the Greenland Ice Sheet, surface meltwater that reaches the ice base can have profound short-term and long-term effects on ice motion. However, while tantalising satellite earth observation data suggest this coupling between surface melt and ice motion is also occurring in parts of Antarctica, it has not yet been observed in the field. Our joint UK and US field team has recently returned from deploying instruments to pinpoint how ice melt affects ice dynamics on the Antarctic Peninsula. These observations will be combined with satellite data to assess the influence of surface meltwater on ice motion around Antarctica. Variations in ice motion are important because they influence the rate of ice discharge into the oceans and thus the cryosphere's contribution to sea level change.

Context

Surface melting and ponding of meltwater is widespread around Antarctica, with lakes and streams a common occurrence on many ice shelves, and in some places, also on grounded ice further inland. The area experiencing melt rates equivalent to those on the Antarctic Peninsula, where today lakes form regularly, is predicted to increase by a factor of five by 2100 (Trusel et al. 2015). On mountain glaciers, ice caps and the Greenland Ice Sheet, surface meltwater that reaches the ice base (via crevasses and moulins) affects ice motion by altering the basal water pressure. High basal water pressure reduces friction between the ice and its bed, leading to faster ice flow and potentially a greater contribution to sea level rise.

Our team has used high-resolution satellite-derived ice velocity data, optical satellite imagery, and regional climate modelling to demonstrate spatial and temporal correlation between sporadic surface melting and short-term increases in ice flow at five

marine-terminating glaciers on the Antarctic Peninsula (Tuckett et al. 2019). While these observations strongly implicated surface meltwater as the cause of the temporary ice acceleration, alternative processes such as variations in ocean melting of glaciers (Wallis et al. 2023) can have similar signatures, so higher frequency field measurements are required to fully assess the possible environmental drivers.

Aim

Our project will quantify the impact of surface meltwater on Antarctic Ice Sheet motion using a targeted multi-year field campaign on Flask Glacier in the Antarctic Peninsula and a continent-wide analysis of satellite earth observation data.

Fieldwork

Our field team returned from Flask Glacier in late December 2024 having deployed several Global Navigation Satellite System (GNSS) receivers on the glacier, an automatic weather station (AWS) (Figure 1) and seismometers at the ice surface. Combined, these instruments allow examination in detail of the magnitude and timing of variations in ice velocity compared to increases in air temperature and surface melting and may enable us to identify the flow of turbulent water at the ice base.

The field team also carried out several Uncrewed Aerial Vehicle flights (Figure 2) to gather high resolution photos of the glacier surface that will be used to create detailed maps of ice motion and changes in surface elevation; both of which can be used to discern the influence of meltwater on ice dynamics.

