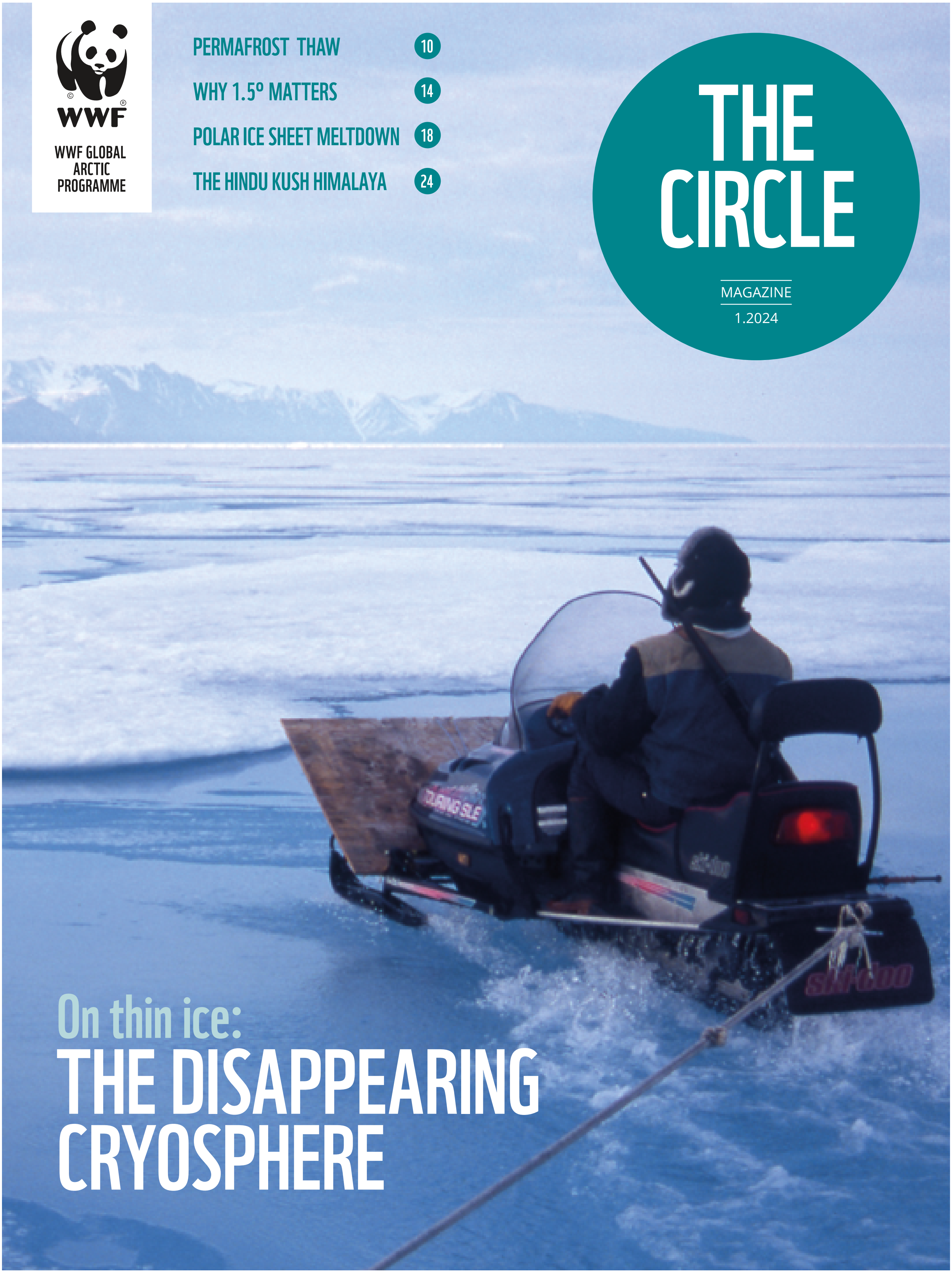

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THE CIRCLE

MAGAZINE

1.2024

On thin ice:
THE DISAPPEARING CRYOSPHERE

The Circle 1.2024 THE DISAPPEARING CRYOSPHERE

COVER: An Inuit hunter travels by snow scooter on melting sea ice, Pond Inlet, Nunavut, Canada.

Photo credit: Peter Prokosch, www.grida.no/resources/4479

THIS PAGE: A family of wild goats pauses against a snowy mountain backdrop in Nepal's Annapurna conservation area.

Photo credit: Zhangwei Ding (distributed via imaggeo.egu.eu)

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EDITORIAL

When it comes to the cryosphere, let's get real

A wild snow leopard triggers a digital single-lens reflex camera trap high up in the mountains of Ladakh in the Indian Himalaya.

Photo credit: © Sascha Fonseca / WWF-UK

ALARMS FROM the Arctic and other frozen regions around the world (known as the cryosphere) keep sounding—and decision-makers around the world keep ignoring them.

Arctic sea ice reached its fifth-lowest maximum level in early March. A few weeks earlier, the Antarctic sea ice minimum was even worse, closely following 2023's jaw-dropping record. Elsewhere, snowpack is at record lows in the Hindu Kush Himalaya, and researchers in Patagonia are tallying the damage from repeated heat waves on that region's glaciers.

New scientific evidence confirms that the world's polar regions began losing ice as long ago as the 1940s, when CO_2 levels in the atmosphere began climbing more steeply. Driven by fossil fuel emissions, levels have risen ever since, breaching 426 ppm in March 2024 for the first time in 15 million years. Ten years ago, CO_2 was still in the 300s. Pre-industrial levels were below 300 ppm.

By any measure, humans are far off-course from the steps needed to halt fossil fuel use. Indeed, course correction was supposed to be the focus of COP28, last year's UN Climate Change Conference in Dubai. Instead, the event was a kind of "realpolitik" for continued fossil fuel use that ignored the simple physical reality of the cryosphere: the melting point of ice.

> Realism in climate negotiations has come to mean bending to the stubborn realities of a world economically dependent on fossil fuels.

Most governments spun the Dubai results as a victory, but for the Arctic, it was a clear failure. Coal will be phased "down," not "out." We will "transition away from" fossil fuels, not cease using them altogether. "Transitional fuels" were emphasized—a thinly veiled reference to fossil gas, which at best still emits 70 percent as much CO_2 as coal (and at worst, emits more)—alongside futuristic carbon capture technologies. Both approaches legitimize continued oil and gas expansion.

Realism in climate negotiations has come to mean bending to the stubborn realities of a world economically dependent on fossil fuels. But as an Arctic and science-based community, it is past time for us to bring a new kind of realism into climate policy—to confront not just the reality of the melting point of ice, but its irreversible global impacts. Unless we truly correct our course by halting CO_2 emissions, the world's ice stores will keep melting. These stores are vital to freshwater supplies, to keeping stored carbon within permafrost, and to keeping ice frozen at the poles. Melted, it will pour into the oceans and wipe out many of the world's low-lying coastal areas with sea-level rises of 10-plus metres, potentially by 2300 should today's emissions continue. These same emissions will also lead to non-survivable acidification in both polar oceans even earlier.

This new realism means facing the cryosphere-consuming consequences of fossil use head on. Fortunately, there are some signs that the message is starting to get through. For example, French President Emmanuel Macron raised these issues at his One Planet Polar Summit just before COP28, joining the new Ambition on Melting Ice High-level Group alongside Italy and the Netherlands. UN Secretary-General António Guterres visited both Antarctica and the Himalayas just before Dubai. And more than 1,000 cryosphere scientists called on COP28 to drop the illusion that 2°C is a safe temperature increase.

But we need more—and we need it now. Not just for the good of the cryosphere, but for the world. ●

PAM PEARSON is the executive director of the International Cryosphere Climate Initiative.

IN BRIEF

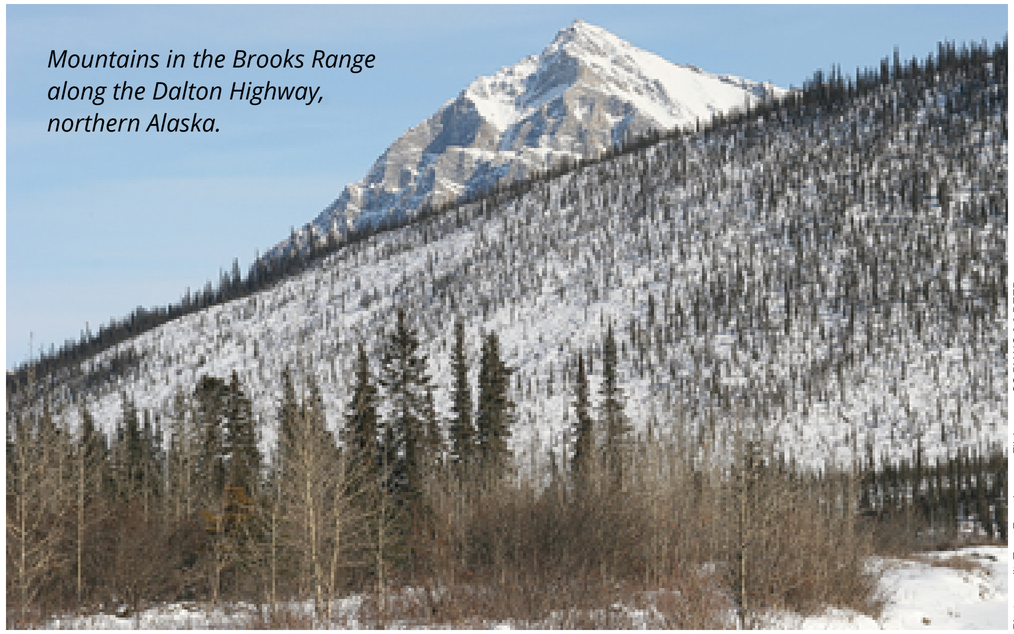
CREEPING TREELINES

Less sea ice could mean more trees in the Arctic

A GROUP OF RESEARCHERS from three American universities have found that the climate crisis may be prompting trees to expand north and at higher elevations. The team studied tree cover in Alaska's Brooks Range, particularly white spruce, and found that the trees were gaining ground in the Arctic. They linked these changes to the loss of Arctic sea ice.

