CHAPTER 3

Mountain Glaciers and Snow

Even 1.5°C Is Too High for Some Mountain Glaciers, But with Visible Benefits This Century to Preserve Ice

Why 2°C is Too High for Glaciers and Snow: Recent and more sophisticated measurements now confirm that essentially all mountain glaciers worldwide are losing ice: some, such as those in the Alps, at distressingly rapid rates over the past two summers alone. If 2°C warming is reached, projections show that nearly all tropical glaciers (north Andes, Africa) and most mid-latitude glaciers outside the Himalayas* and polar regions will disappear, some as early as 2050. Others are large enough to delay complete loss until the next century, but have already passed a point of no return. Even the Himalayas are projected to lose around 50% of today's ice at 2°C. Reestablishment of lost glaciers would require temperatures well below those of today, and take centuries to millennia. As glaciers melt, risks of catastrophic events – landslides, sudden ice shears, and in some cases glacial lake outburst floods – will rise, affecting entire communities. Winter snowpack at 2°C generally will decrease on average, but will also become more volatile; with some years of hardly any snow, as shown in the southern Andes just this past winter season, and others with record-breaking amounts that threaten infrastructure and lives. Losses in both snowpack and glacier ice will have dramatic impacts on downstream dry season water availability for agriculture, power generation, and drinking. Impacts may be extreme in especially vulnerable river basins, such as the Tarim in northwest China and the Indus.

Preserved at 1.5°C: Today's climate is already too warm to preserve some mountain glaciers, which will be lost even with no additional warming than that of today's 1.2°C. Continued warming, even through the brief 1.6°C peak of very low emissions (SSP1-1.9) still means that today's very fast ice loss in glaciers globally will continue through at least the 2050s. However, latest projections show that with very low emissions, this loss will begin to slow in at least some regions around 2060, and stabilize towards the end of this century. Some may even show slow glacier re-growth starting in the 2100s, though this would occur extremely slowly (many decades to centuries). Annual snowpack would stabilize at 1.5°C levels, e.g. still a lower average amount than today, but respond quite quickly to decreases in CO_2 in the atmosphere and resulting lower temperatures. This visible snow and ice preservation, and its benefits for freshwater resources, may be one of the earliest and visible signs to humanity that steps towards low emissions have meaningful results.

Today's Emissions Heading Towards 3°C+: If CO_2 continues to accumulate in the atmosphere at today's pace, which has not paused despite current pledges, global temperatures will reach at least 3°C by end of century. Once 3°C is passed, even most large polar glaciers, and the very high-altitude glaciers in the Himalayas and southern Andes, are unlikely to survive. Complete loss may not occur for one or two centuries, but become inevitable should mitigation remain inadequate in the next few decades.

The 2°C Takeaway: 2°C will result in extensive, long-term, essentially irreversible ice loss from many of the world's glaciers in many major river basins, with some disappearing entirely. Snow cover also will greatly diminish. A rise of 3°C will spread and greatly speed up this loss. If global leaders cause temperatures to reach this point through continued fossil emissions, they are committing the planet to extensive loss and damage of water resources and ecosystems well beyond limits of feasible adaptation.

* As used in this chapter for ease of reference, "Himalayas" refers to the massive mountain and high plateau region running across Central, South and East Asia, from Afghanistan in the west, to Myanmar in the east; sometimes also referred to as "High Mountain Asia."

