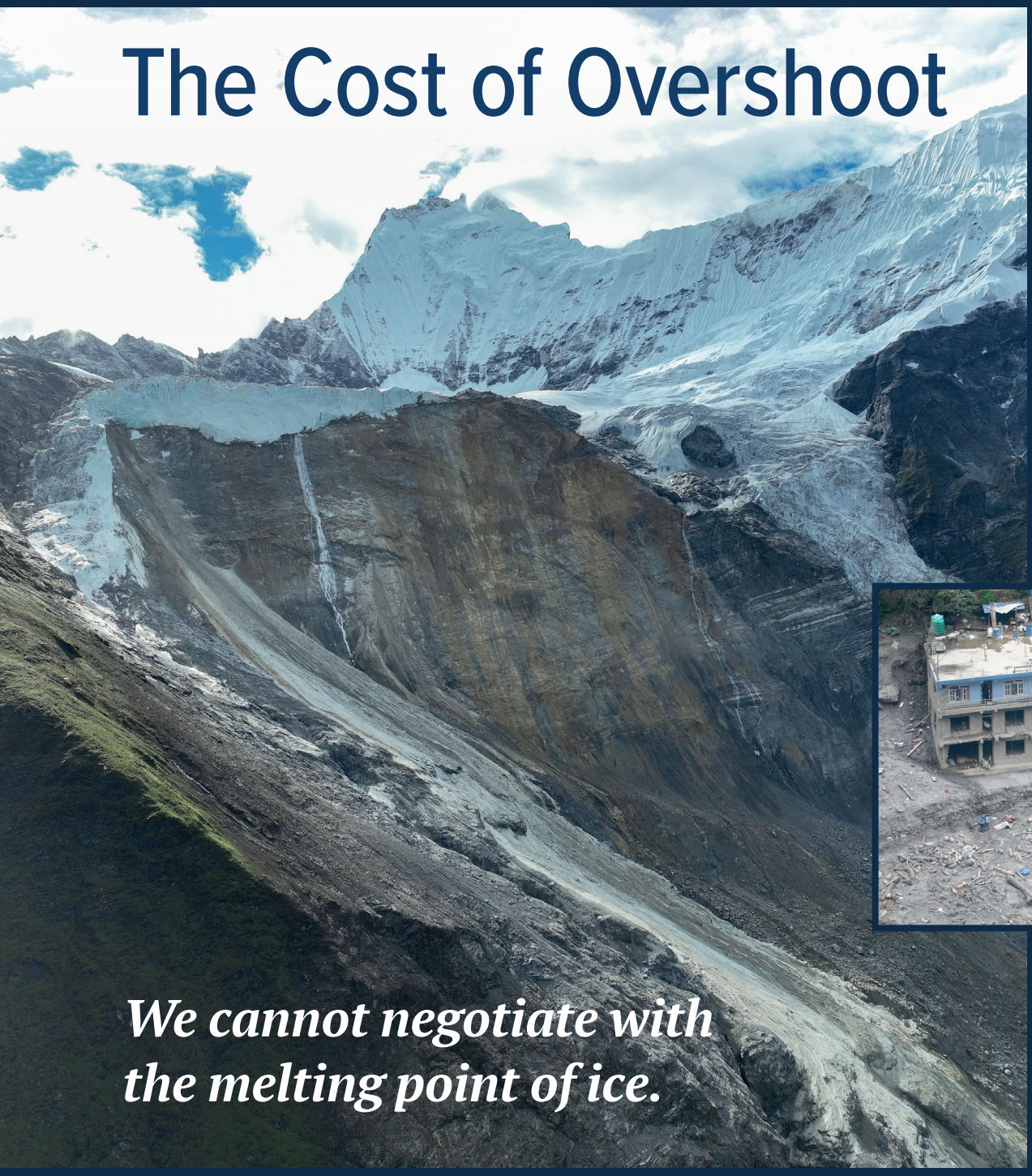
# State of the Cryosphere 2026

## The Cost of Overshoot





*We cannot negotiate with the melting point of ice.*

NOVEMBER 2026

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NOVEMBER 2026

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International Cryosphere Climate Initiative

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*State of the Cryosphere 2026 – The Cost of Overshoot*
We cannot negotiate with the melting point of ice.

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Cover

The Rasuwa disaster, August 2026, killed more than 1400 people; over 5000 missing; and at least $5 billion in infrastructure damage, and is a tragic foretaste of a world under high overshoot.

Left: The sheared-away glacier and mountainside below Tsangbu Peak, part of the Langtang Lirung massif in Nepal. For scale, the sheared edge is over 1 km wide. Photo: Guoxiong Zheng

Right: Damaged buildings in Timure, Rasuwa District, Nepal, near the Nepal-China border. Photo: Alamy / SOPA Images

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# Ice Matters

This Report outlines a stark choice. With some level of overshoot of the 1.5-degree limit inevitable, this generation can decide to return to a pathway consistent with the Paris Agreement: limiting overshoot to a few decades and returning below 1.5°C by the end of this century. Or, we can continue our current path, reaching 3°C or more above pre-industrial temperatures by 2100.

That choice will cause a very different response from the planet's main cryosphere components: its massive polar ice sheets, mountain glaciers and snow, permafrost, sea ice, and polar oceans. Some of these will be near-immediate; others unfold over decades and centuries. Common to all however is that the scale of loss and damage or adaptation needs caused by cryosphere loss – sea-level rise, loss of seasonal water supplies and desertification, weather and ocean current disturbance – will be decided by just how much overshoot we allow.

In my work as UNFCCC Executive Secretary and afterwards, I have seen cryosphere loss firsthand: from Antarctica, to Svalbard in the Arctic, to the mountains of Nepal and Bhutan and near-extinct glaciers in the Alps, like the terribly shrunken Schmiedinger Kees in Austria. I have also seen firsthand the impacts of that loss, from sea-level rise in my own Costa Rica, to growing drought below dwindling glaciers and snowpack in Peru, the western U.S. and Germany.

Sea-level rise from global warming's impact on Antarctica will take centuries to unfold; that on glaciers in the Himalayas and elsewhere is much more immediate. Just how immediate, we saw in the devastating Rasuwa disaster in August, and in Blatten in Switzerland last year.

For each additional increment of $CO_2$ in the atmosphere from fossil fuel use, such damage will expand, because the ice is unforgiving in its response to overshoot. Extreme weather events, heatwaves and wildfires tied to loss of summer sea ice. Meltwater from both polar ice sheets causing sea-level rise and slowing key ocean currents. Acidification and warming of polar waters threatening essential fisheries of cod, salmon and krill.

But emissions are still rising when they should plummet; and fossil fuel expansion continues – defying science, economics, and common sense. Yet we have a way out: because while the crisis is accelerating, so too are the solutions. Renewables are the cheapest, fastest, and most secure source of new electricity almost everywhere. Clean energy has gone from alternative to unstoppable.

We must close the overshoot gap this decade – by tripling renewables, doubling efficiency, electrifying economies, slashing methane and black carbon, reversing deforestation, and speeding the transition from fossil fuels.

For decades now, cryosphere scientists have been sounding the alarm: ice matters, and for each rise in $CO_2$, the global impacts from its loss will grow all more devastating. It is high time we listen, and act accordingly.

**Christiana Figueres**
Former UNFCCC Executive Secretary
Founding Partner, Global Optimism

# Summary for Policymakers

## *The Cryosphere under Overshoot**

### High Overshoot to 3°C with Current Emissions Pathway and Policies

#### CMIP 7 High-low Scenario: peak 2.8–3.2°C, 1.5°C in 2250

**Large and rapid sea-level rise likely would occur from ice sheets at both poles**, even with a return to 1.5°C by the mid-2200s. Such a large rise in global temperature greatly increases the risk of triggering ice sheet instabilities that could cause extremely rapid and irreversible sea-level rise, at rates that could reach as much as 5 cm per year by 2150. (Current rate is around ~0.45 cm per year.) Such extremely rapid sea-level rise is well above the level of 0.7 cm per year thought to be the breaking point for many nature-based adaptation measures like mangroves and salt marshes that protect infrastructure and croplands from rising seas. This places coastal communities and ecosystems at huge risk of loss and damage.

**Rapidly increasing environmental hazards would impact populations both in and downstream of mountain regions**, ranging from water insecurity to ground and glacier collapse–triggered floods. Hazards such as landslides and flooding with extreme snow and rain events would become so frequent as to become unmanageable for some communities during the steepest period of temperature rise. Flooding and too much water eventually would be followed by growing periods of drought and water scarcity, especially in the summer months and with lower projected snowpack levels. This can be expected to drive large-scale downstream population displacement. The 3°C peak temperature level would result in loss of nearly all mid-latitude glaciers outside the highest altitudes (6000 m and above), with even the Hindu Kush Himalaya seeing at least two-thirds loss of glacier ice.

**Nearly all near-surface permafrost would thaw**, triggering more frequent and widespread "abrupt thaw" processes to rapidly expose deeper permafrost to above-freezing temperatures. These processes, which can be accelerated by wildfires, include hillside collapse and sudden lake formation where the lakebed progressively thaws. Permafrost emissions would climb to annual levels of about that of the U.S. today, continuing for 1–2 centuries. During the peak of overshoot, wildfire frequency, intensity and severity would increase, with longer fire seasons and deeper burning of organic soils. Subsequent cooling following peak overshoot will create less favorable conditions for vegetation growth, reducing the amount of carbon that can be reabsorbed from the atmosphere. High overshoot will fundamentally reshape soils and hydrology in these regions for decades to centuries.

Current research points to **longer delays in sea ice recovery than previously thought** with high overshoot, on the level of decades to even centuries due to warmer ocean waters. Already in the 2°C range, Arctic summer (September) sea ice would disappear for at least some period in September each year. That absence will spread to the spring and especially the fall months by overshoot of 3°C. Projected patterns in Antarctica are far less certain, but losses may be as large. This greatly diminished sea ice will carry high global economic from an accelerated rise in global temperatures due to the absence of reflective sea ice, including deadly heatwaves; potential shutdown of important ocean currents; greater Arctic permafrost thaw, with higher emissions and more land collapse; and greater ice loss from Greenland. Antarctic sea ice loss could accelerate sea-level rise from Antarctica due to collapse of its surrounding ice shelves without the protection sea ice provides. Sea ice–based species, ecosystems and human communities will collapse and not be able to recover on time scales relevant to overall survival.

With overshoot to 3°C (equivalent to 550+ ppm (parts per million) $CO_2$ in the atmosphere), **severe and possibly abrupt circulation disruptions become extremely likely alongside widespread ocean acidification**. AMOC (Atlantic Meridional Overturning Circulation) shutdown potentially might occur before 2100, with drastic impacts on temperatures in northern Europe (dropping by up to –20°C from today) as well as on weather patterns globally. Acidifying waters as well as marine heatwaves and other extreme events would spread to most sectors of both polar oceans, with cascading impacts on ecosystem and climate services, fishery survival and global food security. Models

* Findings and overshoot pathways based on *Overshoot and the Cryosphere: Averting Global Meltdown* (2026). United Nations Environment Programme and International Cryosphere Climate Initiative; and *Limiting Overshoot: Navigating exceedance of 1.5°C and pathways towards return* (2026). United Nations Environment Programme. More detail on noted pathways in Chapter 1.

consistently project these changes to be essentially irreversible on human timescales, set by peak temperature and $CO_2$ concentrations in the atmosphere, even after temperatures and atmospheric $CO_2$ levels decline. Reversal of these impacts will not occur on timescales relevant to societies, fisheries, conservation or climate stability.

## Why 1.5°C Stabilization is Too High for Cryosphere

Even in scenarios where global warming remained at 1.5°C, ice loss will continue for millennia. **In Earth's past, this temperature resulted in sea levels ~2–9 meters higher than today** due to loss of portions of the West Antarctic, Greenland and possibly East Antarctic ice sheets. Given the delayed response of ice sheets to warming, recent science shows large amounts of irreversible ice loss committed even at today's warming of 1.4°C. For Greenland, a threshold for long-term ice loss may be triggered well below 2°C of warming, and possibly closer to 1.5°C; parts of West Antarctica may be triggered at even lower constant temperatures. As a result, the best-case scenario at constant 1.5°C would be that it takes centuries to millennia to reach this 'new normal' of sea levels ~2–9 meters higher, allowing at least some coastal communities to adapt or relocate. Latest scientific evidence suggests that a truly 'safe' temperature limit for stable polar ice sheets lies at or below 1.0°C.