When sea ice retreats, large areas of open water are left behind, creating what is known as a warming "lake effect." Typically associated with North America's Great Lakes, this phenomenon speeds up evaporation and leads to heavier snowfall on nearby land. This layer of snow is making it easier for trees to survive in harsh Arctic conditions by insulating the ground and covering up and protecting small seedlings and saplings. It also keeps the ground warm enough for soil microbes to churn out the nutrients that trees need to grow. These insulating snow layers are also speeding up permafrost thaw, making it easier for trees to take hold in the soil.

The researchers used satellite imagery to track changes to the treeline in recent years. Over a four-year period, they also hiked some 2,400 kilometres to inspect trees and gather data. They concluded that distance to sea ice predicts tree growth and the probability of the forest advancing north.



Mountains in the Brooks Range along the Dalton Highway, northern Alaska.

Photo credit: Terry Feuerborn on Flickr.com, CC BY-NC 2.0 DEED

SEA CHANGE

Ice-free Arctic Ocean closer than predicted

THE ARCTIC OCEAN could be seasonally ice-free up to 10 years earlier than scientists once thought.

According to a study published by researchers from the University of Colorado Boulder in the US, the region could have summer days with practically no sea ice within the next few years. As early as 2035, it could experience consistently ice-free conditions each year in September, the month when sea ice concentrations are typically at their minimum. By the end of the century, the ice-free season could last several months each year.

However, the exact year in which this will happen depends on how quickly the world reduces the amount of fossil fuels it burns.

The expected changes "would transform the Arctic into a completely different environment, from a white summer Arctic to a blue Arctic," explains Alexandra Jahn, associate professor of atmospheric and oceanic sciences and a fellow at University of Colorado Boulder's Institute of Arctic and Alpine Research. "So even if ice-free conditions are unavoidable, we still need to keep our emissions as low as possible to avoid prolonged ice-free conditions."

The study defines "ice-free" as fewer than one million square kilometres of ice remaining because the region would be mostly water in that case. That amount represents less than 20 percent of what the Arctic's seasonal minimum ice cover was in the 1980s.

NEW WATER PATTERNS

Climate crisis bringing big changes for Arctic rivers

AS THE ARCTIC WARMS, thawing permafrost and intensifying storms could change how water moves into and through Arctic rivers, according to a new study.

The researchers used historical data, sophisticated computer models of Earth's climate, and hydrology to reach their findings. They say the changes won't affect just Arctic rivers, but also coastal regions, the Arctic Ocean and, potentially, the North Atlantic Ocean.

The region is already seeing more precipitation and thawing permafrost, leading to stronger river flows. Although most water going into Arctic rivers currently flows atop frozen permafrost in spring, the researchers predict that as the Arctic warms, more annual river flow will come from underground sources through subsurface pathways in the degrading permafrost.

When water flows through this soil, it picks up different chemicals and metals, such as nutrients and dissolved carbon, and can transport these to the ocean. As a result, coastal lagoons may become fresher, which would affect organisms throughout the food chain. In addition, warmer river water would melt coastal sea ice earlier in the season.

A canoeist pulls his canoe past ice in a river in the Northwest Territories, Canada.

Photo credit: © Tim Irvin / WWF-Canada

HABITAT DESTRUCTION

Deep-sea mining could worsen the climate crisis

A STUDY published in the journal *Frontiers in Marine Science* reveals that deep-sea mining could increase the scale and speed of climate change by affecting seafloor creatures that store carbon.

The scientists from Norway and the UK surveyed seafloor animals, such as corals, sponges and snails, at 17 different sites on the floor of the Barents Sea. What they found was that these organisms store a far larger amount of carbon than was previously believed—and deep-sea mining could disrupt this.

"Previous estimates have underestimated how much carbon is being removed by marine life because they were based on data from troughs on the ocean floor," explains Terri Souster, a researcher at The Arctic University of Norway and the study's lead investigator. "We systematically assessed a wider range of seafloor sites and found that far more carbon is being removed in continental shelf waters."

Seafloor creatures extract carbon from their food and the surrounding water to grow and build their skeletons or shells. When they die, much of that carbon stays locked away in their shells and skeletons, which sit in sediment on the sea floor. Deep-sea mining and trawling could reduce the oceans' natural ability to remove carbon from the atmosphere by disturbing or destroying these habitats.

A 1.5-degree guardrail for the cryosphere

TRANSLATING SNOW AND ICE SCIENCE INTO POLICY

Earth's cryosphere is on the brink of a preventable disaster. Rising temperatures from carbon emissions are pushing communities closer to the limits of their ability to adapt, forcing mountain regions to cope with water shortages and coastal areas to confront sea-level rise caused by melting polar ice sheets. As **AMY IMDIEKE** writes, the State of the Cryosphere 2023 report clearly lays out why we must keep the global temperature rise below 1.5°C.

AT THE UN Climate Change Conference in December, scientists shared the 2023 report on the state of the cryosphere with government leaders, ministers and climate negotiators working on the frontlines of global policy-making. The report outlines the latest snow and ice science and emphasizes the need for urgent fossil fuel reductions to prevent the worst-case scenarios for future generations. Its message this year was simple: even a 2°C temperature rise is too high to prevent devastating global impacts from cryosphere loss.

"We have time, but not much time," wrote Chilean President Gabriel Boric and Iceland's Prime Minister, Katrín Jakobsdóttir, in the report's preface. "Past alerts are today's shocking facts. Present warnings will be tomorrow's cascading disasters, both within and from the global cryosphere."

> Most recently, researchers discovered that West Antarctica and Greenland will cross irreversible thresholds if global temperatures climb by more than 1.8°C, even temporarily.

FIVE KEY CRYOSPHERE DYNAMICS

The report focuses on five dynamics that are highly relevant to national and global climate policy: permafrost, sea ice, ice sheets and sea-level rise, mountain glaciers and snow, and polar ocean acidification, warming and freshening. The first such report was released just ahead of the landmark climate conference in 2015, with scientists urging greater ambition as the Paris Agreement was concluded.

Cryosphere science is evolving at an incredibly rapid pace. Not only do new findings each year yield worrying observations, such as those concerning recent trends in Antarctic sea ice, but they paint an increasingly detailed picture of what Earth's future will look like under different emissions scenarios due to cryosphere loss.

As a result, the state of the cryosphere report is now released annually before the UN Climate Change Conference each fall. The report is coordinated by the International Cryosphere Climate Initiative and reviewed by an international team of more than 60 cryosphere scientists, including many Intergovernmental Panel on Climate Change authors. As experts in their fields, they take the pulse of the cryosphere, translating the latest science into terms that can be understood by government and business leaders, negotiators and the general public. The report outlines how cryosphere loss will change the world if we do not reduce carbon emissions with enough ambition and urgency.