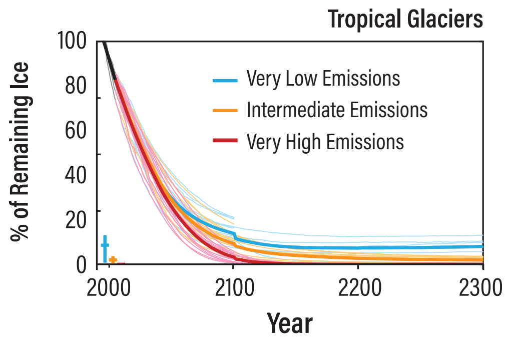
2023 Updates

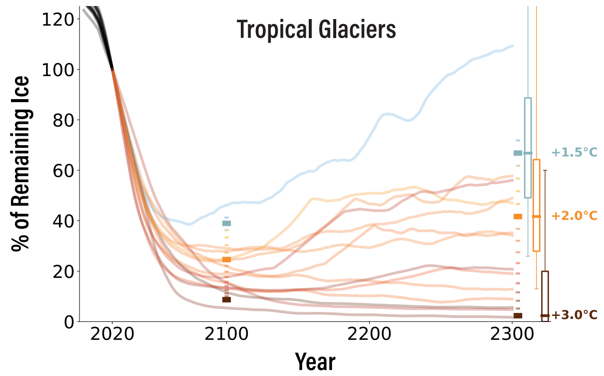
- Improved projections forecast greater glacier loss by 2100, including total or near-total glacier loss in mid- and low latitudes by 2100 under a high emission scenario,[25] as well as up to 80% glacier loss in the Hindu Kush Himalaya.[2,13]
- New research suggests that glaciers can now produce floods even at the highest elevations, which were previously stabilized by snowfall and cooler temperatures.[33]
- One study found that an estimated fifteen million people worldwide are now at risk from glacier lake outburst floods, with most residing in High Mountain Asia and Peru.[30]
- New research highlights growing threats to hydropower in High Mountain Asia due to declining mountain glaciers and thawing mountain permafrost.[17]
- Numerous new studies have identified increasing decline of mountain snowpack,[3,10] with significant impacts on hazard risk, water supplies,[35] and food security, including via global trade.[24]
- Snowpack across the Arctic and near-Arctic, especially in northern Canada and Alaska, melted far earlier than normal, leaving ground bare for longer. Meteorologists attribute some of the record North American summer 2023 heatwaves to this record melt.
- Glaciers in the Swiss Alps lost 10% of their ice in the two years 2022–23, reported the Swiss glacier monitoring agency GLAMOS. These losses were attributed especially to heat waves, which are expected to intensify as time goes on.[6]
- What may have been the most extreme heatwave on the planet in 2023 occurred in the Andes during the southern hemisphere winter, with temperatures up to 20°C above normal for several weeks, leading to concerns for water shortages due to decreased snowpack, especially in Chile, Argentina and Paraguay.[22]
- New research underscores that threats to ecosystems are dramatically growing with loss of the mountain cryosphere, with decline and extinction already observed today.[2,13,36]
- The IPCC AR6 Synthesis Report reiterates the urgency of keeping global average temperature rise below 1.5°C to avoid the most serious consequences and hard adaptation limits for many generations in high mountain and downstream areas.[15]

Background

Many glaciers of the northern Andes, East Africa and Indonesia, especially those close to the Equator, are disappearing too rapidly to be saved even in the present 1.2°C climate.[19] These glaciers have mostly been shrinking since the end of the Little Ice Age, but global warming greatly accelerated their melting. Some of these,

FIGURE 3-1. **New Work on Glacier Projections**





Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–3.0°C

Glacier graphs in this chapter represent innovative new work from Schuster et al. (2023), using projections from the glacier models described in Rounce et al. (2023), Huss and Hock (2015), and Maussion et al. (2019), updating previous projections used in past SoC Reports (Marzeion et al., 2012) with much greater detail for individual glaciers. The most striking and positive difference is for tropical glaciers, showing that these need not be totally lost at even 1.5°C as projected in Marzeion (2012).

However, the reality is that as of 2023, these tiny glaciers near the equator (in Africa, South America and Indonesia) have already lost most of their ice. Those glaciers that remain are already quite small, and at very high altitudes that help protect them from warming. According to the new projections, at least some of these small patches of remaining ice likely will be preserved at 1.5°C, of high symbolic importance to local communities.

TOP: BASED ON MARZEION ET AL. (2012), BOTTOM: SCHUSTER ET AL. (2023)

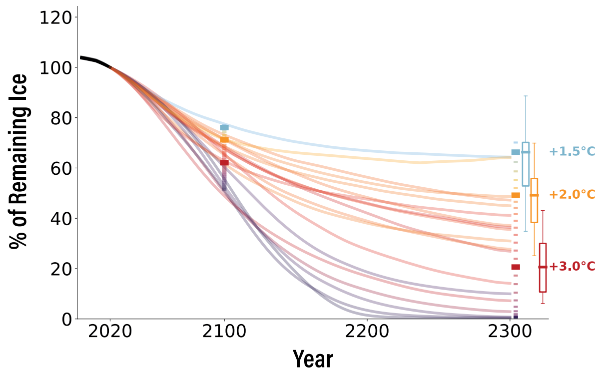
especially in parts of the northern Andes, would have provided a reliable seasonal source of water for hundreds or thousands of years without human-induced warming. Their loss – which for some glaciers may occur by mid-century – would impact rural populations in northern Peru especially, as well as in Bolivia and northern Chile, while also impacting major cities such as La Paz.[16]