Even scenarios where global warming never surpasses 1.5°C would **threaten more than half of the world's glaciers, by number, with extinction**; and as the Nepal Rasuwa disaster showed, with significant risks of disaster events. Mid-latitude glaciers especially would continue their current steep decline for several decades before stabilizing at greatly diminished ice levels. In some regions, such as the Caucasus, Scandinavia, Iceland and the North American Rockies, only 18–35% of the ice that existed in 2020 would remain after several centuries at 1.5°C. Even in the Hindu Kush Himalaya and Central Asia, about one-third of glacier ice would disappear. **Snowpack would similarly stabilize, but at higher altitudes and latitudes than today**, having been replaced by rainfall at lower altitudes and latitudes. These changes would have significant impacts on water resources, but likely within adaptation limits.

**Every fraction of a degree of warming causes more widespread and deeper permafrost thaw.** Long-term 1.5°C stabilization without overshoot would eventually see permafrost soils reach a new equilibrium, although emissions from thawed permafrost typically continue for a few hundred years before petering out once all organic matter – which took thousands of years to accrue – has decomposed. While carbon can again be drawn down into these soils, the process of replacing it will take centuries to millennia.

Even if temperatures stabilize at 1.5°C, **occasional ice-free summers in the Arctic would still occur**; while in the Southern Ocean, the thermal inertia of warmer waters may continue to drive Antarctic sea ice loss for some time. Eventually, however, sea ice at both poles would stabilize at new and lower levels from today, at times with brief summer ice-free conditions.

Under scenarios where global warming remains at 1.5°C or below and $CO_2$ levels stabilize at no more than 450 ppm, the spread of surface ocean acidification is limited, and the risk of irreversible changes in global ocean currents are reduced. Polar species, however, began showing negative impacts from acidification in the 2000s, well before $CO_2$ concentrations first exceeded 400 ppm at around 1°C of warming. These observations mean that **even stabilization at 1.5°C greatly increases risks to polar marine life**.

## Limited Overshoot with Rapid Action to Return Well Below 1.5°C

### Highest Possible Ambition (HPA) or similar pathways: peak 1.7°C, below 1.5°C by 2100, below 1°C by 2150

Given climate inaction to date, even the most ambitious plausible measures now cannot prevent temperatures peaking at the 1.7°C level for around 20 years. However, with the massive expansion of renewable technology, net zero can still be reached in 2050 with sufficient political will. Combined with existing sustainable carbon drawdown, temperatures can decline below 1.5°C by 2100, and below 1°C by 2150. However, temperatures peaking at 1.7°C carries a substantial risk of triggering irreversible loss in some sectors of the Greenland Ice Sheet and especially West Antarctica, because ocean warming – the main factor in ice sheet loss – will take centuries to stabilize in response to reaching net zero. Nevertheless, **a rapid return to below 1°C offers the best chance to slow ice loss and limit future sea-level rise** to rates that allow feasible adaptation over thousand-year time scales.

**Many glaciers would respond relatively quickly to lowered temperatures with carbon drawdown, stabilizing a few decades after net zero is reached.** A return to well below 1.5°C would result in the beginning of some ice regrowth on time scales of decades to centuries with sufficient snowfall. Predicting how snow precipitation patterns will rebound in mountain regions following overshoot remains a challenging research gap, but deeper snowpack would return far more quickly than glacier ice, somewhat alleviating high altitude water storage issues.

Emissions and infrastructure damage from permafrost thaw would likely be greater along this pathway than



**Mount Ağrı (Mount Ararat) is Türkiye's highest peak**, at 5165 meters. Even its glaciers and snowpack, which feed major river systems in western Asia, may disappear, however, even at constant 1.5°C; preserving its ice cap requires very low overshoot followed by temperatures below this level. Photo: blickwinkel/A Harti (Alamy), taken near Dogubayzit, Türkiye

under a stable 1.5°C without overshoot. However, once temperatures decline below 1.5°C – and especially below 1°C – the frequency of heatwaves, lightning strikes and wildfires that trigger abrupt thaw would decrease in the latter half of this century. As a result, **this pathway could produce even less permafrost carbon emissions** than a stable 1.5°C with no overshoot.

With decline to well below 1.5°C by 2100, **sea ice at both poles should begin to recover relatively quickly given less warming of the polar oceans than with higher and more sustained overshoot**; though any slowdown in ocean currents may cause warmer water to remain at the water's surface, delaying recovery on scales of decades or longer. Continued cooling to 1°C under an HPA or similar pathway however should help to avoid the worst feedbacks of sea ice loss.

Peak $CO_2$ levels would hit close to 470 ppm before net zero is reached. Continued carbon drawdown, resulting in $CO_2$ levels of 350–380 ppm by 2150, would **allow surface waters to begin recovery from previous acidification**, but acidifying conditions would spread deeper and continue to negatively affect marine life, as complete rebalancing of ocean chemistry takes tens of thousands of years. Atmospheric temperatures at or below 1°C by 2150 under HPA pathways would decrease but not eliminate completely the risk of AMOC and also AOC (Antarctic Overturning Circulation) shutdown, given the persistence of warmer waters and committed ice sheet melt.

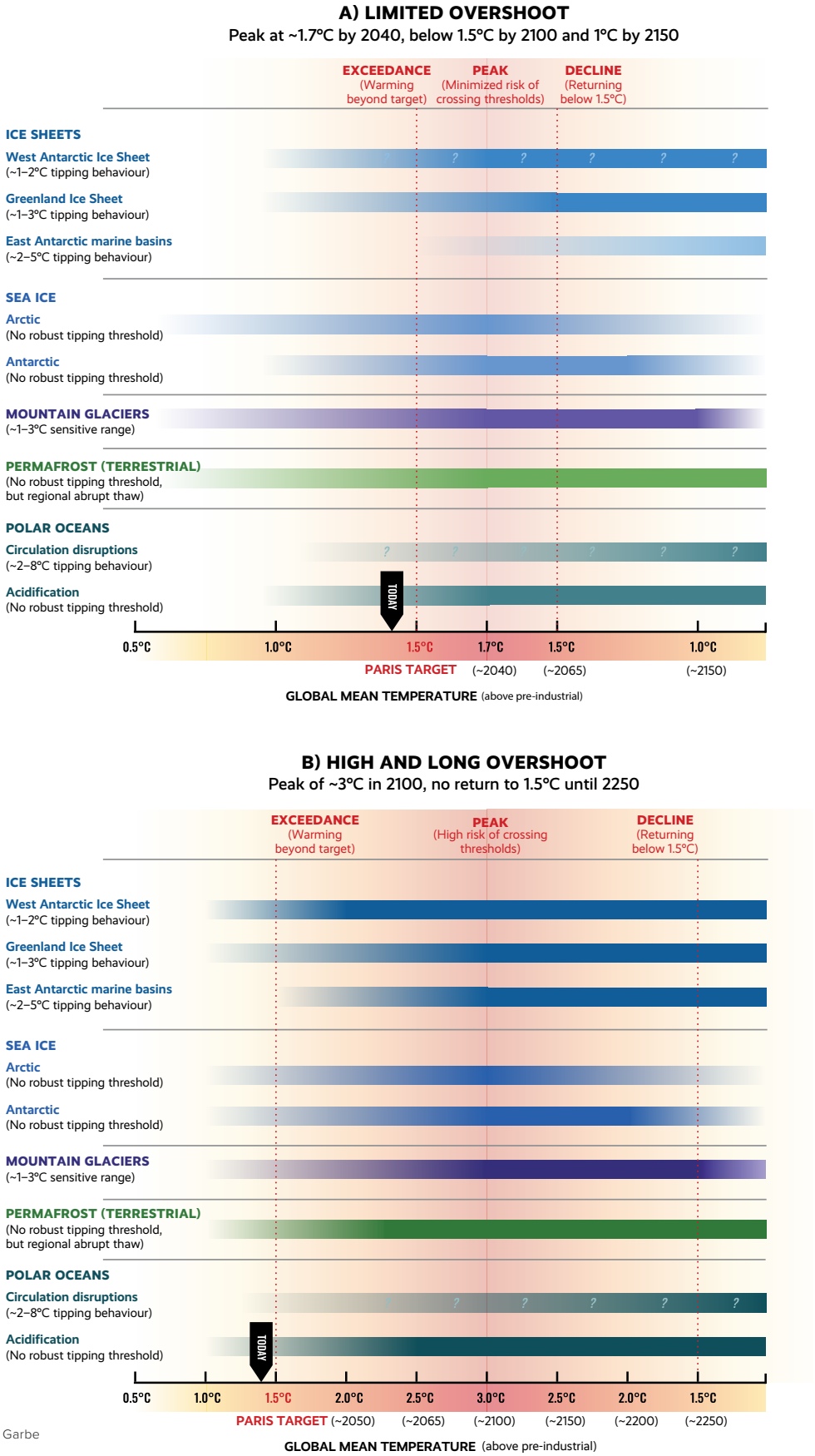
FIGURE, OPPOSITE: **The summary figure on the following page shows the response of different cryosphere elements to *limited overshoot* (including decline to temperatures below 1.5°C by 2100, and to around 1°C by 2150); versus a *high and long overshoot* where temperatures peak at 3°C around 2100 and remain above 1.5°C for at least two centuries. Darker colors mean greater impacts, including higher risks of crossing tipping points. Note the different time and temperature scales on the bottom (x-axis) of the two graphs.**

**Note that nearly all of these cryosphere elements began responding to warming already when global mean temperatures were between 0.5–1.0°C above pre-industrial levels. Note also the irreversible impacts on human timescales from ice sheet loss, permafrost thaw, and polar ocean acidification, and the close-to-irreversible impacts from glacier melt.**

**Whether it will be possible to reverse loss of the West Antarctic Ice Sheet, or disruptions to ocean circulation such as that of the Atlantic Meridional Overturning Circulation, are two of the largest questions facing the global community today.**

Source: ICCI/J. Garbe

FIGURE. **Impacts on Cryosphere Elements from Overshoot and Decline: Limited v. High Overshoot**




Source: ICCI/J. Garbe

CHAPTER 1

# Preserving Cryosphere in an Overshoot World

## *Real Pathways to Return*

Catastrophic events from cryosphere loss such as the Rasuwa disaster in Nepal (cover) make clear the current costs of global warming that will only expand with overshoot of this lower Paris Agreement temperature limit.

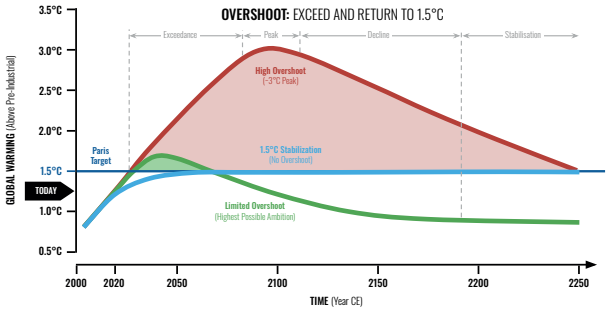
Overshoot will only increase such global loss and damage from ongoing melting in cryosphere regions, as shown in the UNEP spotlight report *Limiting Overshoot* (2026) and the companion UNEP satellite report, *Overshoot and the Cryosphere: Averting a World in Meltdown,* released in parallel to the *State of the Cryosphere 2026*.

These consequences should lead to an appropriately urgent response: rapidly decreasing greenhouse gas emissions, which largely come from fossil fuel use. Nonetheless, the 2026 UNFCCC NDC Synthesis Report[1] and the UNEP Emissions Gap Report[2] reveal that current polices and Nationally Determined Contributions (NDCs) continue to remain far off-track from the needed emissions decline. Instead, emissions continue their march upwards, with average $CO_2$ concentrations in the atmosphere for 2026 expected to be nearly 430 ppm,* the highest in 3 million years and far higher than the 280 ppm pre-industrial level.

As a result, pathways limiting global warming to 1.5°C as outlined by IPCC AR6[3,4] appear no longer possible due to a collective failure to slow carbon emissions over the past three decades, and some overshoot is now inevitable. However, all the above reports also conclude that new doors that have opened to allow a return to the 1.5°C lower Paris Agreement limit by 2100 or even earlier.

This renewal of hope is made possible by the expansion in renewable technologies. Sometimes termed Highest Possible Ambition (HPA) Pathways, these would return temperatures back down to 1.5°C or below by 2100 despite unavoidably higher levels of overshoot to about 1.7°C. First developed by Climate Analytics and the Potsdam Institute,[5] and expanded on by the 2026 Emissions Gap Report,[2] these measures all involve:

FIGURE 1-1. **Overshoot Pathways**




The three pathways used throughout this report: Limited and High Overshoot; in contrast to a constant 1.5°C without decline.