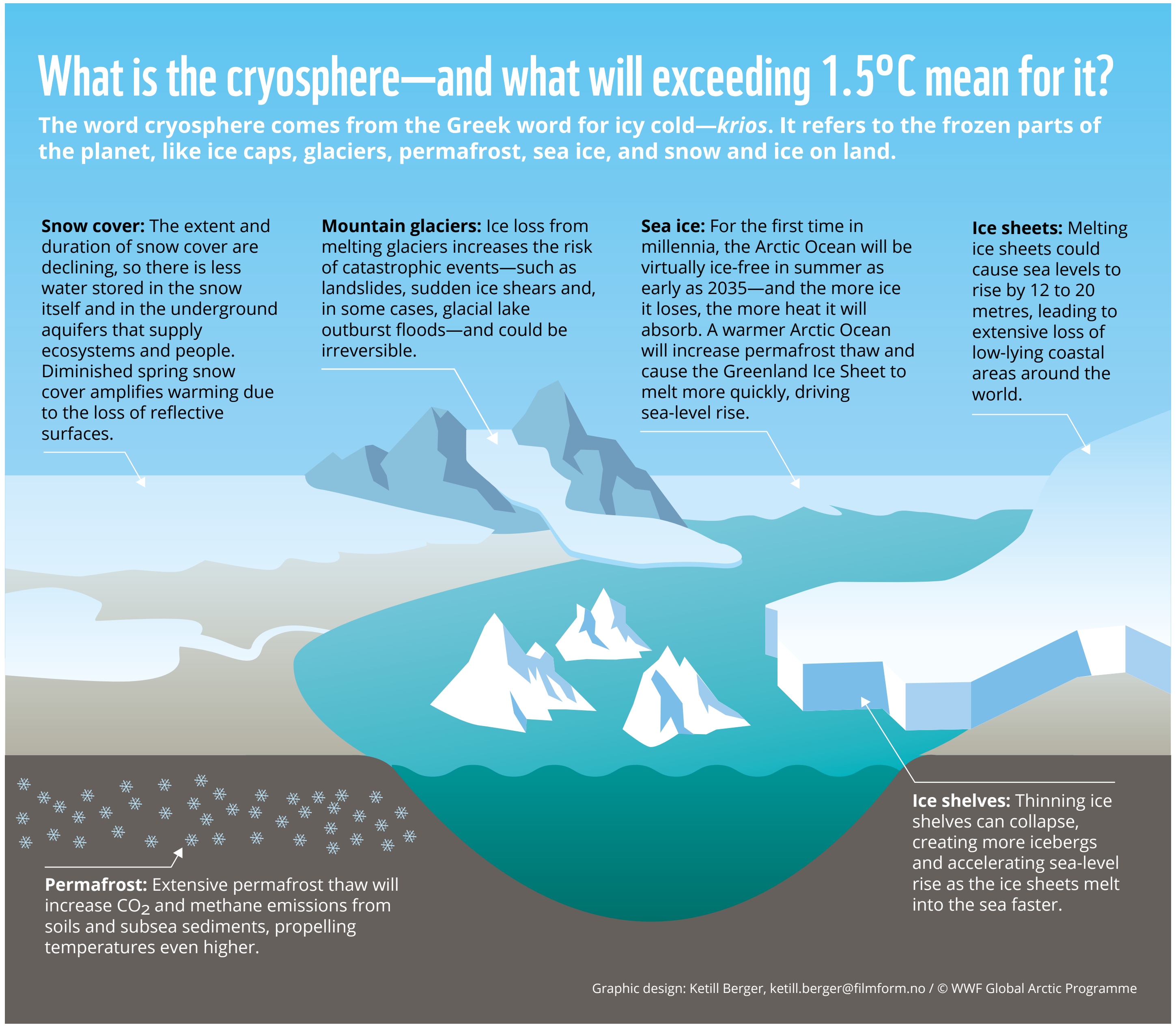
Arctic and Antarctic research have flourished in recent years, with satellite observations, expeditions and collaborative papers exploring even the most remote regions of the Greenland and Antarctic ice sheets—two regions of key concern to low-lying nations far away from the poles.

IRREVERSIBLE CHANGE

Most recently, researchers discovered that West Antarctica and Greenland will cross irreversible thresholds if global temperatures climb by more than 1.8°C, even temporarily. Such a rise would commit these ice sheets to increased ice loss and accelerate global sea-level rise for several centuries. Only the very lowest greenhouse gas emissions scenario—in which temperatures peak around a 1.6°C rise and level off below a 1.5°C rise by the end of the century—avoids long-term acceleration of sea-level rise from the Earth's two great ice sheets.

The latest science is clear: ice sheets have the potential to spur a greater and faster sea-level rise at lower temperatures than previously thought. Most seriously, these changes will be essentially permanent, even with an eventual return to lower temperatures.

Academic work on mountain glaciers has also advanced. More accurate models are forecasting greater ice loss at today's temperatures and indicating that it will take centuries or even millennia for this ice to return, once lost. A high-emissions scenario will result in total or near-total glacier loss in the mid and low latitudes by 2100, including a loss of up to 80 percent among glaciers in the Hindu Kush Himalaya.



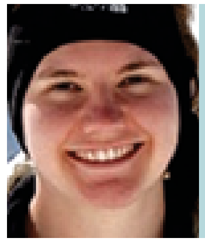
CASCADING IMPACTS

Disappearing glaciers strain seasonal water supplies for high mountain and downstream communities alike, with impacts cascading through agriculture and food security to global trade.

These cryosphere changes are not locked away in some distant future. They are already the reality for millions of people, from those living on unstable permafrost soils in the Arctic to those living in the foothills of the Himalaya and along the coastlines of small island states.

Extreme events are increasing in frequency and severity across Antarctica, including heatwaves, all-time low sea ice conditions, ice shelf collapse, and species population crashes. These trends will continue unless radical actions are taken to reduce fossil fuel emissions to net zero by 2050.

Nonetheless, the State of the Cryosphere 2023 report offers a strong message of hope: cryosphere loss is still preventable. What happens next depends on the actions we take to reduce carbon emissions today. At its core, 1.5°C is a window into what our world could look like for generations to come—and it will be worse if we take too long to act. ●



AMY IMDIEKE is global outreach director for the International Cryosphere Climate Initiative.

Exposed permafrost sediments and ice wedges at a bluff near the Itkillik River, northern Alaska.

Credit: Jens Strauss, Alfred Wegener Institute

Permafrost

THE HIDDEN GLUE HOLDING NORTHERN LANDSCAPES TOGETHER

Permafrost is found under vast areas of tundra and boreal forest in the Arctic regions of Alaska, Canada, Scandinavia, Finland and Russia. But as **CLAIRE TREAT** explains, it is warming and thawing everywhere, with consequences not only for local people and wildlife, but for us all. ➤

Photo credit: Torben Windirsch-Wowode

In northern Finnish Lapland, permafrost provides important habitat for reindeer who forage in early spring.

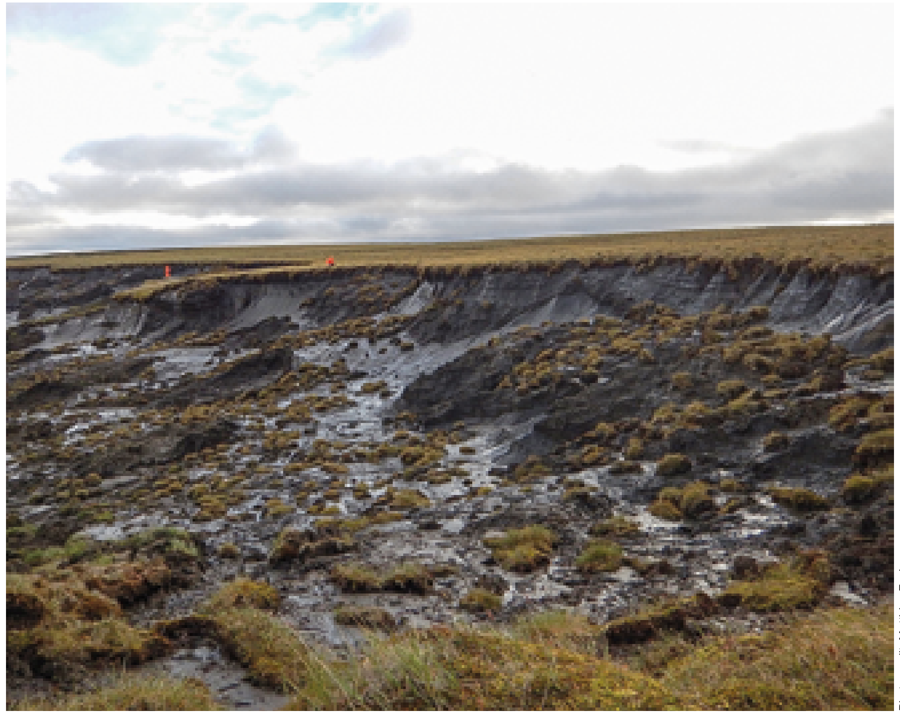


Photo credit: Matthias Fuchs.

Researchers work on an eroding permafrost cliff on Siberia's Bykovsky Peninsula.

PERMAFROST IS THE word for frozen ground in cold regions where temperatures remain below freezing for much of the year. But the word itself is becoming something of a misnomer as permafrost becomes less permanent in response to climate warming, which is occurring far more quickly and having more extreme consequences in the polar regions.