Severe losses also are occurring today from mid-latitude glaciers and others outside the polar regions: these include glaciers in the European Alps, southern Andes and Patagonia, Iceland, Scandinavia, the North American Rockies and much of Alaska, and New Zealand. These losses will continue at a steep rate over the next several decades just from current warming, with smaller glaciers continuing to disappear completely and others decreasing to only 10–20% of their 2010 size. With very low emissions however, up to 40% of glacier ice in these regions could be preserved.[25] Projections in a few glacier regions even show slow re-growth beginning between 2100 and 2300, but only with very low emissions and essentially carbon neutrality by 2050.[20]

Any other emissions path will eventually result in almost complete loss of all land glaciers on Earth outside High Mountain Asia and high-latitude polar regions, which include northern Canada / Alaska and southern Patagonia. With high emissions, and global mean temperature rise exceeding 4°C by 2100, any substantial seasonal snowpack also will become rare outside the polar regions and very high mountains.[19]

Losses in both snowpack and glacier ice will have dramatic impacts on downstream dry season water availability.

FIGURE 3-2. **Glaciers Globally**

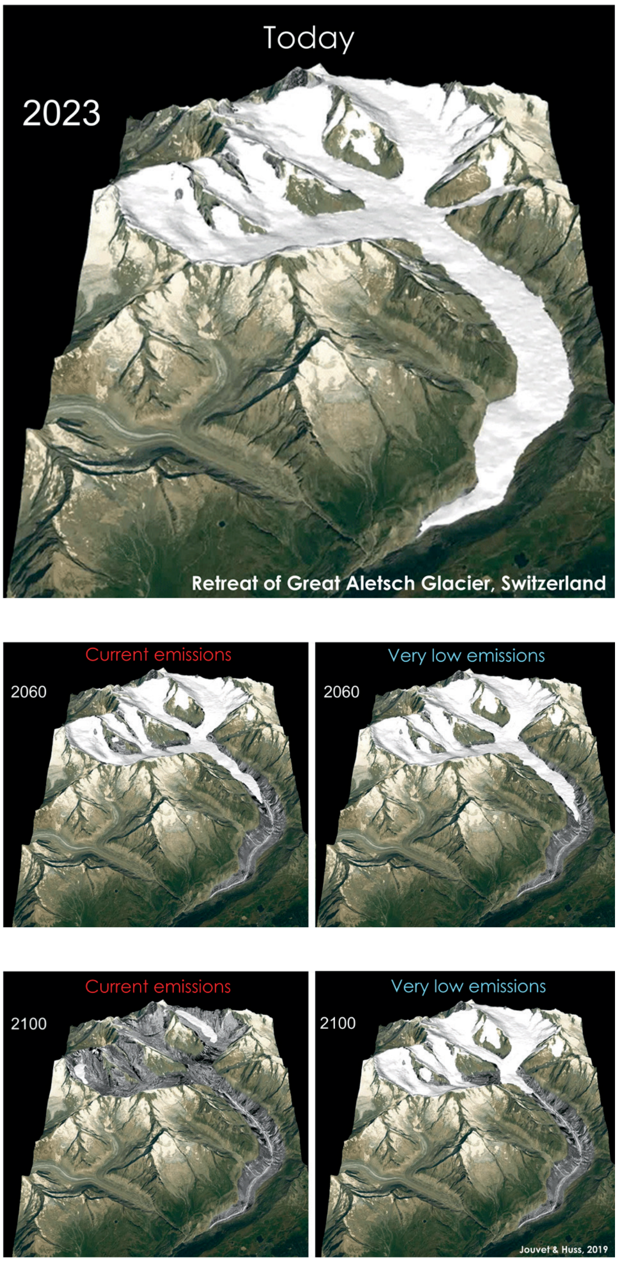


Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–4.5°C

Glaciers worldwide are losing ice at today's 1.2°C. Should current emissions continue, meaning global temperatures reach 4.5°C by 2100, this loss will become quite rapid even for the largest glaciers near the poles that make up most of this all-glacier graph; reaching 50% worldwide glacier loss by 2100 and no glaciers globally by 2200.