Source: ICCI/J. Garbe

1. Phasing out fossil fuels, first in power and transport sectors where cost-effective alternatives are readily available, beginning immediately and with major developed economies leading the way towards effective (>95%) phaseout of:
   - Coal in the 2040s
   - Gas in the 2050s
   - Oil in the 2060s
2. Halting and reversing deforestation
3. Cutting emissions of methane and (for special cryosphere benefits) black carbon as well as other short-lived forcers
4. Scaling up sustainably deployed carbon dioxide removal (CDR) for fast temperature decline once net zero emissions have been reached.

* Forecast 2026 level is 429.4, UK MetOffice, https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/seasonal-forecast/forecasts/co2-forecast

TABLE. **Overshoot Temperature and Peak $CO_2$**

| | Median temperatures | | | |
|---|---|---|---|---|
| **Pathway** | **Peak Temperature** | **2100 Temperature** | **2150 Temperature** | **Peak $CO_2$** |
| HPA Pathway | 1.7–1.8°C | 1.2–1.3°C | 1.0°C or below | ~450 |
| High-Low Overshoot | 2.8–3.2°C | 2.8–3.2°C | ~2.3–2.7°C* | ~650 |
| 1.5°C without Decline | 1.6°C | 1.5°C | 1.5°C | ~430 (constant) |

*assumes carbon drawdown at least as effective as HPA Pathways, taking far longer to return to 1.5°C due to far higher peak temperatures; however, various Earth feedbacks at higher peak temperatures may make return far more difficult and lengthier.

These pathways are ambitious, but eminently achievable with current technologies and measures. They are realistic in foreseeing a tripling of energy demand by 2050 to meet sustainable development goals. Such growing needs, especially in developing countries are met by a tripling of renewables by 2030, six times by 2035 and 15 times by 2050, entirely on par with the rapid expansion of recent years. Net-zero CO2 emissions could be reached by 2045, and net-zero greenhouse gas (GHG) emissions in the 2060s.

Near cryosphere regions, reducing black carbon emissions from the transport (especially maritime in the Arctic), agriculture and household and waste sectors would help limit overshoot — in the Arctic and High Mountain Asia, by half a degree or more — and help prevent both further catastrophic events such as the Rasuwa disaster; as well as reducing negative cryosphere feedbacks such as permafrost thaw emissions and reflective sea ice loss.

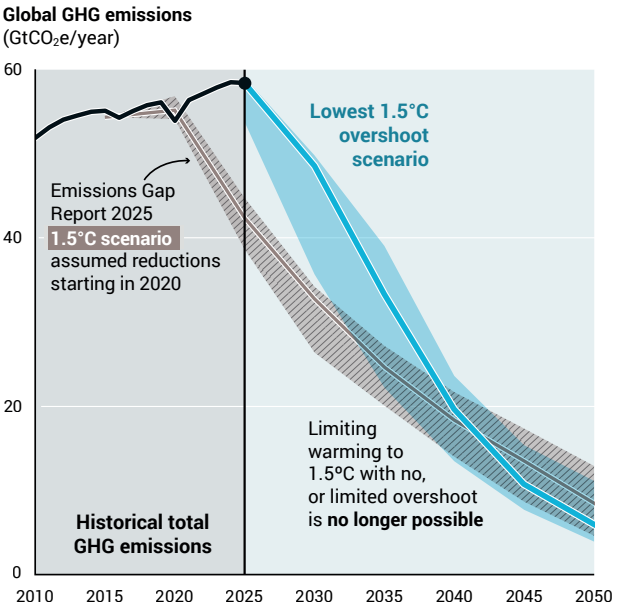
Extra emissions from inaction will then need to be removed from the atmosphere via carbon drawdown to return temperatures back to below 1.5°C by 2100. In addition to health benefits for nearby mountain communities, measures such as limiting slopeside agricultural burning and resulting wildfires alongside reforestation would help avoid landslides and flooding in downstream regions.

Contrary to general perception, temperatures begin to fall almost as soon as $CO_2$ concentrations in the atmosphere decline, and without the known negative side of approaches that would merely mask warming by for example intentionally ramping up sulfate pollution. Each ~220 Gt of carbon drawdown results in ~0.1°C of temperature decline. Existing land-based CDR measures, primarily afforestation and reforestation,[6,7] can already achieve about 2 $GtCO_2$ removal per year.

*New doors have opened to allow a return to 1.5°C by 2100 or even earlier.*

Additional sustainable CDR development through technological advancement might push this to as high as 8.0 Gt/year by 2100, but intensive public and private investment is needed to achieve this, comprising a more effective choice than geo-engineering approaches that, at best, merely mask $CO_2$ impacts. Reserving CDR for actual temperature decline or to offset residual emissions from hard-to-abate sectors is essential. To achieve real temperature decline, CDR cannot be used for offsetting continued fossil fuel emissions.** Every tenth of a degree of temperature rise and year of higher temperatures matters, but the various HPA pathways demonstrate how global warming can still return to below 1.5°C by 2100 after overshoot and (with continued carbon drawdown)

FIGURE 1-2. **Achieving 1.5C in an Overshoot World**




While emissions pathways keeping temperatures at or below 1.5°C are no longer possible because of the delay in collective action, the 2026 UNEP Emissions Gap Report could outline several new pathways that, with steeper emissions reductions and recent expansion in renewables, can actually reach net zero emissions faster than the earlier pathways to keep temperatures as close to 1.5°C as possible.

Source: 2026 UNEP Emissions Gap Report

** To count as CDR, a method must be an intervention which: (1) captures $CO_2$ from the atmosphere; and (2) stores it for a long period of time. When this $CO_2$ comes directly from burning fossil fuels, this counts as an emissions reduction rather than removal.

below 1°C by 2150, which the vast majority of cryosphere scientists now agree is the actual safe planetary boundary to maintain planetary ice stores at levels that might avert some of the worst global feedbacks from cryosphere loss.

Achieving these goals requires political will focused on more than short-term issues alone. Even in a best-case scenario, we must prepare for the impacts of higher and longer levels of overshoot. Tragically, this will result in greater cryosphere loss and downstream impacts, with further sea-level rise, water supply losses and polar ocean acidification damages locked in for hundreds to thousands of years, as outlined in this Report and multiple studies.[8,9] The effectiveness of some adaptation strategies will diminish as global warming escalates.[10]

*1°C is the actual safe boundary to maintain planetary ice stores and avert some of the worst global feedbacks from cryosphere loss.*

**This Report outlines these impacts at three levels, drawing on the findings of the UNEP-ICCI *Overshoot and the Cryosphere* report released concurrently:**

**"Low Overshoot" or HPA Pathways, with overshoot to around 1.7°C, remaining above 1.5°C for about four decades but achieving well below 1.5°C in 2100, and at or below 1°C in 2150.** For purposes of polar ocean acidification and other non-temperature impacts of fossil fuel use, this corresponds to peak $CO_2$ levels around 450 ppm in the atmosphere (see box);

**"High Overshoot," following the AR7 scenario that unfortunately tracks our current emissions pathway, reaching about 3°C in 2100 with peak $CO_2$ levels around 600 ppm and remaining above 1.5°C for about 150 years, or until 2250;**

**"Stable 1.5°C Without Decline," to emphasize the consensus that merely achieving 1.5°C without carbon drawdown and later temperature decline will result in much greater loss and damage than a Limited Overshoot pathway.**

Regardless of any overshoot, limiting global warming to 1.5°C remains the legal, moral, and political imperative to secure a livable planet for present and future generations.[11-13] Many of the impacts of global warming beyond 1.5°C fall disproportionately on the poor and vulnerable.[14]

Our challenge now is to ensure that overshoot is as short and as low as possible; while shaping adaptation measures to prepare for these temporarily higher temperatures, close finance gaps and build capacity for communities to respond to this new normal of near-term warming; cryosphere impacts included.

*References begin on page 38.*

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CHAPTER 2

# Ice Sheets and Sea-level Rise

## *The Higher and Longer the Overshoot, the Greater the Sea-level Rise from Ice Sheet Loss*

The polar ice sheets on Greenland and Antarctica are melting about six times faster today than in the 1990s. Sectors of both ice sheets are approaching thresholds driven by atmospheric and ocean warming that could trigger irreversible retreat and multi-meter sea level rise for centuries to millennia.

### Overshoot to 3°C: Current Emissions Pathway and Policies

#### CMIP 7 High-low Scenario: peak 2.8–3.2°C, 1.5°C in 2250

Overshoot to 3°C would likely lead to large and rapid sea-level rise from both ice sheets, even with a return to 1.5°C by the mid-2200s. Such a rapid rise in global temperature greatly increases the risk of triggering ice sheet instabilities that could cause extremely rapid and irreversible sea-level rise, at rates that could reach as much as 5 cm per year by 2150 (current rate is around ~0.45 cm per year). Such extremely rapid sea-level rise is well above the level of 0.7 cm per year thought to be the breaking point for many nature-based adaptation measures like mangroves and salt marshes that protect infrastructure and croplands from rising seas, placing coastal communities and ecosystems at huge risk of loss and damage.

### Stable 1.5°C without Decline

Even in scenarios where global warming remained at 1.5°C, ice loss will continue for millennia. In Earth's past, this temperature resulted in sea levels ~2–9 meters higher than today due to loss of portions of the West Antarctic, Greenland and possibly East Antarctic ice sheets. Given the delayed response of ice sheets to warming, recent science shows large amounts of irreversible ice loss committed even at today's warming of 1.4°C.* For Greenland, a threshold for long-term ice loss may be triggered well below 2°C of warming, and possibly closer to 1.5°C; parts of West Antarctica may be triggered at even lower constant temperatures. As a result, the best-case scenario even at 1.5°C would be that it takes centuries to millennia to reach this 'new normal' of sea levels ~2–9 meters above today, allowing at least some coastal communities to adapt or relocate. Latest scientific evidence suggests that a truly 'safe' temperature limit for stable polar ice sheets lies at or below 1.0°C.

### Limited Overshoot to 1.7°C with Rapid Action: 2050 Net Zero

#### Highest Possible Ambition (HPA) Pathway: peak 1.7°C, below 1.5°C by 2100, below 1°C by 2150

Given climate inaction to date, even the most ambitious plausible measures now cannot prevent temperatures peaking at the 1.7°C level for around 20 years. However, given the massive expansion of renewable technology, net zero can still be reached in 2050 with sufficient political will. Combined with existing sustainable carbon drawdown, temperatures can decline below 1.5°C by 2100, and below 1°C by 2150. However, temperatures peaking at 1.7°C carries a substantial risk of triggering irreversible loss in some sectors of the Greenland Ice Sheet and especially West Antarctica because ocean warming – the main factor in ice sheet loss – will take centuries to stabilize in response to reaching net zero. However, a rapid return to below 1°C offers the best chance to slow ice loss and limit future sea-level rise to rates that allow feasible adaptation over thousand-year time scales.