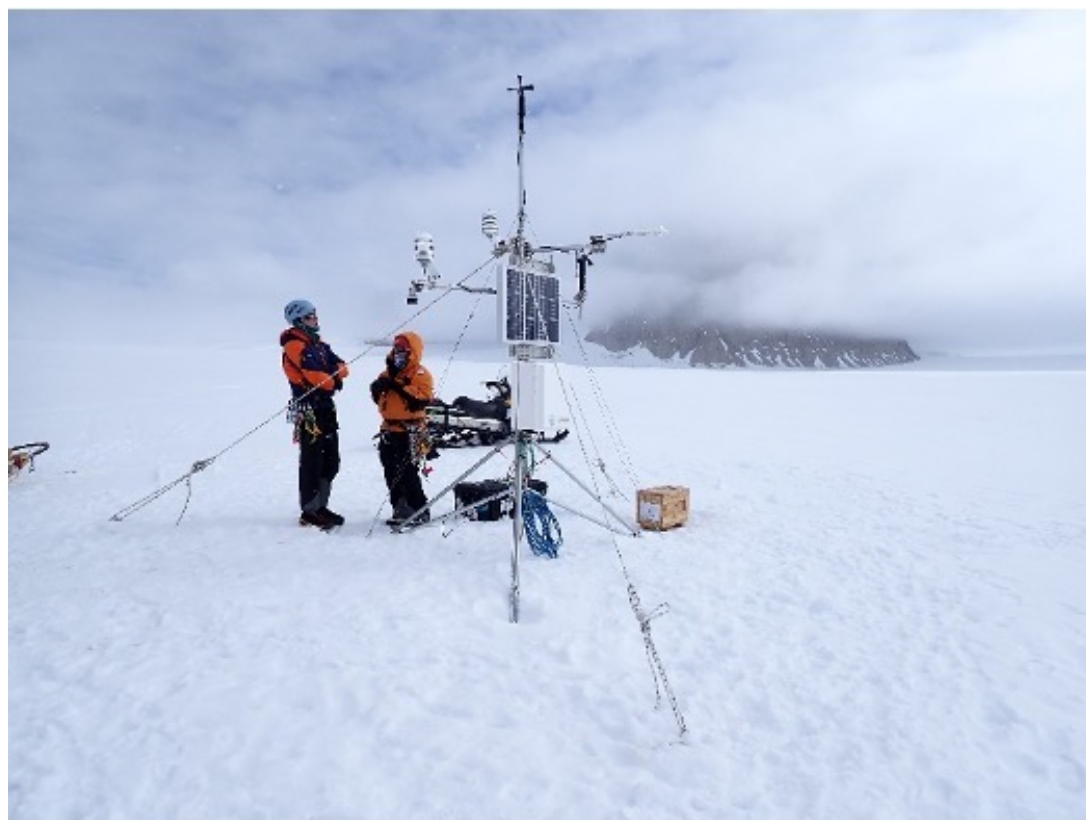


Figure 1. Dr Benjamin Davison and Dr Rohi Muthyala with our Automatic Weather Station on Flask Glacier [Photo credit: Dr Kate Winter].

The GNSS and AWS, equipped with large batteries and solar panels, have been left running over the 2025 Antarctic winter. The team will return in November 2025 to download the data to examine the motion of Flask Glacier and how it has varied across a whole year.

Earth Observation

To expand the spatial and temporal scale of our analysis, a database of ice velocity is being derived and assembled, using satellite data, principally from the European Space Agency's Sentinel-1 radar satellite. This provides ice velocity every 6-12 days,

irrespective of cloud cover or darkness. The focus is on the Antarctic Peninsula where field observations will help to identify the signature of meltwater in the satellite record. Our analysis will then be expanded to cover other regions of Antarctica that experience surface meltwater ponding. By examining time series of ice motion from different locations (e.g. increasing distance from the ocean at the glacier terminus) and in years with varying amounts of surface melting and meltwater ponding, we will assess the impact of surface melting and other environmental drivers on ice motion.



Figure 2. Dr Rohi Muthyala piloting our Wingtra UAV at Flask Glacier [Photo credit: Dr Kate Winter].

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The last British-Irish Ice Sheet: clues from the past to help constrain our uncertain future

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Jeremy Ely is a Senior Lecturer in physical geography at the University of Sheffield. Born in the flatlands of Lincolnshire, he became fascinated by the dramatic topography of ice sheets and glaciers during his PhD. His research focusses on combining the numerical models used to simulate future ice change, with data on glacier/ice sheet behaviour. He has won prizes for his research from the British Society for Geomorphology and the Quaternary Research Association. He leads the Deplete and Retreat, NERC Highlight topic, the aim of which is to better constrain water resource change across the Andes.

Chris Clark is the Sorby Chair of Geoscience at the University of Sheffield. He uses satellite images, elevation models and GIS to discover, organise, and decipher glacial landforms. Such information was used to build dynamic reconstructions of many palaeo ice sheets, including over North America, Britain, Ireland, Greenland and Scandinavia. He discovered mega-scale glacial lineations, recognising their significance as imprints of ice stream flow. He led the BRITICE-CHRONO project collecting new geochronological data to constrain retreat and collapse of the last British-Irish Ice Sheet and collaborating with Dr Jeremy Ely on the ice sheet modelling.

Introduction

Our current ice sheets in Greenland and Antarctica are losing mass in response to human-made climate change. This loss of ice on land is leading to rising sea-levels, risking our populations and cultural and economic capital that is situated near our coastlines. Projecting the behaviour of these shrinking ice masses is critical for planning the future of humanity on our warming planet. Akin to forecasting the weather, predicting the future of ice sheets requires numerical models that simulate potential changes. Various ice sheet models exist for projecting ice sheet change. Given the difficulty of the task and the wide range of future climate pathways, current models have a large uncertainty in their sea-level rise projection (Edwards et al., 2021).