CREDIT: SCHUSTER ET AL. (2023)

FIGURE 3-3. **The Future of Great Aletsch Glacier**



Great Aletsch today (top); and in 2060 (middle) and 2100 (bottom) with low and high emissions. With a great deal of ice loss already in-train with today's warming, the glacier will continue to lose ice through about 2060 even with low emissions; but by 2100, the difference is clear.

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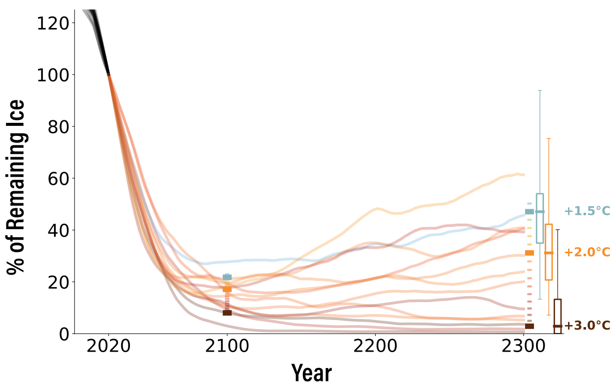
FIGURE 3-4. **Glaciers of the Alps**



Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–3.0°C

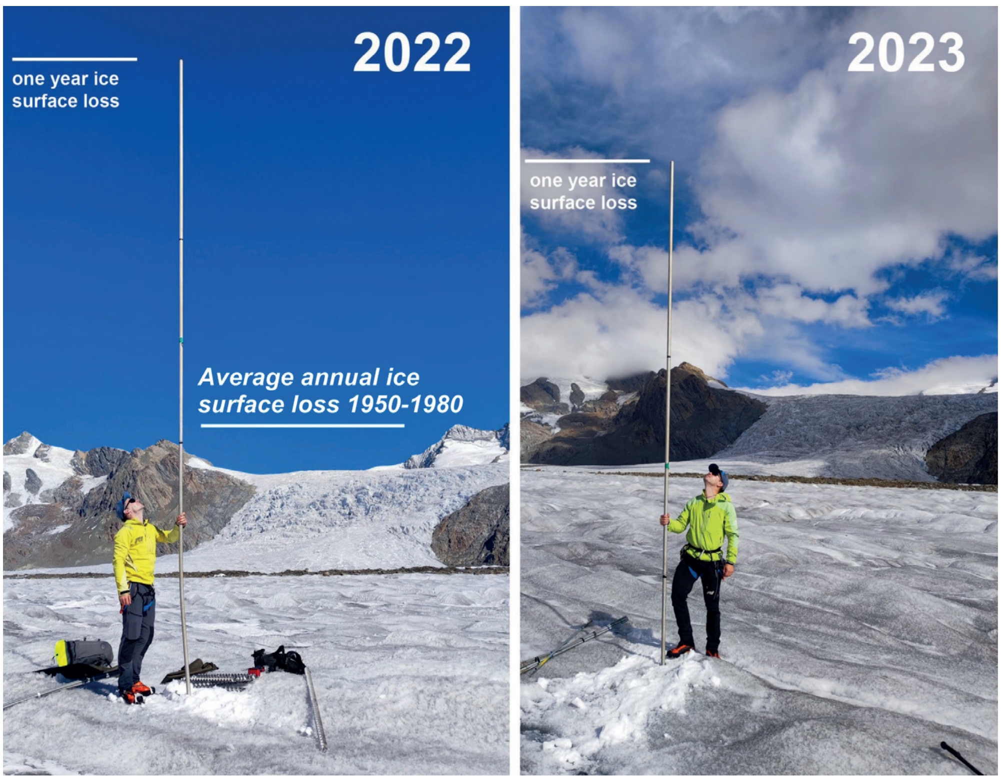
At 1.5°C, not only do models show the Alps preserving more ice, but even showing slow re-growth by 2300.