* https://wmo.int/publication-series/state-of-global-climate/state-of-global-climate-2025
https://climate.copernicus.eu/climate-indicators/temperature

## Background

For the Earth's vast polar ice sheets, the risk of triggering runaway melting increases with every tenth of a degree of warming.[14,15] Both polar ice sheets are sensitive to temperature thresholds which are set to be crossed under today's emissions policies. This would trigger irreversible changes that will afflict humanity for millennia.[16,17] Ice losses from both ice sheets have accelerated in recent decades, with recent observations showing that the Greenland Ice Sheet is currently losing ice five times faster than in the 1990s,[18] and Antarctica's contribution to sea-level rise is now six times greater than it was 30 years ago.[19–21] Given that one billion people live at elevations within 10 meters above current sea level globally, with an estimated 230 million living within just 1 meter,[22] ensuring that the future rate and amount of sea-level rise from ice sheet loss remains as slow and as low as possible is essential if coastal adaptation is to remain feasible and to avoid forced migration on an unprecedented scale. Various geoengineering 'fixes' to slow ice sheet loss have been evaluated by the polar science community and found to be implausible due to significant issues and risks relating to feasibility, cost, predictable adverse consequences, environmental damage, scalability, the lack of any governance, and environmental ethics.[23] The only way to slow and limit sea-level rise is by undertaking deep, rapid and sustained emissions reductions followed by carbon drawdown.[23]

## 2026 Updates

- The Greenland and Antarctic ice sheets lost over 11 trillion metric tons of ice between 1979 and 2023, contributing more than 3 cm to global sea level rise.[3]
- Researchers showed that fractures within Antarctic ice shelves could increase sea-level contributions from West Antarctica by more than 4 times by 2300. Most projections of future Antarctic ice loss omit this effect, suggesting that models need to better account for fracture-driven weakening when projecting future sea-level rise from Antarctica.[4]
- Analysis of tide gauge records and model simulations showed that human-driven sea-level rise has quadrupled the frequency of coastal sea-level extremes since 1900. In nearly half the sites studied, an historical 1-in-100-year event now occurs at least once per decade.[5]
- Satellite observations recorded thirty years of grounding line (the point where the ice sheet meets the ocean floor) retreat in the Antarctic Peninsula, Wilkes and George V Lands of East Antarctica, and the Bellingshausen and Amundsen sea sectors of West Antarctica. The most extreme retreat occurred in West Antarctica where grounding lines have retreated by tens of kilometers, driven by the incursion of ocean warm waters near ice sheet grounding lines.[6]
- An attribution analysis showed that greenhouse gas emissions increased the retreat of West Antarctica's Pine Island Glacier by around 18% since the 1940s, adding several kilometers to the retreat of the grounding line.[7]
- A hypothetical modelling exercise in which the ocean waters surrounding West Antarctica were cooled found that Thwaites Glacier would continue to lose ice even without warmer ocean waters — a key driver of West Antarctic ice loss. The analysis suggests that a historical climate disturbance (possibly an El Niño event in the 1940s) has now pushed Thwaites into a phase of ice loss that will continue for centuries.[8]
- Scientists reviewed the best- and worst-case scenarios for the Antarctic Peninsula under future climate warming. They found that higher emissions will bring more days above 0°C, increased rain, ocean warming, ice shelf surface melting and more intense extreme weather events such as ocean heat waves. Limiting temperatures as close as possible to 1.5°C, combined with effective governance of fisheries, tourism and infrastructure, will result in increased resilience and smaller changes to sea ice extent, glacier retreat, and ecosystems. Higher emissions scenarios will damage pristine systems, cause sustained, irreversible ice loss on human timescales, and spread to Antarctic regions beyond the Peninsula.[9]

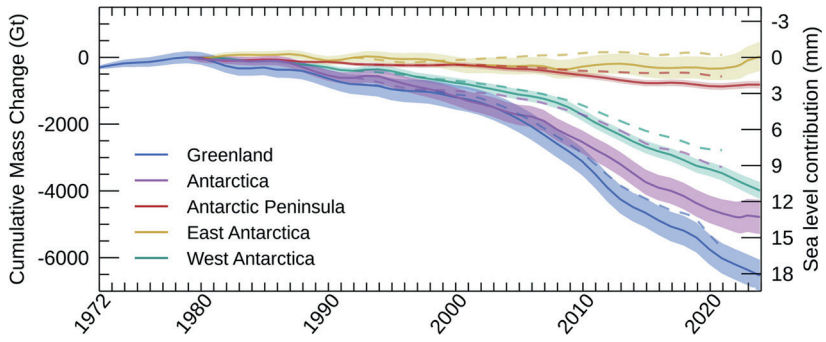
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FEATURED UPDATE

## Different "Tipping Points" for Each Antarctic Ice Sheet Basin

The Antarctic Ice Sheet consists of a number of drainage basins that could cross tipping points at different levels of warming. Researchers found that a global warming threshold as low as 1–2°C above pre-industrial could lead to the long-term irreversible loss of approximately 40% of the marine-based ice in West Antarctica (an amount of ice that equates to over 2 meters of potential sea-level rise). Marine-based sectors in East Antarctica, representing 5 m of potential sea-level rise, are at risk of losing stability at 2–5 °C.[1]

FIGURE 2-1. **Ice loss from the Greenland and Antarctic ice sheets since the 1970s**

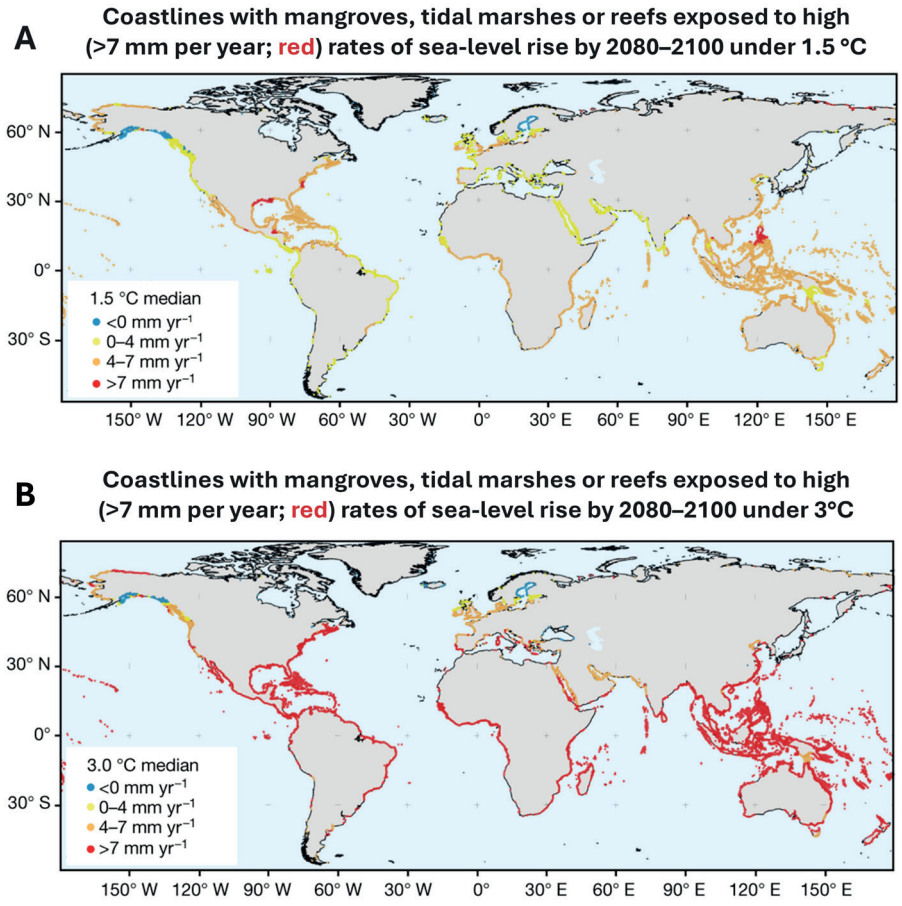



Source: Otosaka et al. (2026).

## 2026 UPDATES (CONTINUED)

- Analysis of changes in the spatial extent and magnitude of extreme melting events on the Greenland Ice Sheet between 1950 and 2023 revealed a significant increase in recent decades. Researchers noted that the area of the ice sheet experiencing extreme melting has expanded substantially in recent decades, with melt extremes increasing in frequency and intensity; and increasingly extending into late summer. They found that 7 out of 10 of the most extreme melting events occurred between 2000 and 2023.[10]
- Sediment drilling records collected offshore of West Antarctica found repeated major ice-sheet retreat events during the Pliocene – a period between 5.33 and 2.58 million years ago, when temperatures were warmer than present. The drill records show that the West Antarctic Ice Sheet underwent at least five periods of major inland retreat in response to past interglacial warming, reinforcing the vulnerability of West Antarctica to global warming.[11]
- A large intercomparison exercise of ice sheet models extended these joint projections of Greenland ice loss until the year 2300. In this exercise, sea-level rise projections from Greenland by 2300 ranged from less than 5 cm to over 3 meters depending on the model and the emissions pathway followed, underscoring the potential for very large long-term ice loss under high emissions. Overshoot scenarios, where temperatures peaked at between ~2–4°C by 2060 before declining to ~1–2°C by 2150 and then stabilizing thereafter, found that sea-level contributions by 2300 could range from 5 to 20 cm, with the ice sheet seemingly stabilized in only a third of the experiments.[12]
- Extreme environmental events in Antarctica are growing in frequency and severity, and are likely to make it more difficult to undertake fieldwork in remote locations critical to understanding and preparing for the global impacts of the Antarctic Ice Sheet's response to global heating.[13]

FIGURE 2-2. **Projected exposure of coastal ecosystems to relative sea-level rise under 1.5°C and 3°C warming scenarios**




Areas in red are at risk of becoming destabilised through shoreline erosion and wave impacts.

Source: Saintilan et al. (2023).

The Earth's climate record makes clear that, in the past, warming of even 1°C above preindustrial temperatures dramatically reshaped the Earth's coastlines due to extensive melting of the West Antarctic Ice Sheet (WAIS),[24] the Greenland Ice Sheet[25,26] and by 1.5°C, possibly parts of East Antarctica.[27] During the Last Interglacial around 125 thousand years ago, when atmospheric $CO_2$ concentrations were two-thirds of 2025 levels and global mean surface temperatures were only 0.5°C to 1.5°C higher than pre-industrial, geological evidence shows that sea levels were 2 to 9 meters higher than present.[15,28] Even greater sea-level rise occurred during the height of the Pliocene 3 million years ago, when temperatures 2-3°C higher than pre-industrial resulted in 10-20 meters of sea-level rise, implying substantial loss of parts of the Greenland Ice Sheet, the WAIS, and portions of the East Antarctic Ice Sheet.[15,28–31] While some of these changes occurred very slowly in the past, there have also been periods of extremely rapid sea-level rise (around 3.5 to 4 meters per century)[32] that also involved the collapse of ice sheets in North America and Europe where processes may have been different. Such extensive and rapid sea-level rise would be catastrophic for today's coastal communities — yet we are currently on track for even higher greenhouse gas concentrations and temperature peaks than those that drove past sea-level rise, and are approaching these temperatures at an unprecedented rate.[33]

The latest investigations of ice sheet behavior, especially interactions between polar ice sheets and the warming oceans that surround them, conclude that ice sheet collapse and the possibility of rapid sea-level rise cannot be ruled out, especially if long-term warming

***A rapid return to below 1.0°C offers the best chance to slow ice loss and limit sea-level rise.***

exceeds 1.5°C.[34–38] This is especially the case for the WAIS (3–4 meters of potential sea-level rise), where the threshold for irreversible ice loss is likely already close (1.5°C or below) due to its great vulnerability to ocean warming.[16,39–41] In the future, extensive melting of West Antarctica's stabilizing ice shelves is predicted to occur even under very low emissions trajectories,[42,43] and modelling suggests that the WAIS could cross a tipping point into unstoppable collapse with less than +0.25°C of further ocean warming.[40] Recent research has highlighted how even current climate conditions, if maintained for long enough (several centuries), could tip the WAIS into a state of irreversible retreat without further warming.[44–46]

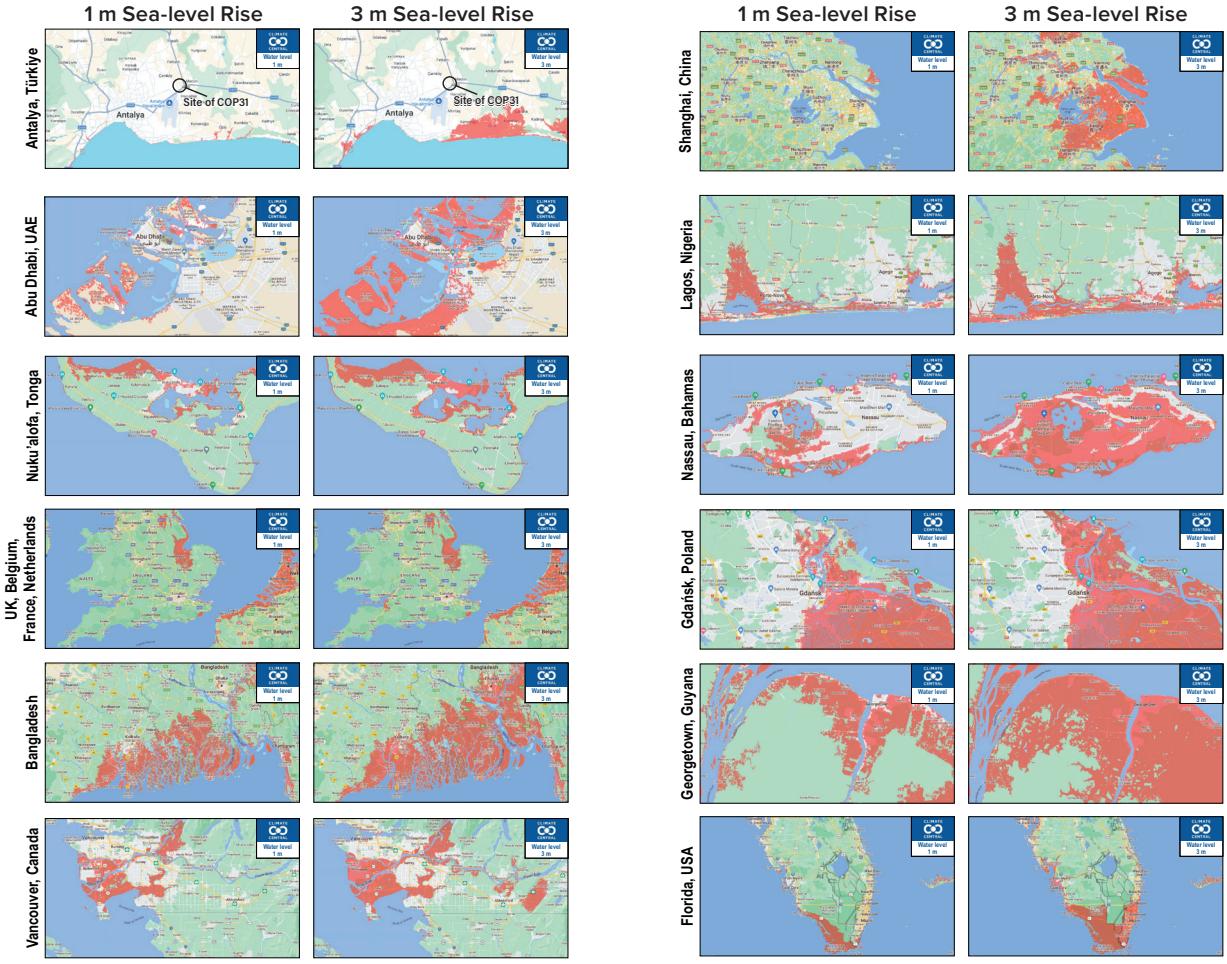
However, ice losses can still be slowed to take place over longer timescales if temperatures remain as close to 1.5°C as possible, with the aim of eventually returning below that level, giving coastal communities greater time to adapt to rising seas. Elsewhere, sectors of the much larger East Antarctic Ice Sheet that are vulnerable to ocean warming, especially the Wilkes Subglacial Basin (3–4 meters of potential sea-level rise), risk crossing a similar threshold around or just beyond 2°C.[1,27]