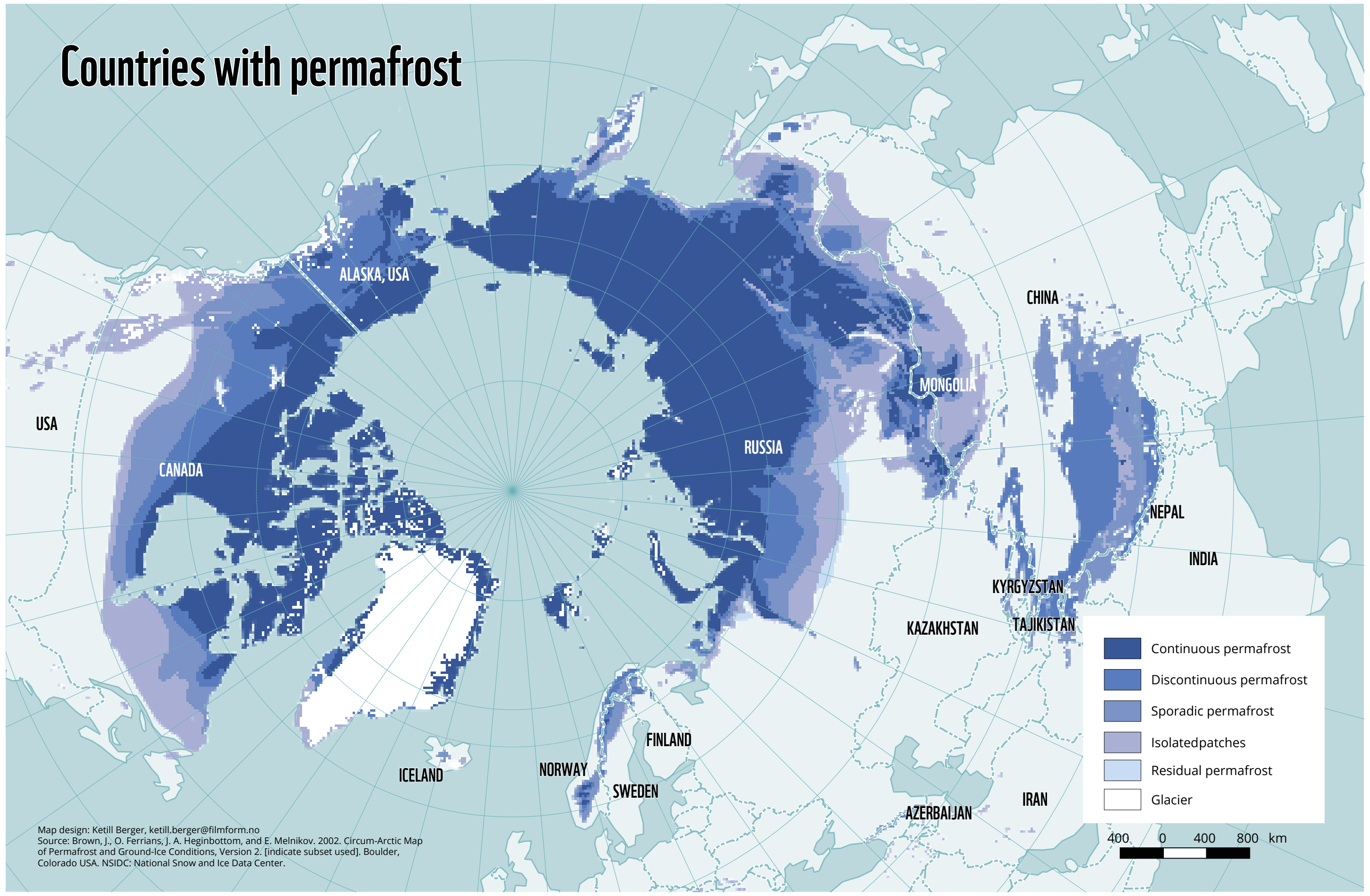
When temperatures rise, permafrost can thaw, causing dramatic changes to the landscape that can have significant consequences for people and wildlife. For example, new lakes can form while others dry up. Thermokarst landscapes can emerge as ground surfaces collapse, creating uneven terrain. When ground ice thaws on slopes, thaw slumps (a type of landslide) can occur as soil, debris and vegetation shift.

Thawing permafrost has the most direct effects on the people and wildlife living in Arctic regions. Coastal areas in these regions see shorelines disappear while coastal communities lose houses and land. Roads, buildings and other infrastructure built on permafrost can begin to fail and need repair or stabilizing. Wildlife like caribou and reindeer count on solid permafrost to move across what would otherwise be wetlands. Palsas (peat mounds with permanently frozen peat and mineral soil cores) have long been ideal spring foraging habitats for reindeer in Finland, Sweden and Norway, but are disappearing.

These are just some of the effects on local people and wildlife that we already know about. There are likely more that we haven't identified yet.

DECOMPOSITION WILL ACCELERATE THE CLIMATE CRISIS

The impacts for those of us not living on permafrost may be less immediate, but they will be no less dramatic. Permafrost regions are key carbon reservoirs. When the ground stays frozen, the permafrost acts as a freezer (or even a glue) for the vast amounts of carbon found in soil that have built up over time. Plant litter, roots and other organic materials in the soil are preserved when they stay frozen. With warming, they will begin



to defrost and decompose, releasing carbon into the atmosphere and accelerating climate warming. The permafrost regions in the northern hemisphere store about twice as much carbon as is currently found in the atmosphere.

We still don't have a good understanding of how much carbon is being released due to permafrost thaw. This is partly because the Arctic is so remote and difficult to access. We have limited measurements of carbon exchange across the vast permafrost region, especially in Russia. There are a number of sites in Alaska, Finland and Sweden that provide important information, but their limited numbers make trends in carbon uptake and release difficult to detect. Based on our best knowledge, we surmise that carbon emissions due to permafrost thaw will be equivalent to emissions from a mid-sized country by the end of the century under a moderate warming scenario of 2 to 3°C.

But we aren't certain. As scientists, we need to figure out how to improve our measurement network and our predictions to answer this key question.

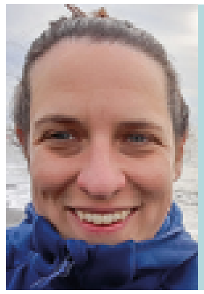
POSSIBLE SOLUTIONS

While the effects of climate warming on permafrost are concerning, there are some glimmers of hope from both the human and natural sides. As scientists, we continue to develop new technologies—such as satellites, drones and new autonomous devices—to measure carbon emissions in remote regions. These are critical to our ability to understand and monitor what is happening.

In addition, nature may help sequester carbon in some areas. For example, flooding associated with permafrost thaw can result in the formation of new wetlands with high rates of carbon uptake. Or warmer temperatures and higher atmospheric carbon dioxide concentrations may enhance plant growth, increasing natural carbon sequestration. Both of these developments could offset a certain amount of carbon losses from thawing permafrost.

Still, the best path to keeping permafrost carbon in the ground is to limit emissions from fossil fuels and deforestation. This way, we can minimize temperature increases and ensure Arctic and boreal soils stay frozen. This can help us to preserve these beautiful and sensitive landscapes and protect those who live on them for the future.

Let's keep permafrost frozen so it can continue to hold ancient carbon sources in place and provide a solid base for the people and wildlife living on its surface.



CLAIRE TREAT is a senior researcher specializing in permafrost carbon and greenhouse gas emissions research at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research.

Steering clear of overshoot pathways

WHY HALF A DEGREE MATTERS SO MUCH

Snow, ice and permafrost—defining characteristics of the Arctic—are vanishing at an alarming rate. Sea ice and glaciers are melting, snow cover is thinning, and the water table is changing. As **HELENA GONZALES LINDBERG** and **GRETE K. HOVELSRUD** explain, many of the impacts of the climate crisis in the cryosphere will be irreversible if we overshoot the 1.5°C Paris Agreement goal.

Svalbard's Gronfjordbreen glacier is melting quickly, destabilizing structures like this cabin as rising waters cause moraines to collapse.

Photo credit: Stan Schouten (distributed via imaggeo.egu.eu)

IN THE ARCTIC, cryosphere changes are driven primarily by warmer air and ocean temperatures. Less snow and ice in the winter and more warm days in the summer may not seem like critical concerns in a region where many people welcome a bit of warmth. But this rapid warming is bringing new, long-lasting changes that will negatively affect human health and well-being.

A global temperature rise of 2°C instead of 1.5°C will increase the probability of ice-free Arctic summers by 10 times. Most projections show an Arctic Ocean largely free of sea ice in September—the month with the least sea ice—as soon as 2050. One recent study suggests this could happen as early as 2035.

In the Svalbard archipelago, at 74 to 81 degrees north, people can already see the changes and their impacts: the autumn season lasts longer, winter arrives later, and sea ice in the fjords is declining drastically. More precipitation and warmer weather increase the risk of avalanches, which already cause accidents (sometimes fatal) in Svalbard regularly. More avalanches—as well as landslides and floods—will restrict snowmobile and dog sledding routes and threaten housing and infrastructure. These changes will have severe impacts on some residents' lifestyles.

"LAST-CHANCE" TOURISM WORSENING THE IMPACTS

The cryosphere changes caused by the climate crisis are also affecting tourism, which became an industry in Svalbard in preparation for the closure of most coal mines in 2018. Ironically, "last-chance" tourism—which involves tourists travelling to the Arctic to see the loss of sea ice and melting glaciers—is contributing to the changes. This happens indirectly through greenhouse gas emissions from air travel and cruise vessels travelling to and from Svalbard ➤

Limiting global warming to 1.5°C by 2100 is still within reach. But urgent action is needed in the coming decades if we want to prevent the Arctic cryosphere from disappearing completely.

as well as directly through increased local emissions, waste, wear and tear on the sites visited, and other human disturbances around the archipelago.

Less sea ice means ships have greater access to fjords in spring, which is good for tourism but creates difficult conditions for those who live in the region and travel by snowmobile. Likewise, the shorter winter extends the cruise tourism season but reduces the number of days available for skiing.

While human activities in Svalbard's permanent settlements (mainly Longyearbyen and Barentsburg) do have an environmental footprint, tourism has a greater one: tourists outnumber residents during the high season. The Norwegian authorities have implemented strict regulations on travel for tourism, fieldwork and more in Svalbard to keep the vulnerable environment as untouched as possible. While the impacts of tourism are expected to continue to increase, at least in the short term, there are efforts to develop new and more sustainable tourism services and change the way tourism is done in Svalbard and the rest of the Arctic.