One way to improve the skill of our ice sheet models is to compare them with observations. The models used to forecast the weather, for example, can be tested against an abundant library of observations – partially due to the long history of humans monitoring weather conditions, but also a consequence of the shorter timescales over which weather changes. Ice sheet-wide observations are much more difficult to make and are limited to the satellite era. Thus, some researchers have turned to the study of now extinct ice sheets (palaeo-ice sheets). These have repeatedly grown and shrunk in places in the Northern Hemisphere during natural 120,000-year phases of cooling and warming during the past 2.58 million years. Evidence for these ice sheets is best preserved from the most recent maximum phase, which occurred approximately 26 to 19 thousand years ago.

One such palaeo-ice sheet, estimated to be ~1.5 km thick in places, subsumed most of Britain and Ireland, and has been studied for over 100 years (Geikie, 1894). The goal of BRITICE-CHRONO, a NERC-funded consortium grant led by the University of Sheffield and involving over 40 academics, was to improve ice sheet models by enhancing the database of observations pertaining to recession of the last British-Irish Ice Sheet (Clark et al., 2022). Our work has led to the British-Irish Ice Sheet now being the best constrained retreating palaeo-ice sheet in the world, and to better methods and routines for model-data comparison procedures.

Methods

As the last ice sheet grew over, flowed across and deglaciated Britain and Ireland, it left behind a record of its behaviour. This evidence primarily takes two forms: landforms and sediments.

As the ice sheet moved, it eroded, transported and deposited sediment and rock. The net result of this redistribution of materials is recorded by glacial landforms. These range across scales from large armchair shaped hollows eroded into mountains, known as cirques (corries in Scotland, cwms in Wales), to streamlined hills several meters high formed at the

base of the ice, known as drumlins. Each landform type can be interpreted as providing different information on glacier and ice sheet behaviour. Cirques tell us where glaciers likely initiated when climate started to cool, and drumlins give us ice sheet flow direction. We compiled all the mapped evidence of glacial landforms into a single database and map, the BRITICE Glacial Map (Clark et al., 2018; www.briticemap.org) composed of over 170,000 landforms (Figure 1), revealing the evidence of glaciation across Britain and Ireland at previously unprecedented detail and coverage.