In contrast to Antarctica, which is currently losing most of its mass through ocean melting and iceberg production, approximately half of the mass lost from the Greenland Ice Sheet is due to increased surface melting,[47]

FIGURE 2-3. **High Overshoot Sea-level Rise Risks for Vulnerable Coastlines**

**1 meter Sea-level Rise.** Now long-term inevitable (by mid-2100's), but potentially by 2070 with high overshoot

**3 meters Sea-level Rise.** Likely inevitable in 1000–2000 yrs; but potentially by early 2100's with high overshoot




These maps show sea levels that, with high overshoot and potential ice sheet instabilities noted above, might be reached by 2070 (1 m) and in the early 2100's (3 m), well beyond coastal adaptation limits. For more locations, see coastal.climatecentral.org/map/

Source: Climate Central

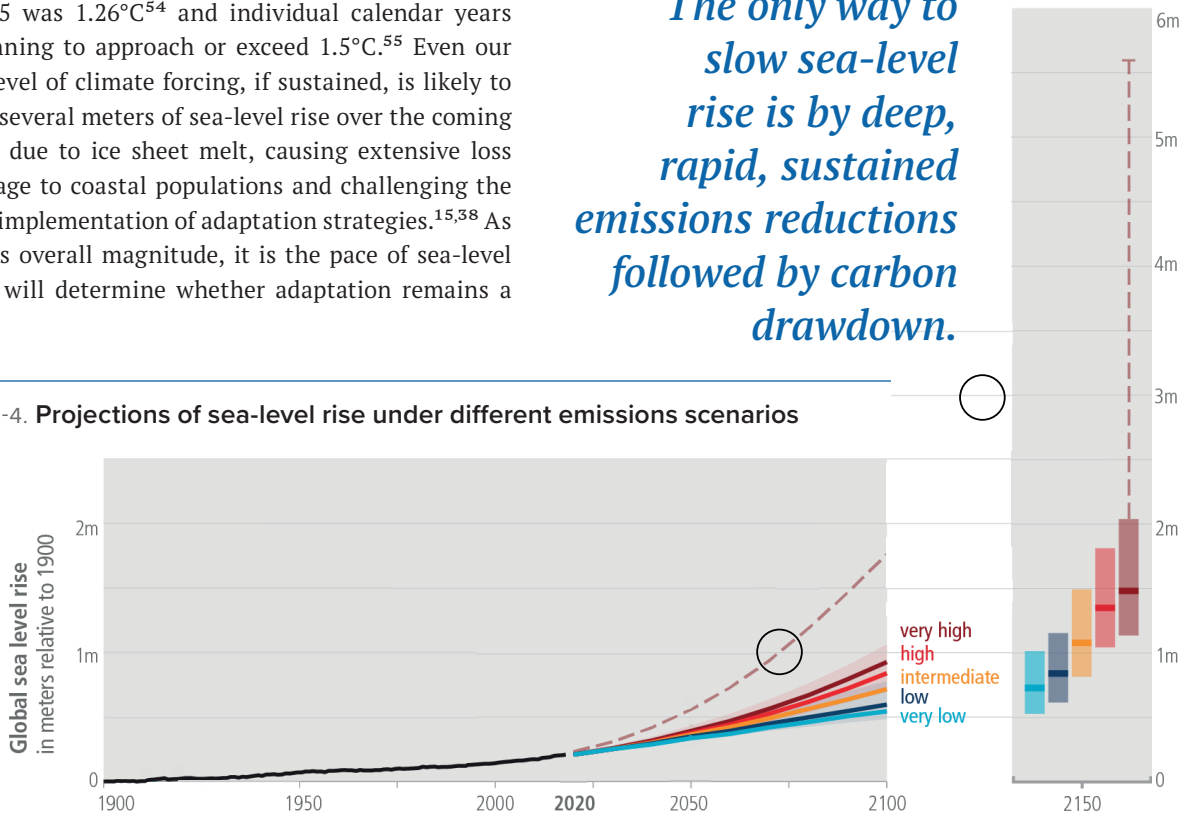
which is expected to become even more dominant in the future.[10] As warming continues, increased melting and faster ice flow into the ocean risks thinning and lowering the ice sheet surface into altitudes with warmer air temperatures, exposing successively greater amounts of the ice sheet to above-freezing temperatures; this vicious cycle could eventually lead to the unstoppable loss of most of the ice sheet.[48–50] Ice losses in Greenland may be further exacerbated by reductions in ice surface albedo caused by surface melting, the deposition of black carbon and dust, algae growth and rainfall.[51] Rainfall on the Greenland Ice Sheet has increased by 33% since 1991, and the frequency of extreme deluges is increasing.[52] Evidence from ancient soil recovered from beneath the northwest sector of the modern-day ice sheet shows that the ice margin retreated at least 200 km inland of its present position when $CO_2$ concentrations of only 280 ppm were sustained for 30,000 years in the past.[25] Similar analysis has recently shown that even the central summit of Greenland was ice free sometime within the last 1 million years,[26] implying that at least 90% of Greenland's ice must have melted at a time when $CO_2$ concentrations were far below even today's levels – let alone the concentrations towards which humanity is rapidly heading.

For a growing number of ice sheet experts, the true "guardrail" to prevent dangerous levels and rates of sea-level rise is not 2°C or even 1.5°C, but likely closer to just 1°C above pre-industrial;[15,53] yet, the decadal average for 2016–2025 was 1.26°C[54] and individual calendar years are beginning to approach or exceed 1.5°C.[55] Even our current level of climate forcing, if sustained, is likely to generate several meters of sea-level rise over the coming centuries due to ice sheet melt, causing extensive loss and damage to coastal populations and challenging the effective implementation of adaptation strategies.[15,38] As well as its overall magnitude, it is the pace of sea-level rise that will determine whether adaptation remains a feasible possibility for many coastal communities. This is when abrupt sea level changes mentioned earlier, such as those recorded during Meltwater Pulse 1A, are very relevant for adaptation. The IPCC[34] suggests that rates of sea-level rise exceeding 10 mm per year (1 m per century) would limit the success of coastal adaptation measures. For example, the ability of many prominent nature-based solutions for shoreline protection and carbon sequestration, such as coastal mangroves and salt marshes, to adjust to rising seas may be severely hindered under such high rates of sea-level rise. Should warming reach 3°C, nearly all the world's mangrove forests and coral reef islands and almost 40% of tidal marshes would be exposed to unsustainable rates of sea-level rise exceeding 7 mm per year, driving long-term retreat and ecosystem instability.[56] Such rates will be realized shortly after 2050 if the currently observed acceleration in the rate of sea-level rise continues.[57]

Every tenth of a degree by which warming can be limited matters for the stability of Earth's ice sheets. Higher temperatures, sustained for longer periods of time, will result in both faster melt and more rapid rates of sea-level rise. This could be as much as 50 mm (5 cm) per year from Antarctica alone by 2150 if current emissions policies cause critical thresholds for Antarctic stability to be crossed.[35] That is a rate not seen since deglaciation at the

***The only way to slow sea-level rise is by deep, rapid, sustained emissions reductions followed by carbon drawdown.***

FIGURE 2-4. **Projections of sea-level rise under different emissions scenarios**




Source: IPCC AR6. The dotted line represents a "low confidence" (unknown probability) but "high-impact" scenario.

FEATURED UPDATE

## Sea-level Rise Underestimated, Exposing Tens of Millions More

A review of 385 coastal hazard studies published between 2009 and 2025 found that more than 99% incorrectly integrated sea-level and land elevation data. These errors led to a widespread underestimation of present-day sea level, with true measured values about 0.25 meters higher on average than those commonly used in risk estimates. In the Indo-Pacific region, some errors exceed 1 meter. When coastal elevation is correctly aligned with sea level measurements, the global land area falling below 1 meter of sea-level rise increases by 31–37%, and 48–68% more people would be exposed — increasing earlier estimates to 77–132 million people. Overall, this study shows that the impacts of sea-level rise under climate change have been systematically underestimated; devastating impacts from coastal flooding could occur earlier than expected from climate projections – particularly in the Global South.[2]

end of the last ice age, when sea levels rose by 130 m. This is more than ten times larger than present-day rates of around 4.5 mm per year, which have doubled in the past 30 years.[57] A key message for policy makers and coastal communities is that once ice sheet melt accelerates due to higher temperatures, it cannot be stopped or reversed for many thousands of years, even if temperatures later stabilize. Indeed any reversal of sea levels will not occur until temperatures go well below pre-industrial levels, initiating a slow ice sheet re-growth.[17] Overshooting the lower limit of the Paris Agreement would therefore cause permanent loss and damage to the Earth's ice sheets, with widespread impacts that are not reversible on human timescales. The emissions policies set by decision makers today will therefore determine the rate and magnitude of future sea-level rise, and its associated risks to national security and development, for centuries to come. To minimize the risk that impacts from ice sheets will exceed the limits of adaptation, $CO_2$ emissions must be at least halved by 2030, and reduced to zero by mid-century. Otherwise, world leaders are *de facto* committing to erase many coastlines and displace hundreds of millions of people – perhaps much sooner than we think.

*References begin on page 38.*


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CHAPTER 3

# Mountain Glaciers and Snow

## *Growing Catastrophic Events with Overshoot*

Mountain glaciers are steeply losing ice across the planet. Disaster events with loss of life and infrastructure, such as that in Nepal in late August have grown in frequency as glaciers melt and the ground beneath them thaws and becomes more unstable. Snow cover has declined sharply across the Arctic over the past four decades; and mountain snow drought conditions have occurred more frequently, contributing to severe downstream drought including in the Western United States and Europe in summer 2026.

### Overshoot to 3°C: Current Emissions Pathway and Policies

#### CMIP 7 High-low Scenario: peak 2.8–3.2°C, 1.5°C in 2250

High overshoot would drive rapidly increasing environmental hazards for populations both in, and downstream of, mountain regions from glacier and snowpack melt, ranging from water insecurity to ground and glacier collapse-triggered floods. Hazards, such as landslides and flooding with extreme snow and rain events, would become so frequent as to become unmanageable for some communities during the steepest period of temperature rise. Flooding and too much water eventually would be followed by growing periods of drought and water scarcity, especially in the summer months and with lower projected snowpack levels. This can be expected to drive large-scale downstream population displacement. The 3°C peak temperature level would result in loss of nearly all mid-latitude glaciers outside the highest altitudes (6000 m and above), with even the Hindu Kush Himalaya seeing at least two-thirds loss of glacier ice. Projections show that notably lower ice levels, with only limited regrowth would persist even after a return to 1.5°C, producing less downstream water availability compared to minimal or non-overshoot scenarios.