CREDIT: SCHUSTER ET AL. (2023)

In those "high altitude and high latitude" regions, only 35-75% of glacier volume will remain by the end of this century under high emissions scenarios.[19] However, if we follow a very low emissions pathway, the glaciers and snowpack of High Mountain Asia – important for seasonal water resources – will stabilize and eventually begin to return. Glaciers in Central Asia and the southern Andes also would preserve twice as much ice with rapid emissions reductions consistent with the 1.5°C limit.[25] At higher emissions levels resulting in peak temperatures above 2°C, losses in high altitude and high latitude regions will continue. With very high emissions, similar to today's year-on-year rise in CO_2 concentrations, this loss would be ever more rapid.[19] In the Hindu Kush Himalaya, 70-80% of current glacier volume will disappear by 2100 under such a high emission scenario; whereas a low emissions scenario could limit glacier loss to 30%.[13]

Glaciers generally gain mass via snow deposition in winter, and lose mass as meltwater in summer over the course of a year. Global warming means that a given glacier will experience a net loss of ice every year at higher and higher elevations, because the annual gain by snowfall turning to ice decreases, and an increasing loss from

FIGURE 3-5. **Two Record Years of Ice Loss**



Height of glacier ice loss at Konkordiaplatz, Switzerland, during record melt years 2022 and 2023 compared to the average yearly ice loss between 1950–1980. The Swiss Alps as a whole lost 10% of their remaining ice in just two summers.

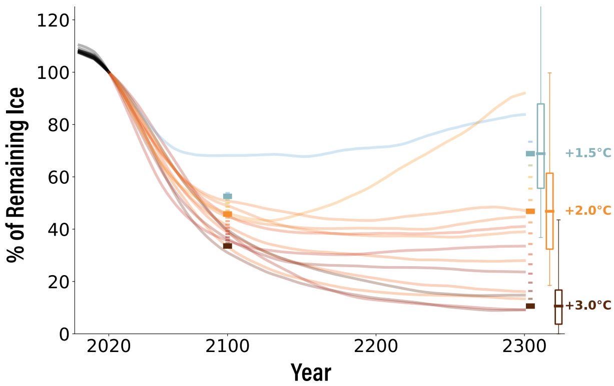
PHOTO: MATTHIAS HUSS.

Image by Praful Rao of Save the Hills

Flood damage in Rangpo caused by the Sikkim flood, when the Teesta III dam was swept away by a GLOF in October 2023.

A low emissions scenario could limit glacier loss to 30% in the Hindu Kush Himalaya.

FIGURE 3-6. **Glaciers of High Mountain Asia**



Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–3.0°C

High Mountain Asia includes the highest mountains of the world, in the Hindu Kush Himalaya. Even these extremely high altitude glaciers, which provide seasonal water to at least 2 billion people, will lose most of their ice by 3°C; 1.5°C preserves much more.

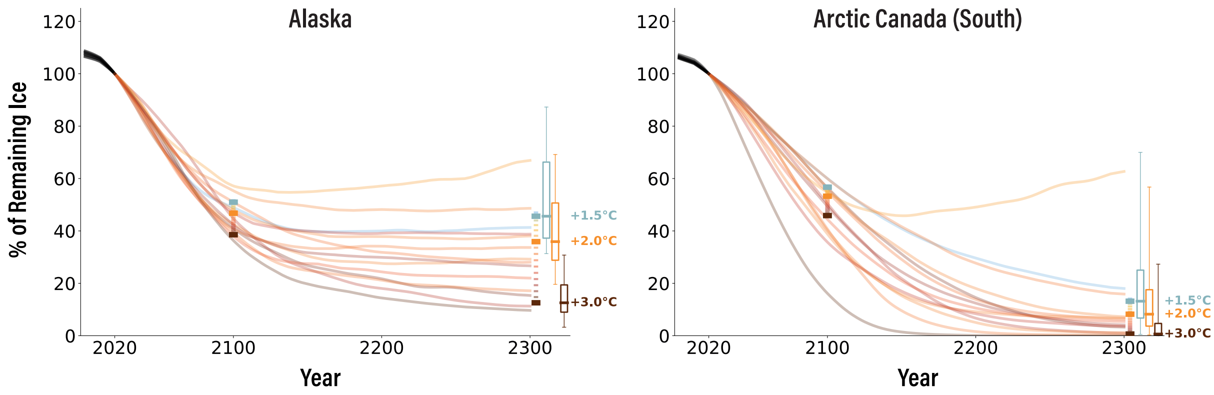
CREDIT: SCHUSTER ET AL. (2023)

melting especially at low elevation significantly outpaces the gain each year. A threshold is crossed when the entire glacier, from bottom to top, is losing ice each year: at that point, the glacier is doomed. The majority of glaciers in the European Alps experienced this during the summer of 2022,[34] with an overall loss of 6% of the total volume of Swiss glaciers alone in one single melt season.[29]