TIPPING POINTS AND COLLABORATION

The changing Arctic cryosphere and interlinked consequences for the environment and people are major causes for concern. With climate change leading to disappearing sea ice, glaciers and permafrost, humans have set in motion some irreversible shifts and significant tipping points.

Still, we are continuing our quest for solutions to address (or even reverse, in some cases) these increasingly rapid processes. Currently, we are studying three interconnected aspects of climate change as a grand challenge: adaptation, mitigation and transformation.

The adaptation aspect is fraught with challenges stemming from social tensions and conflicts over different land and resource uses. As a result, when exploring adaptation, mitigation and transformation processes, scientists and researchers must ensure that local communities, Indigenous Peoples, policy-makers and business developers are involved. That is the only way we can succeed at preventing further loss of the cryosphere and adapting to the ongoing changes.

Limiting global warming to 1.5°C by 2100 is still within reach. But urgent action is needed in the coming decades if we want to prevent the Arctic cryosphere from disappearing completely. The cryosphere is vital for many traditional ways of working, travelling and living meaningful lives in the north. ●

HELENA GONZALES LINDBERG is a senior researcher, social scientist and co-lead in the EU Horizon 2020 PROVIDE project on Paris Agreement Overshooting.

GRETE K. HOVELSRUD is a professor and Arctic anthropologist with 40 years' experience in the Arctic. She co-leads the EU Horizon 2020 FACE-IT project.

Mapping Greenland

FREE RESEARCH TOOL INSPIRES RESEARCH AND LEARNING

Often when people think of Greenland, they picture icebergs floating in pristine fjords, brightly coloured homes dotting the coastline, and large expanses of ice. But as **TWILA MOON** and **ALYSE THURBER** write, Greenland also hosts some of the most important environmental data in the world, with clues to the Earth's climate history.

RESEARCHERS FROM AROUND the world have long flocked to Greenland to explore and learn from its landscapes, ecosystems and communities. Now, a diverse team from the National Snow and Ice Data Center at the University of Colorado Boulder is making these data more accessible for decision-makers, educators and the public through a project we are part of known as QGreenland.

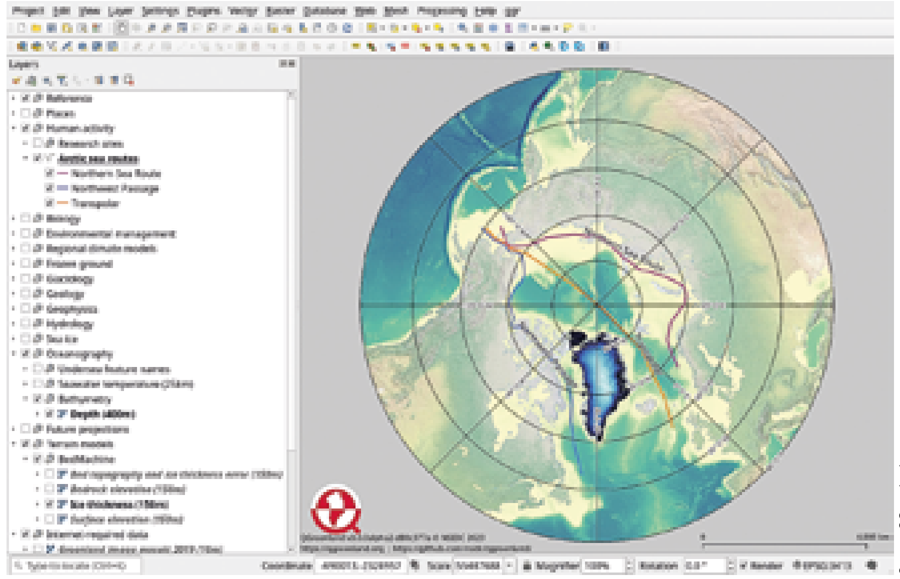
The project came about because hundreds of researchers collect environmental data in Greenland and share the information with colleagues around the world through online platforms, databases and articles in scientific journals. But sharing data in different formats and storing information in different places can make it difficult for the public to use and may slow scientific progress. QGreenland tackles this problem.

BRINGING GEOSPATIAL INFORMATION TOGETHER

The QGreenland team wanted to bring geospatial data about Greenland together in a single, easy-to-use tool. Geospatial data are those associated with a location. For example, the digital map application that runs on your phone shows geospatial data like street names, hospital locations and restaurant phone numbers. QGreenland has similar information about roads and infrastructure in Greenland, but also includes research data about the environment.

QGreenland runs on downloadable geographic information system (GIS) software and includes everything from the locations of seabird nesting colonies and fishing zones to ice sheet changes and ice core locations. Having these data together in a single location accelerates the pace of scientific discovery, allowing researchers to better plan for future data collection and run data analyses that include the broader data landscape.

For example, on board the oceanographic research ship *RV Armstrong*, scientists use QGreenland to consider a variety of environmental factors at once when determining where to collect ocean sediment samples. Using QGreenland visuals, scientists can show students how factors like water depth, sea ice location and local geography help determine the best location.



Source: QGreenland

A view of the QGreenland QGIS map environment, where users can interact directly with data layers, including turning them on or off, moving them around, and using many direct analysis tools. Data layers are listed on the and shown on the right, including ocean bathymetry, Greenland Ice Sheet thickness, and Arctic shipping routes. This image shows the largest QGreenland data boundary for the Arctic widely, while some data are limited to focus on the Greenland region more closely.

SUPPORTING DECISIONS AND EDUCATION

Brendan Reilly, a researcher with the Lamont Doherty Earth Observatory at the Columbia Climate School in the US, has told us that he and his colleagues use QGreenland as the starting point for their cruise GIS, keeping it hooked up to the ship's navigation so it is permanently displayed in the main lab. "We've been using it to make real-time decisions for our geophysical surveys and sediment coring locations, and it's been a great educational tool for discussing sites with our students," he says.

QGreenland is also a valuable educational tool. Online video tutorials and a user guide we created help anyone—even people who have never used GIS software—to view data and create maps quickly. The high-resolution satellite images give students a sense of the vastness of the ice sheet while also revealing smaller-scale details, like how meltwater flows across the surface on its way to the ocean.

Sharing data in different formats and storing information in different places can make it difficult for the public to use and may slow scientific progress. QGreenland tackles this problem.

We have also developed a high school curriculum called Exploring Sea Level Change to help students and teachers visualize how much of the ice sheet might melt within the coming millennium in a rapidly warming Arctic.

In this series of lessons, students use the amount of ice melt predicted in Greenland to create sea-level rise flood maps of coastal cities near them. This helps students better understand how ice in the Arctic can directly affect their lives and communities, despite how far away it may be.

The QGreenland team is now developing tools to make it easier to add other data to QGreenland or create similar data tools for other areas. Ultimately, QGreenland is helping us all see the bigger (more complex) picture for Greenland. It is showing us that the Arctic is so much more than the ice most people picture—and giving us a better understanding of the planet in the context of rapid change. ●

TWILA MOON leads the QGreenland project and is deputy lead scientist and science communication liaison at the National Snow and Ice Data Center, University of Colorado Boulder.

ALYSE THURBER is the education and outreach lead for QGreenland and a member of the CIRES Center for Education, Engagement, and Evaluation at University of Colorado Boulder.

A tale of two ice sheets

WARM WINDS AND MELTING ICE

"When those ice shelves disappear, they will release the buttressing force that was holding back the ice streams on the continent itself. When the ice shelf disappears, that land-based glacier is going to speed up and go straight into the ocean because there's no ice shelf there anymore."

This massive iceberg was created when a piece of ice shelf broke loose on the coast of Antarctica.

Photo credit: Peter Prokosch, www.grida.no/resources/3170

We've long known that the Antarctic and Greenland Ice Sheets contain more than 99 percent of the freshwater ice on Earth. But recently, a study by researchers at the University of California, Irvine (UCI) and Utrecht University revealed that these two ice sheets have begun trending in different directions: Greenland's ice surface has been melting faster in recent years while the Antarctic sheet is experiencing a contrasting trend.

According to **CHARLIE ZENDER**, a professor of Earth system science at UCI who co-led the study, it all comes down to downslope winds. These currents of warm, dry air can rapidly melt glacial snow and ice. In Greenland, the melting caused by these winds has increased by more than 10 percent in the past two decades. However, the impact of downslope winds on the Antarctic ice sheet has decreased by 32 percent. Zender spoke to *The Circle* about what the findings could mean for our understanding of the cryosphere.

A large, meandering glacial-melt stream feeds a supraglacial lake in Greenland.

Photo credit: Ian Joughin (distributed via imaggeo.egu.eu)

Why did you decide to look at the role of downslope winds in ice sheet melt?

The idea was sparked by colleagues at the University of Utrecht who discovered that a lot of melt was occurring during polar nights around their weather stations on an ice shelf in Antarctica. At one station, 23 per cent of the total melt every year was occurring after the sun went down. As a cryospheric climatologist, that surprised me because I wouldn't expect melt when the sun wasn't up. These colleagues made the case that wind was causing this melt.