### Stable 1.5°C without Decline

Even scenarios where global warming never surpasses 1.5°C would threaten more than half of the world's glaciers, by number, with extinction; and as the Nepal disaster showed, with significant risks of disaster events. Mid-latitude glaciers especially would continue their current steep decline for several decades before stabilizing at greatly diminished ice levels. In some regions, such as the Caucasus, Scandinavia, Iceland and the North American Rockies, only 18–35% of the ice that existed in 2020 would remain after several centuries at 1.5°C. Even in the Hindu Kush Himalaya and Central Asia, about one-third of glacier ice would disappear at that temperature level. All the small glaciers in the tropics of East Africa and Asia (Indonesia) would disappear; though contrary to popular perception, these small, tropical glaciers would have slowly melted away even at pre-industrial temperatures, as they were remnants of the last Ice Age. In the higher-altitude tropical Andes, more than half of today's ice would remain. Snowpack would similarly stabilize, but at higher altitudes and latitudes than today, having been replaced by rainfall at lower altitudes and latitudes. These changes would have significant impacts on water resources, but likely within adaptation limits.

### Limited Overshoot to 1.7°C with Rapid Action: 2050 Net Zero

#### Highest Possible Ambition (HPA) Pathway: peak 1.7°C, below 1.5°C by 2100, below 1°C by 2150

Even the most ambitious measures now cannot prevent overshoot to around 1.7°C for about two decades, with today's steep glacier loss continuing. However, given the rapid development of renewable technologies and with sufficient political will, net zero can still be reached in mid-century. If this is followed by sustainable carbon drawdown, it can result in temperatures below 1.5°C by 2100. Many glaciers would respond relatively quickly, stabilizing a few decades after net zero is reached. A return to well below 1.5°C would result in the beginning of some ice regrowth on time scales of decades to centuries with sufficient snowfall. Predicting how snow precipitation patterns will rebound in mountain regions following overshoot remains a challenging research gap, but deeper snowpack would return far more quickly than glacier ice, somewhat alleviating high altitude water storage issues.

## 2026 Updates

- Cryosphere loss is accelerating changes in river patterns in the Himalayan uplands, causing significant adaptation challenges for downstream communities regarding agriculture, water security and hazards. Comparing these river systems between 1980–2000 versus 2000–2020 shows large impacts from cryosphere loss – river migration, cutoff and avulsion rates roughly doubled between these two periods, with the destabilization of riverbanks driving these changes.[4]
- Two-thirds of Central Asia's glaciers larger than 1 $km^2$ experienced their worst year for ice loss in 2025 since at least 1991. As much as 2% of the region's ice mass was lost last year, with the biggest decrease in the western Tien Shan and western Pamirs. Data and models suggest the melt is outside annual variability and indicative of increasing glacier loss in Central Asia.[5]
- Tropical glaciers in Indonesian New Guinea declined 97% between 1980 and 2024, leaving just two remnant glaciers in Indonesia, colloquially known as the "Eternity Glaciers." Assuming current trends continue, these two remnant glaciers face extinction later this decade. Their loss will mark the end of tropical glaciers in Asia.[6]
- For many Indigenous Peoples, loss of glaciers means a cultural and spiritual imbalance that goes beyond changes in ecosystems, to reshaping connections with the land. For example, the loss of the Chacaltaya glacier in Bolivia has been interpreted by the Aymara community that the protective power of their deities has weakened. From the Andes to the Rwenzori Mountains of eastern Africa to the high peaks of the Hindu Kush Himalayas, many Indigenous communities have seen glaciers as homes of deities, and with their melt, the consequential loss of spiritual protection and connection.[7]
- Melting polar sea ice may contribute to snowfall reduction in the Himalayas by weakening the subtropical jet stream and driving it closer to the equator. In climate model simulations, this loss in snow highlights how changes in the polar regions affect regions thousands of kilometers away, including consequential food and water security due to snow drought.[8]
- Greece's mountain snowpack is fast disappearing, with 58% lost in the past four decades. Satellite observations and models show warming temperatures lead to both more rapid snow melt and more winter precipitation falling as rain. This contributes to a loss of critical seasonal water storage that will be unable to support downstream water needs.[9]
- Glaciers are critical habitats for many endemic species, but these ecosystems remain unprotected by legal frameworks regionally and globally. The EU Habitats Directive is the principal EU legislative mechanism protecting these habitats yet is not implemented to support comprehensive biodiversity and systematic monitoring.[10]
- In 2025, rapid ice loss and glacier retreat led to a landslide in an Alaskan fjord, triggering the second largest landslide tsunami runup ever recorded after Lituya Bay, Alaska (1958), reaching 481m high across the fjord. Along with similar cases in Norway and Greenland, this highlights how retreating glaciers can lead to significant landslides, endangering mountain and coastal stability by removing structural support from rock walls.[11]
- The winter 2025 wildfires in Southern California were the costliest in history with an extended season continuing into the winter. Low snow cover in Eurasia may have fueled the inferno by impacting atmospheric currents, showing how changes in snow cover in one region may trigger extremes in another.[12]
- Since the International Geophysical Year in 1957, nine North American glaciers have been monitored providing melt-rate benchmarks. Sixty years of baseline aerial surveys and more modern satellite measurements have found that each has lost ice mass, reflecting a 33% loss in area. Based on current trajectories of ice loss, only three of the nine will remain by 2100.[13]
- In the western United States, around 10,000 rock glaciers[14] – ice covered by rocky debris – are creating climate refugia by remaining cooler than the warming surroundings. Although they cannot replace other glaciers or snowpack, rock glaciers are less sensitive to melt and thus continue to provide critical summer meltwater and habitat.[15]

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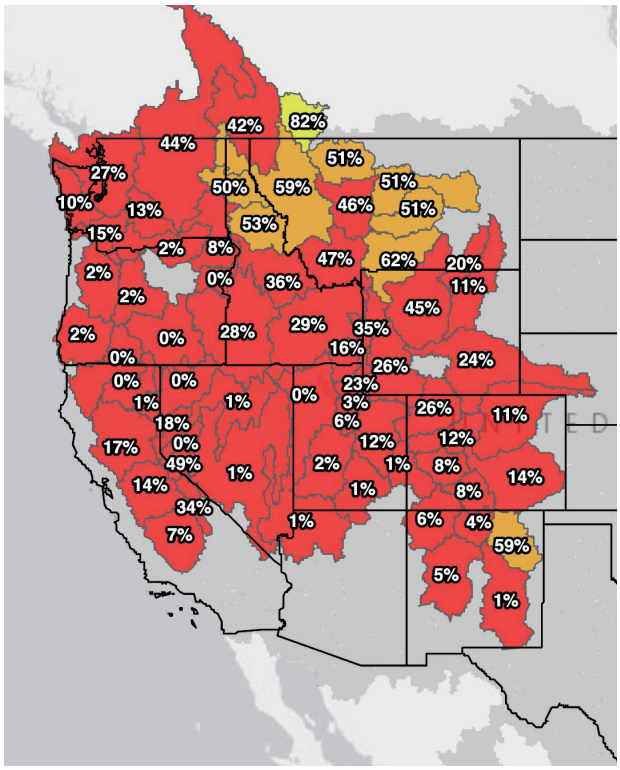
## Background

Glaciers gain mass (ice) via snowfall in winter and lose mass as meltwater in the summer melt season. A glacier is in balance when snowfall, especially high up on the glacier, replenishes what is lost during the summer. Global warming has now disturbed this balance for every observed glacier on the planet, with a net loss of ice occurring almost every year. For example, between 2000 and 2023, glaciers outside of the ice sheets in Greenland and Antarctica lost an average of 273 gigatons each year, with ice loss 36% higher in the second half of that period compared with the first.[18] A threshold or "tipping point" of glacier survival is crossed when the entire glacier, from bottom to top, is snow-free at the end of the summer, leading to the eventual total demise of the glacier.

Glaciers and snowpack serve as an important water source to both nearby and downstream communities, especially in arid regions and/or during warmer periods. Their importance varies, with some contributing only a few percent of water supply over the course of a typical year, but even these may become essential during dry seasons, heat waves and droughts.[19,20,21] Loss of water resources from changing glaciers and snowpack has already contributed to increasing tensions and conflicts in some regions.[22] This underscores the global importance of mountain cryosphere, something which both the International Year of Glaciers' Preservation (2025) and the Decade of Action for Cryospheric Sciences (2025–2034) have emphasized, despite misperceptions that it is a distant or "niche" issue. Therefore, rapid decreases in global emissions are necessary to preserve as much ice and snow as possible.

Glaciers in some regions, such as the tropical Andes, or the Indus and Tarim basins in High Mountain Asia, contribute a high proportion of seasonal water supplies; for example, in the dry Tarim and Aral Sea basins glaciers can contribute close to 100% during the summer.[23]

FIGURE 3-1. **Record Low Snow in Western United States**




Winter snow levels in the western United States reached record lows in parts of the country in 2026 and contributed to worsening drought throughout the year. This map highlights snowpack values for watersheds in the region as percentages of the 1991–2020 median as of May 14, 2026.

Source: USDA

*[At 3°C] flooding and too much water would be followed by growing periods of drought and water scarcity.*

### 2026 UPDATES (CONTINUED)

- Seals caught closer to Greenland's coast and tidewater glaciers eat heavier and more frequent meals than those farther away because meltwater beneath tidewater glaciers forces nutrients and fish to the surface. However, glacier retreat reduces these foraging areas, affecting their range and habit, and changing Arctic ecosystems as well as decreasing food security for Inuit communities.[16]
- Capping temperature rise to 1.5°C spares almost 50% of today's glaciers from extinction by 2100. Under higher emission scenarios, only 20% would remain under current policy-aligned warming (2.7°C by 2100) and fewer than 10% at 4°C. While the percentage of glaciers lost is not the same as percentage of overall glacier ice lost, this study captures the vulnerability of the world's ice to temperature rise.[17]

FIGURE 3-2. **2022-26 Ice Loss at the "Top of Europe": Great Aletsch Glacier, Switzerland**




Record ice loss 2022–26 as measured on Great Aletsch Glacier at Konkordiaplatz, Switzerland. 2026 melt was 5.8 meters. Such steep losses will continue even under HPA pathways, stabilizing once net-zero emissions are reached.

Photos: Matthias Huss.

**FEATURED UPDATE**

## Increasing Snow Droughts Threaten Crop Yields

Snow droughts in winter wheat regions across the Northern Hemisphere are leading to reduced productivity in part due to dry soil and freeze stress. Between 1960 and 2020, snow drought has increased 5.3–6.7% per decade. New research shows that, within this time of snow drought – between 1982–2016, a quarter of the cropland showed yield sensitivity to snowpack loss. Snow droughts are projected to increase further, risking crops and regional food security.[2]

Rapid melting of glaciers has temporarily increased water flow from glaciers in some river basins, but as these glaciers continue shrinking, glacier water availability will begin to decrease (referred to as passing "peak water"), reaching zero if the glacier disappears entirely. While snowpack tends to provide a greater percentage of water, it is also highly variable year-on-year; so glaciers have provided a more reliable flow of water supplies each year. As a result, their loss—together with decreasing snowpack at much larger elevation ranges, including lowlands as well as middle latitudes—may make certain economic activities, and even continued human habitation, impossible in some river basins.

Indeed, most glacier-covered regions outside upper latitude polar regions and High Mountain Asia have already passed this period of "peak water."[24,25] Adaptation efforts are therefore needed immediately to prepare for this future, in tandem with mitigation efforts to preserve glaciers as much as possible. In addition, glaciers have deep cultural and spiritual significance for Indigenous Peoples and local communities, as shown e.g. in recent studies from the Peruvian Andes and the Swiss Alps.[26,27]

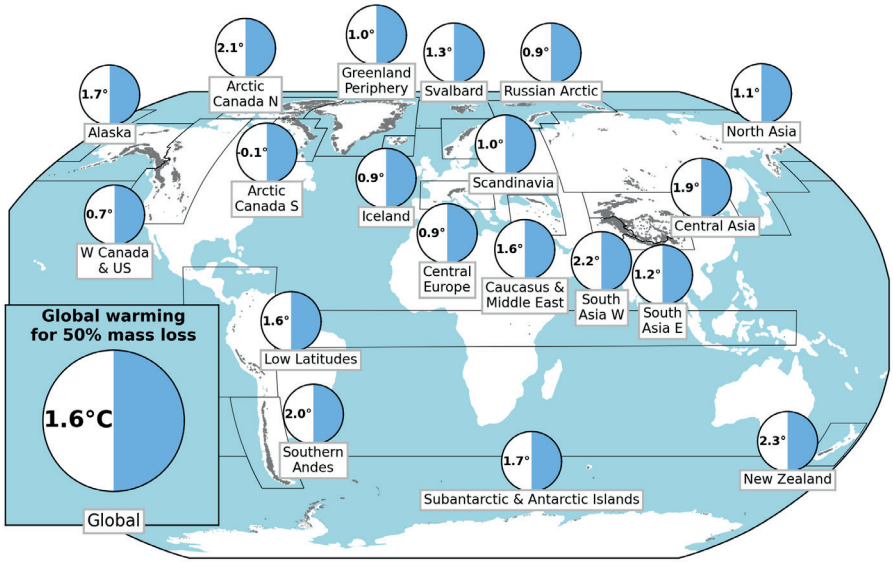
FIGURE 3-3. **How much ice will remain?**

| Region | Temperature causing 50% loss | % Remaining at 3°C | % Remaining at 2°C | % Remaining at 1.5°C |
|---|---|---|---|---|
| Rockies (W. Canada/U.S.) | 0.7°C | 0% | 10% | 20% |
| Iceland | 0.9°C | 0% | 10% | 35% |
| European Alps | 0.9°C | 5% | 15% | 35% |
| Scandinavia | 1.0°C | 0% | 0% | 20% |
| Central & Eastern Himalaya | 1.2°C | 15% | 25% | 40% |

Many important mid-latitude glacier regions will have almost no ice remaining if temperatures reach even 2°C for a sustained period. Percentages are in comparison to 2020 ice mass levels.