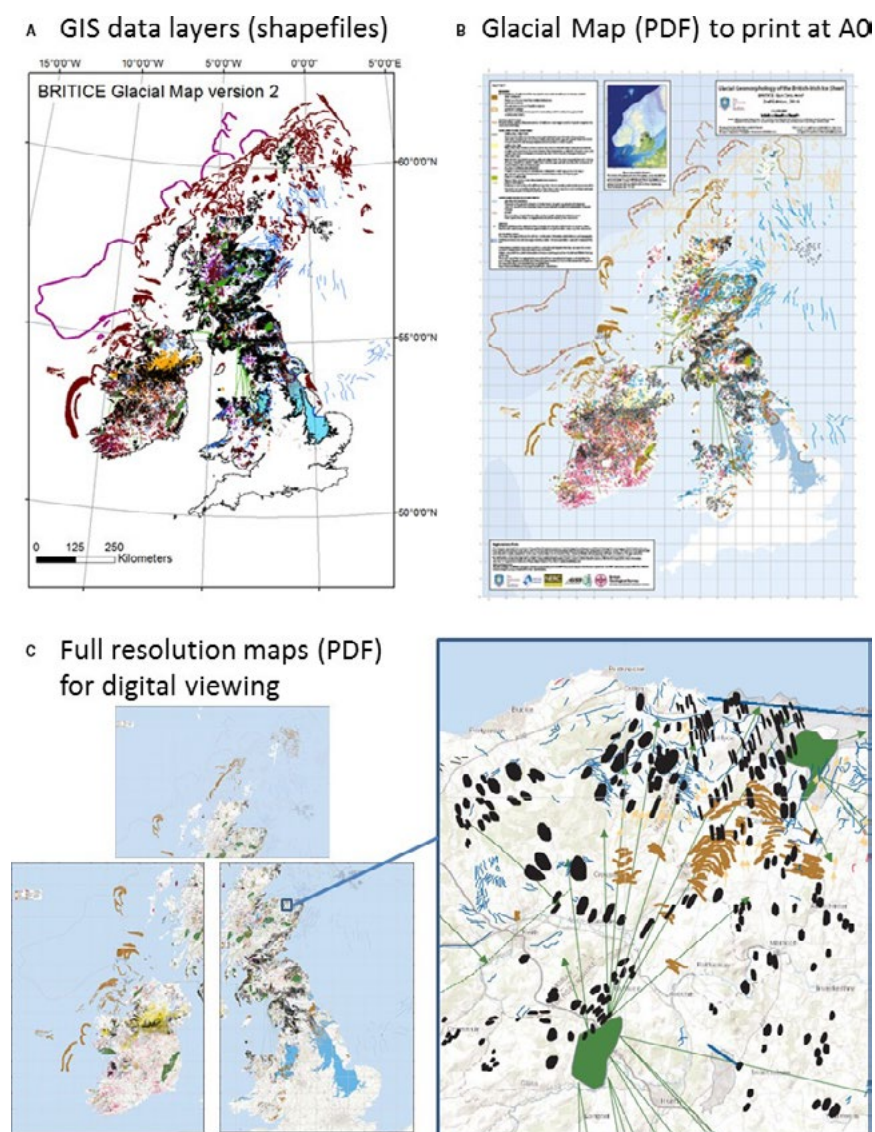
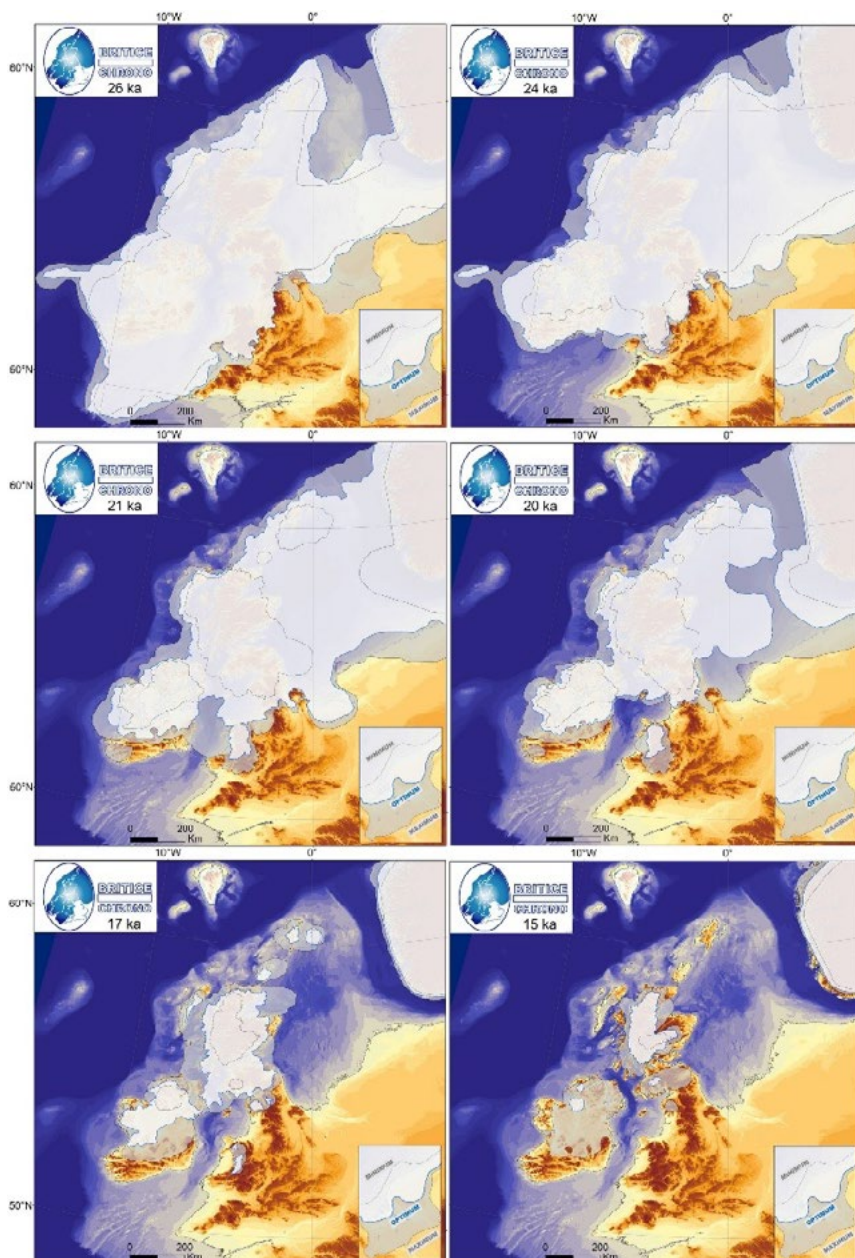


Figure 1. Available formats of the BRITICE V.2 glacial map.