Charlie Zender

Everyone thinks of surface melt as driven by sunlight—and we know it is the number one contributor to sea-level rise from new freshwater entering the ocean. But I don't think anyone appreciated how much of sea-level rise might be due to the wind component of melt. So, we set ourselves the task of finding out.

How did you go about answering that question?

We had already looked at all the weather stations on the Antarctic peninsula and the relative role of wind versus sunlight in ice melt. But to answer the question on a more regional scale, we needed to go to areas where observations hadn't been made yet.

We trained a machine learning algorithm to infer what the melt would be in between these weather stations by considering things like wind speed, sunlight and distance from the coast. The algorithm was able to emulate what the weather stations were measuring. This enabled us to estimate the melt produced in between the observations and look at the entire Antarctic peninsula.

When did you start looking at how these winds were affecting melt in Greenland?

Antarctica has ice shelves. Understanding surface melt is super important here because the more liquid there is, the more tendency there is for ice shelves to hydro-fracture and disappear. Hydrofracturing is when ice melts so fast on the surface that it creates cracks or fractures in the ice shelf, accelerating its overall thaw. Once we established that wind-driven melt was contributing to the break-up of ice shelves, we wanted to answer the question on a global scale: What's the relative role of wind versus sunlight heating in causing surface melt generally?

No one had looked at this very carefully in Greenland because there isn't as much reason to do it there. Greenland lacks significant ice shelves, but it has extensive katabatic winds—another type of downslope wind. These winds gather momentum from the coldest region at the top. They flow downhill and they're persistent. So, we knew the winds would have an impact on overall melt in Greenland—we just didn't know how much.

We also knew Greenland was generally much warmer than Antarctica. What we did not yet realize was that Greenland doesn't need wind as much as Antarctica does to tip the energy balance from frozen to melting.

When you compared Greenland to what you had been finding in Antarctica, what was the difference?

There were two big differences: Antarctica has a long-term trend toward decreasing surface melt, which surprised us. We think that's partly due to the recovery of the ozone: the more ozone there is, the more sunlight gets absorbed in the upper atmosphere rather than hitting the ice surface and contributing to melt. We were surprised because with global warming, we assume everything is heating up at the ➤

same rate. But in fact, it's regionally very different. Greenland experienced a transition from a very gradual increase in surface melt from the sixties to the nineties to a doubling of the rate starting around 1990, which is when we think the ice sheet really started to be influenced by global warming.

The second difference between the two is that in Antarctica, the wind-contributed portion of the melt is not changing very much—whereas in Greenland, wind as a contributor to surface melt is getting less and less important as the ice sheet reaches the thawing point. In Greenland, you don't need wind to observe melting because the sun warms the ablation zone up to zero degrees all on its own.

What can we learn about climate change and the cryosphere from these findings?

Antarctica is, in many ways, the last refuge from climate change. It's so isolated and cold that the warming it is experiencing overall is still a ways off from triggering the rapid melt we are seeing in Greenland. Greenland is giving us a glimpse of what the future of the Antarctic ice sheet might look like.

The other thing is that, although the overall melt rate for Antarctica is decreasing, during certain seasons in the warmest parts of Antarctica, there are ice shelves at risk of being fractured by the weight of melted water. When those ice shelves disappear, they will release the buttressing force that was holding back the ice streams on the continent itself. When the ice shelf disappears, that land-based glacier is going to speed up and go straight into the ocean because there's no ice shelf there anymore.

So, understanding the processes that lead to the surface melt can help us make the first predictions of ice shelf break-up in Antarctica. In other words, which ice shelf will be next, and when can we expect it to disintegrate due to hydro-fracture? These results will also improve our estimates of sea-level rise because we'll better understand the balance of wind- and solar-driven melt. ●

An ancient gas—and a big problem

MELTING GLACIERS AND METHANE EMISSIONS

The Svalbard archipelago is one of the fastest-warming places on the planet. As **GABRIELLE KLEBER** explains, its glaciers are melting at an alarming pace, leaving bubbling seeps of methane gas behind. Methane is a potent greenhouse gas that contributes substantially to global temperature rise, compounding the problem.

MORE THAN HALF of Svalbard is covered by the ice of 1,600 glaciers. The remaining land is exposed to the Arctic elements—so deeply frozen that it stays that way year-round. Together, the glaciers and permafrost create a solid, impermeable layer that caps the rocks beneath.

In Svalbard and other parts of the Arctic, many of these deeper rocks are rich in organic carbon, including methane. As long as the cap of glaciers and permafrost remains frozen, the methane can stay sealed. But as glaciers melt away and permafrost thaws, the methane can find its way to the surface, where it is released into the atmosphere.

> We believe that the groundwaters gurgling up in front of glaciers on Svalbard are emitting up to 2,310 tons of methane per year.

As Svalbard's massive glaciers melt, they are exposing land that has been covered by ice for a long time. In these recently exposed "forefields," we find that many groundwater springs are starting to emerge. These waters have been stored within the rocks beneath glaciers and permafrost, but with the removal of their frozen cap, they can reach the surface. The problem is that they contain methane gas, which is dissolved into the groundwater as the water flows through rocks. Like a cap being removed from a bottle of soda, the gas is released into the atmosphere quickly when the groundwater reaches the surface.

MEASURING THE METHANE IN GROUNDWATER SPRINGS

I was part of a research team from Norway and the UK that wanted to understand how much methane gas is being released by these groundwater springs. Travelling by snowmobile or on skis, we set off on a mission to visit as many springs as we could. We reached 78 different glaciers on Svalbard and took samples at more than 120 groundwater springs so we could measure the levels of methane in the water. In all but one spring, we found that the water contained very high concentrations of methane—in some cases, up to 600,000 times higher than a normal body of water. By the time this water reaches the surface, it is carrying a lot of excess methane.

In total, we believe that the groundwaters gurgling up in front of glaciers on Svalbard are emitting up to 2,310 tons of methane per year. That's like 229 million party balloons' worth of

A glacier and terminal moraine at Tinayrebukta, Svalbard, Norway.

methane being released into the atmosphere every year. To put that in context, it's also roughly equivalent to the annual methane emissions from 30,000 cows. Considering that there are more than 900 million cattle worldwide, the methane emissions from glacial groundwaters on Svalbard are dwarfed by emissions from industries like agriculture and waste management. But what's troubling is that Svalbard is certainly not the only place where groundwater emissions of methane are happening, and it is unclear how many more may turn up as the Arctic continues to warm.

THE IMPACT OF GEOLOGY

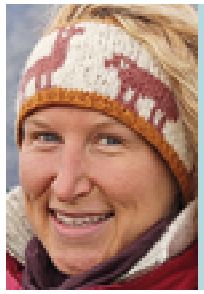
The levels of methane in the groundwater springs we measured appeared to be connected to the type of geology that the water emerges from. We found that the waters with the highest concentrations had flowed through underground layers of shale rock. The shale on Svalbard was formed up to 160 million years ago from mud at the bottom of a shallow sea that was compressed into rocks. Lots of organic material, such as plant life and small marine organisms, was compacted into these layers of rocks as they formed. Over time, under high pressure and temperatures, this material turns into fossil fuels, like methane.

This means the methane that's being flushed out of the rocks and brought to the surface by the groundwater now may be ancient gas that's been sequestered for millions of years.

This is concerning because we know there are large reservoirs of fossil fuels, including methane, stored deep within the rocks in many regions of the Arctic. Therefore, we should expect that this phenomenon is widespread, and that methane is seeping out in front of retreating glaciers across the Arctic. Moreover, as glaciers continue to melt at an accelerating pace, we believe methane emissions from shale rock will amplify.

Melting glaciers and thawing permafrost are uncovering pathways for ancient methane gas to be unearthed—a feedback loop caused by climate change. These methane emissions are out of our direct control: once this release mechanism has been triggered, we can neither stop it nor reverse it.

What we *can* do is focus on drastically reducing the emissions that are within our control. Doing so could help to curtail more methane from being uncovered by melting glaciers. ●



GABRIELLE KLEBER is a postdoctoral researcher at the University of Tromsø in Norway who studies methane release from glacial landscapes.