Source: GlacierMIP3 (Zekollari, Schuster et al., *Science*, 2025)

FIGURE 3-4. **Nearly All Glacier Regions Lose 50% Ice Below 2°C**




Glaciers are highly sensitive to temperature. All but a few glacier regions lose 50% of their ice at temperatures well below 2°C, and essentially all ice by 3°C if these temperatures are maintained for longer than decadal scales. The above map shows at which stable temperature 50% of the ice in each region would disappear. In most regions, this is at temperatures below today's 1.4°C; and note that in South Arctic Canada, it is actually below pre-industrial, at -0.1°C.

Credit: Lilian Schuster (2026), based on Zekollari, Schuster et al. 2025

*A very low emissions pathway is essential to preserve the ecosystem services glaciers provide.*

FEATURED UPDATE

### Ice Loss in Alaska and Iceland Much Greater Than Previously Thought

Glacier loss in both Alaska and Iceland has been underestimated by 9% and 32% between 2002–2025 because models failed to account for the rebounding of Earth's surface as the ice melts. Satellite measurements did not accommodate uplift in measurements in these regions, and therefore underestimated ice loss. It can be assumed that comparable corrective measurements are now needed across other large, glaciated regions around the world where past measurements have not captured similarly significant uplift. Given their size, estimates in these regions especially may have missed even more significant ice loss.[3]

Many glaciers of the tropical Andes, East Africa and Indonesia, especially those close to the Equator, are disappearing too rapidly to be saved even at present levels of warming.[28,29] These glaciers have mostly been shrinking since the end of the Little Ice Age, but global warming greatly accelerated their melting.[30,31]

Severe losses are also occurring today from lower and mid-latitude glaciers and others outside the polar regions: including the European Alps, southern Andes and Patagonia, Iceland, Scandinavia, the North American Rockies and much of Alaska, Southern Alps of New Zealand, the Caucasus and parts of High Mountain Asia. Under a high emissions scenario, these losses will amount to a total or near-total loss of smaller glaciers and those at lower latitudes and altitudes by 2100.[32,33] Others, such as those in the Hindu Kush Himalaya, may experience loss up to 80% of their current volume by the end of the century on current emissions trajectories.[24] However, at current emission levels, warming oceans are beginning to drive year-round glacier melt on Svalbard, showing that even high-latitude winters are becoming insufficient to protect against runaway ice loss.[34] Despite this, when compared with policy-aligned 2.7°C, global temperatures peaking at 1.5°C saves more than twice as much ice globally – with at least some portion of ice remaining even in the most vulnerable regions – and would lead to some stabilization around 2060, according to latest models.[33,35]

FIGURE 3-5. **The Future of Chhota Shigri Glacier, India**




Chhota Shigri in 2026; and in 2100 with overshoot to 3°C (top right), and stabilized under an HPA-like pathway (bottom right), with temperatures below 1.5°C in 2100. Chhota Shigri is one of many glaciers feeding the mighty Indus River system.

Source: Stills from an animation by Enrico Mattea; to view this and other glacier animations, see iccinet.org/statecryo25/glaciers.

**FEATURED UPDATE**

### Exposure to Hazards from "Hanging Glaciers" in Ganges Headwaters Nearly 20 Times Greater Today

Warming temperatures and changing precipitation in northern India's Alaknanda basin, one of two main headwaters of the Ganges, is causing glaciers to thin and detach, leaving ice perched on steep slopes. Known as "hanging glaciers," these can detach, triggering ice avalanches and secondary downstream hazards, such as glacial lake outburst floods. Exposure to such ice avalanches is increasing, with projections of 19-fold exposure risk in 2030 than in 2000.[1]

Any other path with higher emissions will eventually result in almost complete loss of all mid-latitude glaciers by 2300, many as early as 2050.

Glaciers can shrink and even disappear completely over the space of just decades to a century. The territory that later became Glacier National Park in the U.S. had around 150 glaciers at the end of the Little Ice Age in 1850; today, fewer than 30 remain, and those have shrunk by about two-thirds in surface area.[36] In contrast, projections show that significant ice mass regrowth takes centuries to millennia, but only with very low emissions (carbon neutrality by 2050) and carbon drawdown (negative emissions) thereafter resulting in decreasing temperatures by 2100.[37] Therefore, while early glacier regrowth can be one of the earliest indications of planetary recovery, the changes to the mountain landscape are essentially permanent on human timescales.

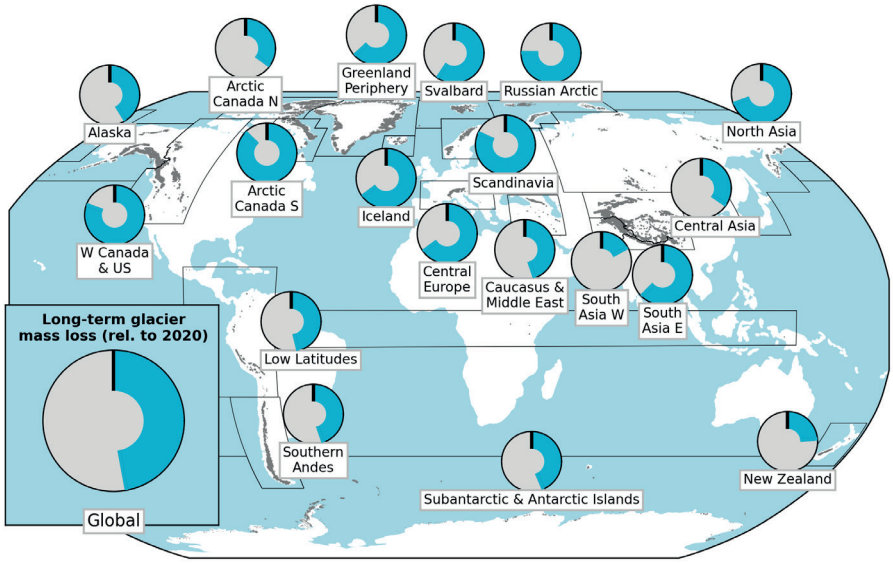
A very low emissions pathway is therefore essential to preserve the ecosystem services glaciers provide, which are already facing losses and extinctions, and to minimize the risk of severe hazards such as glacial lake outburst floods and other ice-rock cascades that accompany loss of mountain glaciers.[38,39,40,41,42,43] The need to cut emissions is underscored by recent research that confirms even high-altitude glaciers previously considered to be less hazard-prone are capable of producing catastrophic and cascading floods.[44,45]

With high emissions, and global mean temperature rise exceeding 4°C by 2100, any substantial seasonal snowpack will become rare outside the polar regions and very high mountains.[46] Snowfall has already become less reliable in many mountain watersheds, with extreme snow droughts alternating with extreme snowpack, which increases the risks of avalanche and flood, such as in California, USA (2023) and the Hindu Kush Himalaya (2023–2024).[21,46,47] Snowfall declines as temperatures rise above freezing at higher and higher altitudes, with precipitation that would have fallen as snow in past decades, instead coming down as rain, and often in extreme quantities that run off quickly rather than recharging underground aquifers.

With rising temperatures due to high emissions, snow will become less frequent, especially at lower elevations and latitudes, and the winter season will shorten.[48,49] Even in the high-latitude Arctic, spring snow melt has been occurring 1–2 weeks earlier over the past fifteen years; and the 2023–24 snow season in parts of Canada was the shortest in over a quarter-century.[50] Water stored in the snow and snow-fed underground aquifers will decrease, as already reported in many mountain areas.[51,52] Additionally, newly ice- and snow-free regions may transform from a carbon sink into a net source.[53] Continued declines in annual snowpack will result in negative economic impacts for many sectors, especially agriculture, hydropower, tourism, and health;[54] and threaten the availability of sufficient water supplies for major downstream population centers, from Los Angeles and Bangladesh to Marrakech and Delhi.[55,56,57,58]

In both the Arctic and mountain regions, the wellbeing of people and many species depends on seasonal snow cover. For reindeer-based Arctic Indigenous cultures, more animals are lost to starvation when winter rain falls on snow, forming thick layers of ice that make it impossible for reindeer to forage.[59,60] Reduced snow cover also increases the severity of wildfires, as well as elevates risk for natural hazards such as mudslides or drought in the wake of fires.[61] Moreover, when landing on ice or snow, the black carbon from wildfires and other sources can spur significant melt by increasing heat absorption.[62,63]

FIGURE 3-6. **Extensive Ice Loss in Glacier Regions at 1.5°C Baseline**




Circles show the proportion of ice lost in each glacier region at stable 1.5°C based on 2020 ice levels – which in some regions, already had extensive loss since the mid-1900's. For most glacier regions, regaining at least some portion of their ice mass would require lower temperatures, as with limited overshoot-and-decline pathways to 1°C and below through sustainable carbon drawdown.

Credit: Lilian Schuster (2026), based on Zekollari, Schuster et al. 2025

The 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, hydropower and irrigation. Stronger pledges will also significantly benefit economies dependent on snowpack for power generation, agriculture and revenue from snow tourism.[64] Lower emissions can 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.[33] New research highlights overconfidence in the ability to draw down temperatures with any overshoot of 1.5°C, reinforcing the need for drastic emissions cuts.[65] Nevertheless, even with 1.5°C-consistent pathways, mountain and downstream populations must be prepared for current steep losses to continue through at least mid-century, requiring adequate adaptation and disaster prevention measures.

A sharp strengthening of climate action towards the 1.5°C limit will determine the future beyond mid-century, with 2025 NDCs essential for course-correction towards a credible 1.5°C goal for the benefit of at least 3 billion people seasonally dependent on a healthy mountain cryosphere.[37,66]

*References begin on page 38.*

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CHAPTER 4

# Polar Oceans

## *More Extreme Acidification, Warming and Ocean Current Slowdowns with Higher Overshoot*

The Arctic and Southern Oceans are experiencing rapid, interconnected physical, chemical and ecological changes due to the combined effects of rising temperature and atmospheric $CO_2$ levels, including rapid acidification from $CO_2$ absorption by polar waters. The triple threat of acidifying, warming and freshening waters challenges polar marine life, including economically important fisheries. Two major drivers of ocean currents (the Atlantic Meridional Overturning Circulation (AMOC) and the Antarctic Overturning Circulation (AOC)) have measurably slowed due to a combination of meltwater from the Greenland and Antarctic ice sheets, sea ice loss and warming surface waters. Polar oceans form the foundation of the global ocean circulation system, distributing heat, carbon, oxygen and nutrients around the world.

### Overshoot to 3°C: Current Emissions Pathway and Policies

#### CMIP 7 High-low Scenario: peak 2.8–3.2°C, 1.5°C in 2250

With overshoot to 3°C (equivalent to 550+ ppm (parts per million) $CO_2$ in the atmosphere), severe and possibly abrupt circulation disruptions become extremely likely alongside widespread ocean acidification. AMOC shutdown potentially might occur before 2100, with drastic impacts on temperatures in northern Europe (dropping by up to –20°C from today) as well as on weather patterns globally. Acidifying waters as well as marine heatwaves and other extreme events would spread to most sectors of both polar oceans, with cascading impacts on ecosystem and climate services, fishery survival and global food security. Models consistently project these changes to be essentially irreversible on human timescales, set by peak temperature and $CO_2$ concentrations in the atmosphere, even after temperatures and atmospheric $CO_2$ levels decline. These include persistently warmer waters (leading to continued ice sheet melt from below), acidifying waters that are detrimental to marine life, and disruption of global ocean currents, for the next centuries to millennia. Reversal of these impacts will not occur on timescales relevant to societies, fisheries, conservation or climate stability.