A) As a database.
 B) As a cartographically generalised map.
 C) As a series of detailed map sheets.
 From <https://onlinelibrary.wiley.com/doi/full/10.1111/bor.12273>

Sediments deposited by the ice sheet hold information on the timing of ice sheet growth and retreat, key to determining the pace at which ice sheets respond to climate change. Prior to BRITICE-CHRONO, years of research had sampled sediments across Britain and Ireland in an ad hoc manner. We compiled and quality checked these data. In BRITICE-CHRONO, we conducted over 1,500 person-days of

field sampling, distributed across two cruises that sampled sediments from the sea-floor and land-based fieldwork. These field campaigns were targeted to increase the spatial coverage along key and understudied areas of the former ice sheet. Samples were sent to NERC laboratories and subjected to various dating techniques.



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Figure 2. The data-based reconstruction of the last Ice Sheet to cover Britain and Ireland. Each panel shows the minimum, maximum and optimum extent of ice according to the data, at a point in time (ka means 1,000 years ago). The black line denotes the past shoreline, as global and local changes in ice volume led to sea-level changes. From <https://onlinelibrary.wiley.com/doi/full/10.1111/bor.12594>

The information gleaned from the landforms and sediments described above was used to infer the overall behaviour of the ice sheet following two methods. First, we used human interpretation to reconstruct the ice sheet at 1,000-year intervals. This was done by inspecting the evidence in an iterative manner and constructing maps of ice sheet extent (Clark et al., 2022). Second, we used state-of-the-art ice sheet models, the same that are used to predict the fate of the Antarctic and Greenland ice sheets, to simulate the flow of the ice (Ely et al., 2024). These ice sheet models were driven with information on past climate over Britain and Ireland, and new tools were created to compare the computer-based simulations to the data-based evidence.

Results

Our new data-driven reconstruction of the last British-Irish Ice Sheet is summarised in Figure 2 (Clark et al., 2022). At its maximum, the ice sheet contained enough ice to lower global sea levels by 1.8 m. At this point, the ice sheet was coalescent with the Eurasian Ice Sheet, forming a dome of ice that covered the North Sea. Marine sectors of the ice sheet retreated and upon separation from the ice sheet over Europe, the British-Irish Ice Sheet began to collapse. Isolated and surrounded by water in a globally warming climate, it eventually retreated to high ground at around 15 thousand years ago.

One large lesson from this reconstruction is that different regions of the ice sheet behaved distinctively, responding to different drivers of change (sea level, ocean warming, and atmospheric temperature change). Furthermore, many of these regions rapidly changed, especially those in contact with the ocean, demonstrating the fragility and sensitivity of ice sheets to climatic changes.

Our numerical modelling efforts focused on two questions: i) can we use our data to improve the formulation of ice sheet models?; and ii) can models reproduce the data we have?

For the former, in Gandy et al. (2019) we focused on simulating the fastest-flow portions of the ice sheet, ice streams. These exist in Greenland and Antarctica today and are responsible for discharging the vast majority of ice mass from ice sheets. In attempting to simulate the ice streams of the last British-Irish Ice Sheet, we developed an improvement to the ice sheet model used in the UK Earth System Model (BISICLES; Gandy et al. 2021). For the latter, we conducted numerous model experiments designed to replicate its growth and retreat (Ely et al., 2024). Our results show that the models are capable of capturing the broad characteristics recorded in our data. However, improvements in understanding of the physics that occurs beneath ice sheets, as well as past climate and ocean conditions are required.

A further implication of this improved understanding of the ice sheet history is that it helps us better understand the ongoing impact of glaciation on Britain and Ireland today. The land is still adjusting to the load imposed by the weight of the ice sheet growing and then shrinking. Land in Scotland is rising, adjusting to the loss of ice, and land further south is lowering. In Bradley et al., (2023), we demonstrated the importance of knowing the details of the ice sheet for estimating the rates of this adjustment, which need to be accounted for in any sea level forecasts.

Understanding the response of ice sheets to climate change is critical for planning for our future. Our research shows that the data available from palaeo-ice sheets can play an important role in understanding ice sheet behaviour and improving numerical models. The lesson from the past is that ice sheets are sensitive to atmospheric and ocean temperatures and can disappear quickly and are highly conditioned by particularities of the geography and topography of their host landmass. As humans we must acknowledge that the fate of the ice sheets is dependent upon the amount of greenhouse gasses that we collectively decide to emit.

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