People and nature on the brink

AN SOS FROM ASIA'S WATER TOWERS

The snow and ice in the Hindu Kush Himalaya—a massive mountain range in central and south Asia—provide water to up to two billion people in Asia and support a region of vast, interconnected biodiversity. Researchers with the International Centre for Integrated Mountain Development (ICIMOD) say the consequences of climate change in these mountains are impossible to overstate. **SUNITA CHAUDHARY** makes the case for urgent action. ➤

Photo by Cristian Grecu on Unsplash

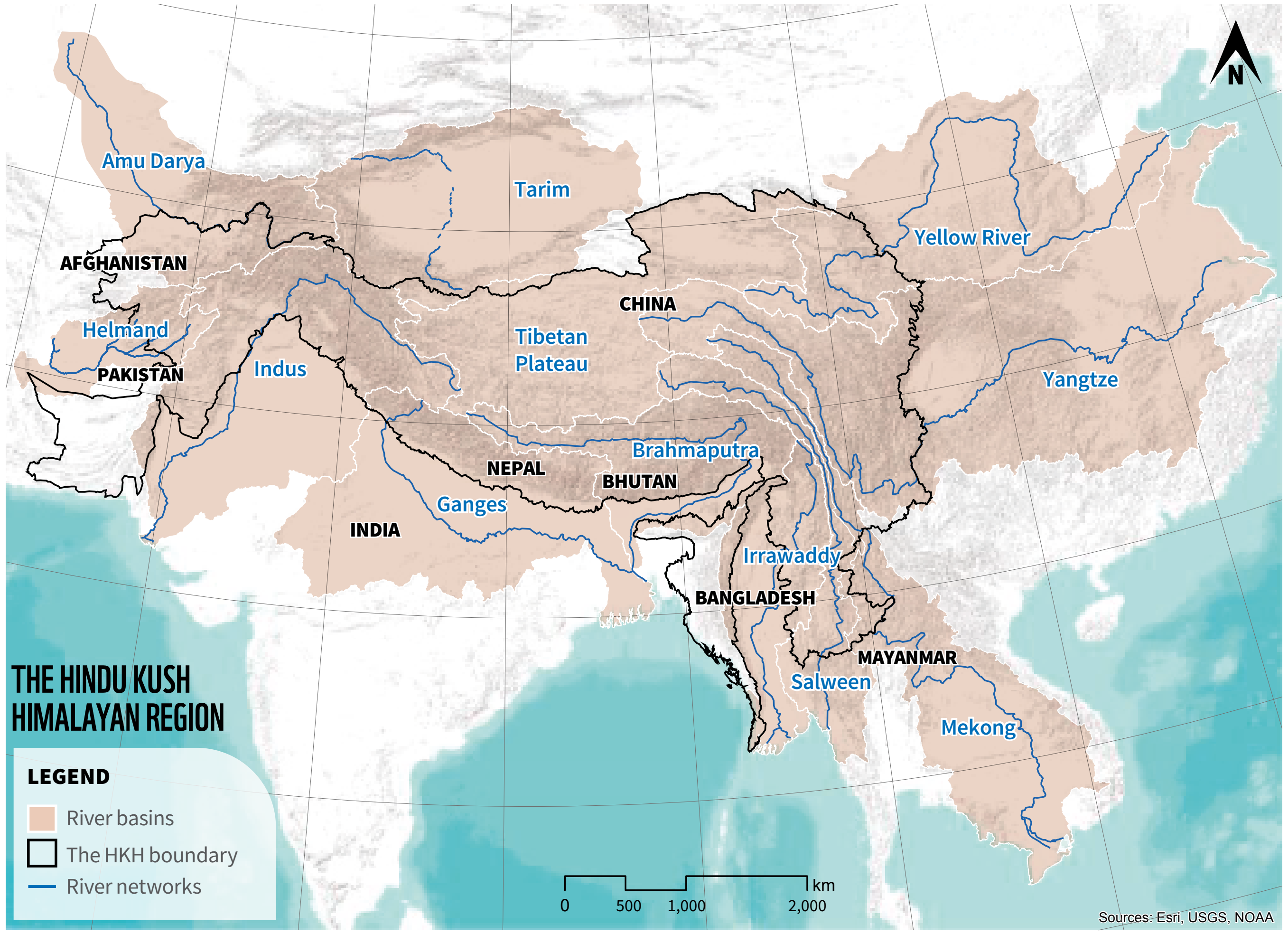
A young Tharu girl in southwestern Nepal digs to find drinking water.

THE MOUNTAINOUS "water towers" of the Hindu Kush Himalaya hold the third-largest mass of frozen water reserves in the world after the Arctic and Antarctic. But unlike those remote regions, this one is densely populated. Rivers originating here are critical for 271 million people living in the mountains and another 1.65 billion people downstream.

The mountain range stretches from Afghanistan in the west to Myanmar in the East and includes much of Pakistan, all of Nepal and Bhutan, mountainous border regions of India and China, and portions of Bangladesh. People in all these areas are at risk as glaciers, snow and permafrost in the region undergo unprecedented and largely irreversible changes due to the climate crisis.

These changes threaten the timing, availability and seasonal distribution of mountain water resources as well as food security, energy, ecosystems and livelihoods. The changes are already hitting some communities hard in the form of floods and landslides. During the last monsoon season, we saw devastating losses hit community after community as slopes made unstable by thawing permafrost and extreme rainfall led mountainsides to calve away, creating rivers of sediment capable of sweeping away everything in their path: homes, farms, hospitals, roads, schools, hydropower. ➤

These changes threaten the timing, availability and seasonal distribution of mountain water resources as well as food security, energy, ecosystems and livelihoods.



Map source: Water, ice, society, and ecosystems in the Hindu Kush Himalaya. An outlook. ICIMOD, 2023.

A DISAPPEARING WAY OF LIFE

I approach the subject of cryosphere loss as an ecosystems specialist and trained conservationist, but also as a *Tharu* Indigenous woman. I was born and raised in an Indigenous community in a subtropical forest and riverine landscape of Nepal, in the foothills of the Himalayas. Our community's deep connection to the land (*jamin*), water (*jal*) and forest (*jungle*) is integral to our physical, mental and spiritual well-being.

During my childhood, I gathered wild mushrooms and harvested vetiver grass from the nearby forests to weave baskets. But unprecedented flooding, erratic rainfall, droughts and wildfires have had profound impacts on our *jamin*, *jal* and *jungle*. Mushroom gathering is rare now, and we must walk several kilometres into the forest to find vetiver grass.

These changes hit me deeply as a *Tharu* woman. Our culture is at odds with the extractive industrial and economic models that are accelerating today's polycrisis. Instead, we have a deeply felt knowledge of the extent to which the health of our communities and of the land are entwined. Just like Indigenous Peoples in the Arctic, it is impossible to live as close to the land as we *Tharu* do and not feel this indivisibility in your bones.

NEARLY THREE-QUARTERS OF BIODIVERSITY ALREADY LOST

Of course, what I see as a biodiversity expert is just as devastating.

The astonishing biodiversity of the Hindu Kush Himalaya is disappearing with extraordinary speed. A staggering 70 percent of plant and animal diversity in the region has been lost in the last century, and wildlife, rivers and springs, forests, rangelands and wetlands are in crisis. With up to 85 percent of rural communities directly reliant on nature for food, water, flood control and more, the impacts extend beyond nature and will compound the vulnerability of the 271 million people who live in these mountains.

Without action, this outlook is set to worsen rapidly. Significant increases in extreme and unprecedented climate events have already resulted in massive environmental and socio-economic damages.

ICIMOD has been working for the peoples, nature and governments of this mountain biome for four decades. Given the pace and scale of the environmental and climate risks the region faces, we are now focused on doing our utmost to stave off the precipitous declines in nature, the losses in the cryosphere, and the changes in water availability.

Photo credit: Jitendra Bajracharya/ICIMOD

Visiting Darchula Village in Nepal to select sites for long-term environmental and socio-ecological monitoring. Front: Sunita Chaudhary; back (left to right): Darchula Village community resource person; Nabin Bhattarai (ICIMOD); Chandra Kant Subedi (Tribhuvan University).

ALL HANDS ON DECK

In a 2023 flagship report, Water Ice Society and Ecosystems in the Hindu Kush Himalaya, we stated categorically that deep cuts to emissions must start now. Every increment of a degree of warming matters to the glaciers here and the hundreds of millions of people and countless irreplaceable lifeforms that depend on them.

These changes hit me deeply as a *Tharu* woman. Our culture is at odds with the extractive industrial and economic models that are accelerating today's polycrisis.

Everyone alive today must press world leaders to ensure that the people who are most affected and least to blame are compensated and offered support to adapt. Last year, we launched a major advocacy drive, #SaveOurSnow, to rally scientists, athletes and communities across Earth's frozen zones to press their governments for faster action.

At ICIMOD, much of my work focuses on improving our understanding of what is happening in high-altitude ecosystems and communicating this to decision-makers. My colleagues and I are working to increase funding for local and Indigenous groups' environmental stewardship, supporting the growth of green, circular enterprises in the region, promoting sustainable agricultural management practices and policies, and supporting clean-air innovators tackling air pollution in our region.

We have also joined governments and negotiators from our region and other mountain and cryosphere zones to call for action at key global events. Despite some progress at COP28—including the first mention of mountains and the cryosphere in the final decision texts—things clearly need to move much, much more quickly. The good news is that in some corners, change is coming faster than anticipated as people begin to realize that it will be far less expensive to avoid the worst effects of the climate crisis than to adapt to them later.