Glaciers can shrink and even disappear completely over the space of just decades or a century. When Glacier National Park in the U.S. was created in 1910, it had around 150 glaciers; today, fewer than 30 remain, and those have shrunk by about two-thirds. Half of the glaciers in World Heritage sites globally will likely disappear by 2100 if emissions continue under a "business-as-usual" scenario.[32] From 1901 to 2018, glaciers outside Antarctica contributed nearly 7 cm to global sea-level rise.[8] While such melt has been rapid, large glaciers grow back only slowly, especially at temperatures above pre-industrial. Limited modeling seems to indicate that "re-growth" of large mountain glaciers, to scales present in the mid-1900's or even today, would take many centuries; and perhaps even millennia in some regions (see glacier graphs figures).

Therefore, on human timescales, the disappearance of today's glaciers is an essentially permanent change to the mountain landscape. Very low emissions are key to ensuring as little ice as possible is lost during this current period of rapid decline. A very low emissions pathway is essential to preserving the ecosystem services glaciers

FIGURE 3-7. **Large Arctic Glaciers of North America**



Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–3.0°C

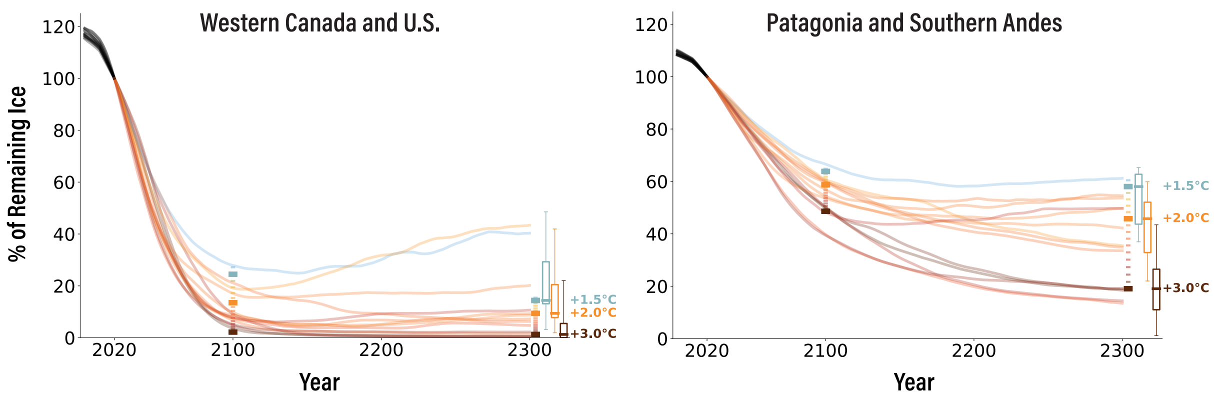
Very large glaciers, such as those in Alaska and Arctic Canada behave somewhat like ice sheets: slow to melt in the beginning, but then accelerating and continuing for centuries. So unlike smaller glaciers, their melt continues to accelerate through 2300, depending on global temperature in 2100.

CREDIT: SCHUSTER ET AL. (2023)

provide, and to minimizing the risk of severe hazards such as glacial lake outburst floods that accompany loss of mountain glaciers.[27,28,30,37]

Glaciers and snowpack have varying importance to nearby communities and those further downstream as a source of water for drinking and/or irrigation, with some contributing only a few percent over the course of a year, but of greater importance during dry seasons, heat waves and droughts.[4,23,31] Glaciers in some regions, such as the tropical Andes, or the Indus and Tarim basins in High Mountain Asia, contribute a high percentage of seasonal water supplies; in the dry Tarim and Aral Sea basins, close to 100% during the summer months.[13] While the rapid melting of glaciers temporarily increases water availability, as the glaciers continue shrinking that seasonal availability will begin to decrease (referred to as passing "peak water"). This may make certain economic activities – and even continued human habitation – impossible. Indeed, most glacier-covered regions outside high latitude polar regions and the Himalaya have already passed this period of "peak water".[11,12] Extensive adaptation therefore needs to begin immediately to prepare for this future, even as mitigation to preserve glaciers as much as possible is also prioritized.

FIGURE 3-8. **Glaciers of the Americas**

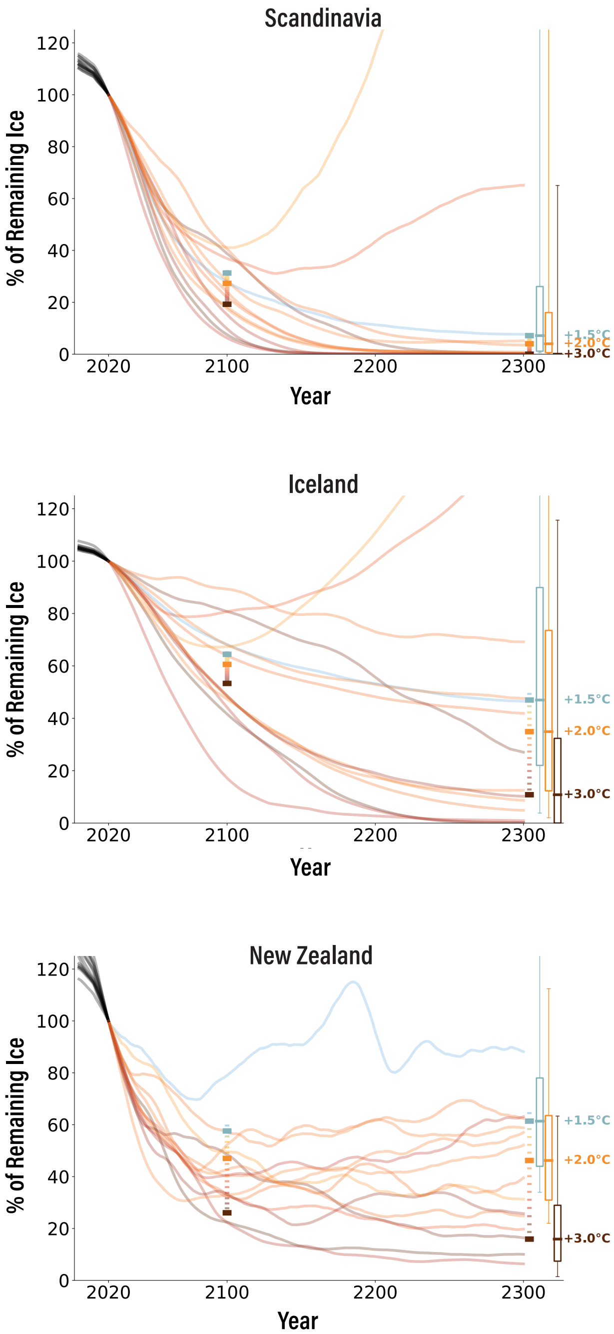


Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–3.0°C

The glaciers of western Canada and the U.S. are steeply losing ice today; but remaining within 1.5°C can preserve 50% more ice in 2100. The glaciers of Patagonia are among the fastest receding in the world; but these models show that loss slowing and preserving about 50% of their current ice by 2300; with much greater losses at 3°C.

CREDIT: SCHUSTER ET AL. (2023)

FIGURE 3-9. **Mid-Latitude Glaciers**



Smaller mid-latitude glaciers show surprising uncertainties in these new projections, especially Iceland and Scandinavia, where some models assume shutdown of the AMOC, causing that region to cool and glaciers actually to grow. However, most models show these glaciers preserving much more ice at 1.5°C. In the case of Scandinavia, only low emissions preserve amounts reliably above zero.

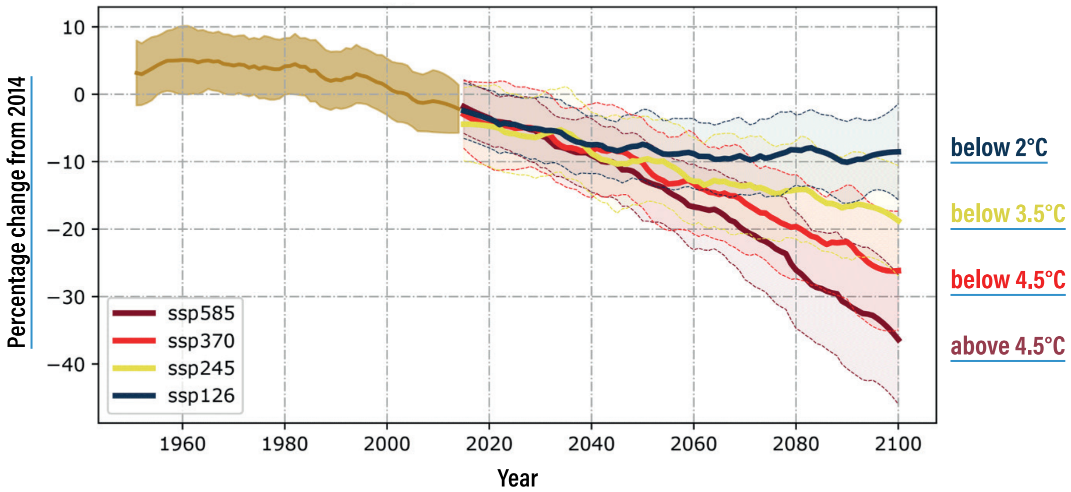
CREDIT: SCHUSTER ET AL. (2023)