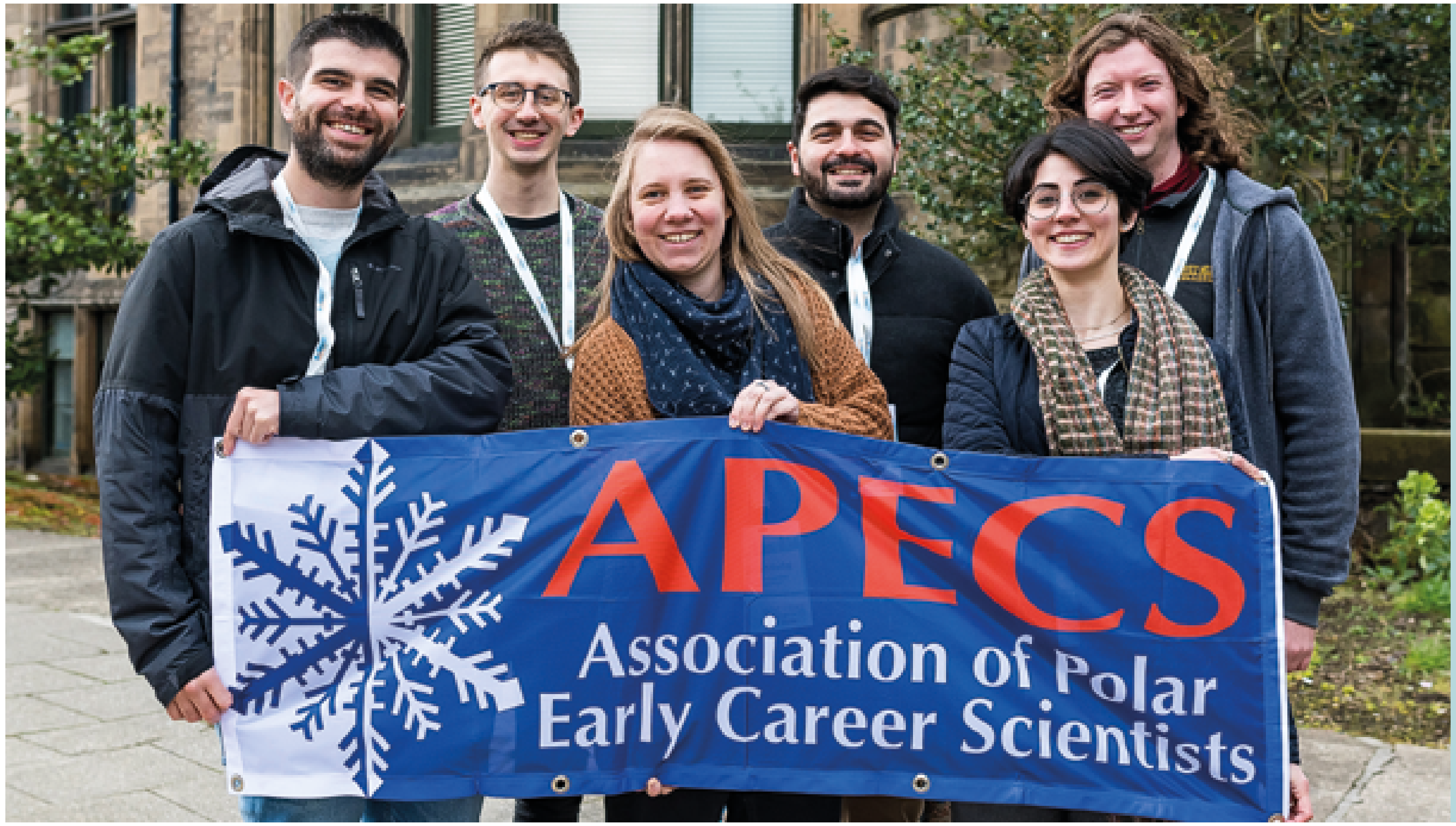
We all need to hold on to hope—and to use our votes and voices to press for the survival of snow, ice, species and humanity. It is not too late to avert the worst, but the work must start now. ●

SUNITA CHAUDHARY is an ecosystem services specialist with the International Centre for Integrated Mountain Development.

Early career researchers

SHAPING THE FROZEN FRONTIER

Early career researchers play a crucial role in understanding and addressing the evolving challenges related to the frozen realms of our planet, the cryosphere. Members of the executive of the **ASSOCIATION OF POLAR EARLY CAREER SCIENTISTS (APECS)** share some of their contributions and initiatives—and why their voices and work matter to the future of the cryosphere.



This article was contributed by the following early career cryosphere researchers (shown from left to right):

JOSÉ QUEIRÓS, University of Coimbra, Portugal

WILLIAM DAVID HARCOURT, University of Aberdeen, UK

LINA MADAJ, Vrije Universiteit Amsterdam, the Netherlands

HUGO GUÍMARO, University of Coimbra, Portugal

DENIZ VURAL, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Germany

RYAN O'HARA, Harvey Mudd College, US

GWENAËLLE GREMION, Université du Québec à Rimouski, Canada (absent from photo)

THE CRYOSPHERE ENCOMPASSES various forms of frozen water and water-related features, including sea, lake and river ice, snow cover, glaciers, ice sheets, and permafrost. But increasing air temperatures are altering these frozen landscapes, leading to permafrost thaw, declining sea ice, and glacier retreat.

These developments highlight the important role of the cryosphere in our global climate system. Studying it requires the use of diverse research techniques across the fields of geophysics, Earth system science, social science and more.

Buoyed by peer-to-peer support and organizations seeking their perspectives, early career researchers like us have the potential to contribute significantly to scientific studies and foster collaborations across the cryosphere research communities.

NETWORKING, SHARING, COLLABORATING

The opportunity to explore the pristine environments of the cryosphere has expanded in step with new technologies that enable us to collect critical data. Early career researchers, including APECS members, are harnessing these tools to drive fundamental cryosphere research.

Studies indicate that compared to senior researchers, those who are just starting out in their chosen fields are more adept at incorporating multidisciplinary perspectives into their work. They are also more likely to participate in networking activities, where they can forge connections with peers across diverse disciplines. These collaborations facilitate the exchange of ideas, encourage interdisciplinarity, contribute to the development of new strategies, and can help integrate Indigenous knowledge. It's an approach that also enriches the contribution and review process when it comes to answering key scientific questions.

As future leaders at the early academic stages (whether at the masters, doctorate or postdoc level), we are uniquely positioned to witness and be affected by changes in the cryosphere. Drawing on our experiences, we play a crucial role in applying scientific knowledge to policy-making with a more eco-friendly approach.

> As early career researchers, we have the skills to incorporate science into multidisciplinary approaches to tackle cryosphere changes, promote collaboration with policy-makers, and encourage public action.

PROVIDING A VOICE FOR EARLY CAREER POLAR RESEARCHERS

Since the fourth International Polar Year (2007–08), APECS has played a key role in amplifying the voices of early career researchers and elevating our visibility among our research peers. It provides a unique platform for nearly 5,000 researchers from more than 80 countries and fosters opportunities for innovative, international, interdisciplinary collaborations among them. It recruits, retains and promotes the next generation of polar and cryosphere enthusiasts.

The association has also organized online conferences, world summits, and sessions at scientific conferences to better address the needs of early career researchers in polar and cryosphere sciences. For example, APECS was present at the One Planet - Polar Summit in Paris in November 2023 and the Polar Symposium in Monaco in February 2024.

As early career researchers, we have the skills to incorporate science into multidisciplinary approaches to tackle cryosphere changes, promote collaboration with policy-makers, and encourage public action. As trailblazers leading these discussions, we have the potential to inspire innovative thinking and bring about lasting positive changes in our communities for a better environment.

We are the generation tasked with addressing the critical challenges facing the cryosphere and the Arctic, so our role holds immense significance for the future of the planet. The impacts of climate change on frozen landscapes are undeniable, with permafrost thaw, declining ice cover, and glacier retreat being just a few examples. These changes affect local ecosystems and communities, but also have far-reaching implications for global climate systems.

Our generation must take proactive steps to mitigate these effects, using our multidisciplinary perspectives and innovative approaches to drive scientific research, inform policy-making, and inspire public action. By harnessing our collective expertise and leveraging platforms like APECS to amplify our voices, we can lead the way towards sustainable solutions that protect the integrity of the cryosphere and ensure a healthier planet for generations to come. ●

APECS MEMBERS MAKING A DIFFERENCE IN THEIR FIELDS

Early career researchers specializing in the cryosphere:

- have actively contributed to assessing Intergovernmental Panel on Climate Change reports since 2018, resulting in multiple publications
- organized a Cryosphere Pavilion session at COP 28 titled "Youth in the Poles: The Role of ECRs in Preserving the Cryosphere"
- submitted an information paper to the 2023 Antarctic Treaty Consultative Meeting—the primary forum for discussing Antarctic policy, science and logistical issues—with the support of several delegations
- led a recent PLOS Climate collection featuring opinion and review papers on a wide range of topics
- actively participate and collaborate in the International Arctic Science Committee, the Scientific Committee on Antarctic Research, the Climate and Cryosphere of the World Climate Research Program, and the Southern Ocean Observing System
- have conducted globally recognized initiatives, such as Antarctica Day and Polar Weeks, to raise awareness about climate change and the significance of polar regions

THE BACK PAGE

Photos courtesy of unknown (1920) and Bruce F. Molina (2005), obtained from the Glacier Photograph Collection, Boulder, Colorado, US: National Snow and Ice Data Center/World Data Center for Glaciology.

Alaska's Pedersen Glacier: Then and now

In the early 20th century, the Pedersen Glacier in Alaska's Kenai Mountains was calving icebergs into a marginal lake near Aialik Bay. By 2005, the glacier had retreated so much that the lake had transformed into grassland. From 1984 to 2021, the Pedersen Glacier retreated by 3.2 kilometres.