Reestablishment of lost glaciers would require temperatures well below those of today, and take centuries to millennia.

In addition to glaciers, mountains also store water in the form of snow. In fact, seasonal freshwater in many mountain and lowland regions is dependent on annual snowfall, and meltwater from snow is of greater important than meltwater from glaciers in many areas. However, snowfall has become less consistent in many mountain watersheds, with extremes of “snow drought” alternating with high amounts of snow, or wet snow, that increase the risks of avalanche and flood,[14] such as in California, USA in winter 2023. In many mountains, it now appears that snow generally is following the same downward trajectory as glaciers: snowfall is reducing as temperatures rise above freezing at higher and higher altitudes, with precipitation that would have fallen as snow in past decades, increasingly coming down as rain,[8] and often in the form of hazardous extreme rainfall.[21] At lower elevations and latitudes, snow will fall less often or not at all, and the winter season will shorten.[26] Seasonal snowpack will not form, resulting in loss of stored water in the snow itself and in underground aquifers. A decreasing extent and duration of snowpack has already been observed in many mountain areas.[3,10] Continued declines in annual snowpack will result in negative economic impacts for many sectors, especially agriculture, hydropower, and tourism,[9] with global ramifications; and threatens the availability of sufficient water supplies for downstream populations.[18]

Mountain snow sustains water supplies for ecosystems and people far beyond mountain regions, as meltwater travels great distances across grasslands and deserts to densely populated and cultivated coastal regions. For example, people in cities as diverse as Los Angeles, Delhi, and Marrakech are to some degree dependent on meltwater from snow. In the western U.S., rising temperatures have caused a general decrease in annual snowpack, leading to ever more severe water shortages.[7] In both the Arctic and mountain regions, the well-being of people and many species depend on seasonal snow cover. For reindeer-based Arctic Indigenous cultures, increasing numbers of animals are lost to starvation when more unseasonal rains falls on snow, forming thick layers of ice that makes it impossible for reindeer to access grazing through the ice cover. Decreases in snow cover negatively impact snow-dependent tourism, especially in the United States, Japan, and Europe.[9,11] Lack of mountain snow cover also increases the risk of wildfires, as well as natural hazards that can materialize as disasters

FIGURE 3-10. **Decline in Northern Hemisphere Snowpack**



Under a high emissions scenario, snow cover in the Northern Hemisphere will decline by nearly 50% by 2100.

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such as mudslides in the wake of such wildfires. In some areas, the impacts of glacier melt and snowmelt on freshwater availability have already contributed to increasing tensions and/or conflicts related to water resources.[1]

A strengthening of climate pledges will have especially significant benefits for those communities in the Andes and Central Asia that are most dependent on glacier runoff as a seasonal source of water for drinking and irrigation. Stronger pledges also will significantly benefit economies dependent on meltwater from glaciers and seasonal snowpack for power generation, agriculture and revenue from snow tourism, such as in the European Alps and North American West. Low emissions also allow local communities more time to adapt, even in those equatorial and mid-latitude regions where smaller glaciers are doomed to disappear completely even at 1.5°C.

Every fraction of a degree of global temperature rise substantially impacts the loss of the mountain cryosphere.[5,25] To preserve as much glacier ice and ecosystem services as possible, a sharp strengthening of climate action is needed towards the 1.5°C limit. This requires a general 50% reduction in human-induced GHG emissions by 2030, and stronger commitments and implementation of actions in the near-term 2030–2040 timeframe. These low emissions pathways, minimizing overshoot, could make the difference between rapid and disruptive loss of regionally important glaciers and snowpack, and significant steps towards their preservation.

Every fraction of a degree of global temperature rise substantially impacts the loss of the mountain cryosphere.

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