### Stable 1.5°C without Decline

Scenarios where global warming remained at 1.5°C or below, and $CO_2$ levels stabilized at no more than 450 ppm,* would have limited the spread of surface ocean acidification and reduced the risk of irreversible changes in global ocean currents. Polar species however began showing negative impacts from acidification in the 2000's, well before $CO_2$ concentrations first exceeded 400 ppm at around 1°C of warming. These observations mean that even stabilization at 1.5°C greatly increases risks to polar marine life.

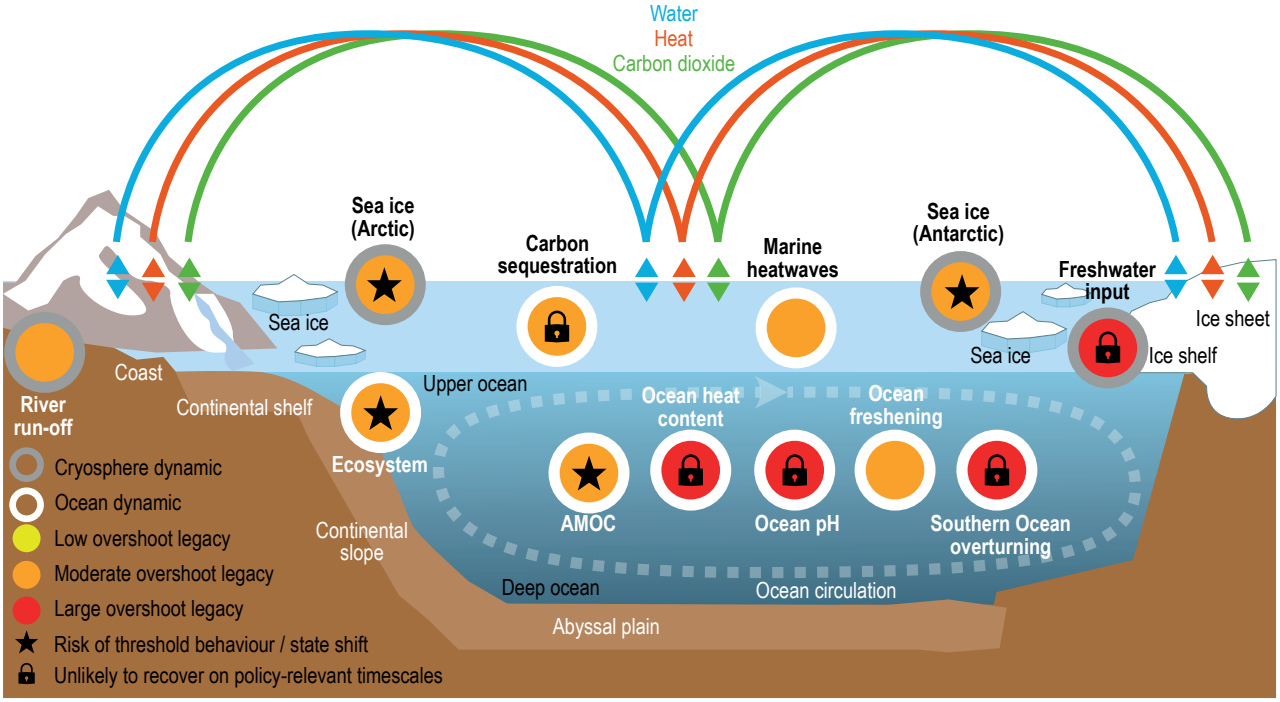
### Limited Overshoot to 1.7°C with Rapid Action: 2050 Net Zero

#### Highest Possible Ambition (HPA) Pathway: peak 1.7°C, below 1.5°C by 2100, below 1°C by 2150

Even the most ambitious measures now would result in peak temperatures around 1.7°C for about two decades, meaning peak $CO_2$ levels close to 470 ppm before net zero is reached. With sustainable carbon drawdown, temperatures would fall well below 1.5°C by 2100. Continued carbon drawdown, resulting in $CO_2$ levels of 350–380 ppm by 2150, would allow surface waters to begin recovery from previous acidification, but acidifying conditions would spread deeper and continue to negatively affect marine life, as complete rebalancing of ocean chemistry takes tens of thousands of years. Atmospheric temperatures at or below 1°C by 2150 under HPA pathways would decrease, but not eliminate completely the risk of AMOC and AOC shutdown, given the persistence of warmer waters and committed ice sheet melt.

* There is growing evidence that Earth's temperature may be more sensitive to $CO_2$ concentrations in the atmosphere, given temperatures nearing 1.5°C already at today's 427 ppm (2025 average).

FIGURE 4-1. **Overview of Ocean Impacts under Overshoot**




Overview of legacy impacts resulting from overshoot that temporarily exceeds 1.5°C on various components of the polar oceans, compared to a temperature stabilization at below 1.5°C. Some dynamics, such as the overturning circulations in the Atlantic and Southern Oceans or sea ice, face increased risk of large-scale, abrupt changes under overshoot (marked with stars). Other dynamics, such as the warming and acidification of the deep ocean, are associated with irreversible consequences under overshoot that may not recover on human timescales (marked with locks). Importantly, even low overshoot with HPA pathways results in some moderate and irreversible polar ocean changes.

Source: Adapted from IPCC SROCC (2019) for the ICCI/UNEP Cryosphere Overshoot Report (2026)

## 2026 Updates

- Marine heatwaves in the North Atlantic have increased sharply since 2003, triggering widespread ecological changes across multiple levels of marine food webs. A new synthesis shows that these extreme heat events caused rapid shifts from species adapted to colder, ice-associated environments toward species better suited to warmer conditions, affecting organisms from microscopic plankton to whales. The impacts extended across connected ocean regions and altered ecosystem and socio-economic dynamics. However, the magnitude of ecological responses varies between heatwave events, highlighting uncertainties in predicting future ecosystem impacts.[4]
- Global ocean warming continued in 2025, with the upper 2000 meters of the ocean gaining around 23 zettajoules of heat (equivalent to around 250 times the world's annual electricity generation) compared with 2024—an increase of about 8%. Multiple independent datasets confirm that ocean heat content is rising more than twice as fast in recent decades compared with the long-term average since 1960. More than half of the global ocean experienced annual average temperatures among the five warmest years on record, including parts of the Southern Ocean. Although global sea surface temperatures declined slightly from the 2024 record due to emerging La Niña conditions, 2025 remained the third-warmest year observed.[5]

*continued on next page*

# Background

Rising atmospheric $CO_2$ is driving climate change and rapidly acidifying the world's oceans, especially the Arctic and Southern Oceans. $CO_2$ dissolves in seawater, and oceans globally absorb around 30% of human $CO_2$ emissions every year.[12,13] However, this dissolution of $CO_2$ in water forms carbonic acid, altering ocean chemistry. Since colder and fresher water absorbs more $CO_2$ than warmer and saltier water, the polar oceans combined have already taken up over half of the total global oceanic carbon uptake—mostly in the Southern Ocean—making them disproportionately affected by acidification.[14,15]

Over the past several million years, average ocean acidity has been relatively stable. While polar oceans have undergone changes in the Earth's past, these shifts

## 2026 UPDATES (CONTINUED)

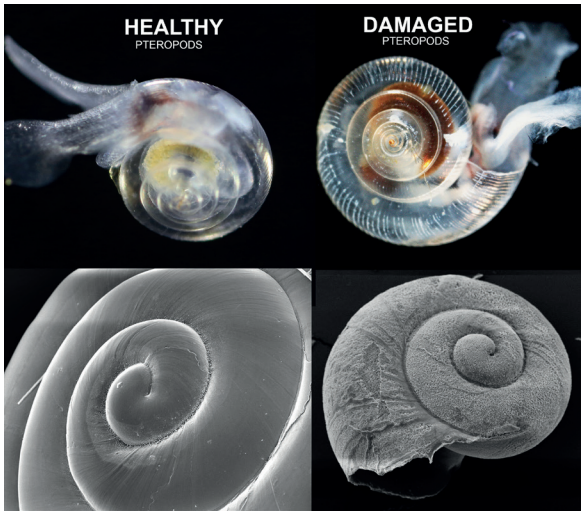
- Freshwater input from the melting Greenland Ice Sheet can trigger rapid ocean warming in the subpolar North Atlantic, creating a potential feedback loop that may further accelerate ice loss. Model simulations show that a relatively small increase in meltwater discharge can warm subsurface waters by around 1°C within a decade in regions surrounding Greenland and the Labrador Sea. Freshening strengthens ocean stratification and reduces the Labrador Current, allowing more heat to accumulate near the coast. These changes could influence the stability of both the Greenland Ice Sheet and the AMOC.[6]
- A collapse of the AMOC could release around 50–80 ppm additional $CO_2$ into the atmosphere due to increased release of $CO_2$ from the Southern Ocean. This is because AMOC collapse would result in the opposite effect, a stronger overturning, of Southern Ocean waters, which are extremely carbon-rich. While an AMOC collapse would cool much of the Northern Hemisphere and thereby the global climate, this $CO_2$ increase would still result in approximately 0.2°C of additional global warming. However, the difference in regional impacts would be extreme, with still-substantial cooling in the Arctic and North Atlantic, but pronounced warming in the Antarctic, which could lead to additional ice sheet melt and global sea-level rise.[7]
- The stability of the AMOC may depend not only on future greenhouse gas emissions, but also on natural climate variability beginning to operate near critical thresholds. Climate model simulations show that even under the same $CO_2$ stabilization pathway, internal atmospheric fluctuations can push the AMOC either toward recovery or into long-lasting collapsed state due to self-reinforcing freshwater and salt feedbacks. The likelihood of crossing this threshold increases if climate mitigation is delayed.[8]
- The risk of an AMOC collapse may depend not only on how much global warming occurs, but also on how quickly. Climate model simulations show that under very gradual $CO_2$ increases, the AMOC can remain stable up to around 5.5°C of global warming; but a faster rise in $CO_2$—similar to the rate of increase today—can trigger collapse at warming levels as low as 2°C. This is because slow warming allows the ocean to adjust through changes in evaporation and sea ice that counteract destabilizing feedbacks. These findings indicate that rapid emissions reductions could substantially reduce the risk of collapse.[9]
- Warm circumpolar deep water is moving closer to Antarctica, increasing ocean temperatures nearer to Antarctic ice shelves. Combining ship-based observations with Argo float data and machine learning, researchers found that since 2004, the thickness of warm water in the upper 2000 meters has increased near the Antarctic coast. The core of this warm water mass has shifted poleward by more than a kilometer per year on average, indicating greater delivery of heat to the continental shelf. These changes could increase basal melting of Antarctic ice shelves, potentially destabilizing the ice sheet and increasing future sea-level rise.[10]
- Increasing meltwater from the Antarctic Ice Sheet is projected to substantially reduce the formation of AABW, a key component of global ocean circulation, and, at the same time, significantly weaken the Antarctic Circumpolar Current (ACC). New ocean model simulations show that AABW transport could decline by about 30% by 2100 compared to today under a high emissions scenario, while ACC transport could decline by about 15–20%. Although these changes lead to a slight strengthening of the AMOC over the next few decades in the model, continued freshwater inflow from ongoing Antarctic ice sheet melt is expected to ultimately weaken it in the long term.[11]

occurred far more slowly. Even so, these previous changes to ocean chemistry and acidification were accompanied by mass extinctions.[16] Today's ocean acidification is occurring faster than at any point in at least the past 300 million years.[17] The speed of today's acidification is therefore a key part of its threat: occurring too quickly to allow many species to adapt, evolve and survive.[18,19]

Ocean acidification harms marine invertebrates such as pteropods, sea urchins, clams and crabs by weakening their shells and causing them to expend more energy maintaining their internal pH.[20,21,22] These animals are fundamental to polar marine food webs and provide sustenance for iconic megafauna and key commercial species like salmon and cod. Disruptions at this base level of the food web cascade through the ecosystem, ultimately affecting fisheries and human food security.[23,24]

Widespread levels of corrosivity have already been observed in the Arctic Ocean,[25,26] alongside declines in pH over several decades in the Southern Ocean, including in Antarctic Marine Protected Areas.[27,28] Damage to vital marine invertebrates such as pteropods has been observed in both the Arctic Ocean[29,30] and Southern Ocean.[31]

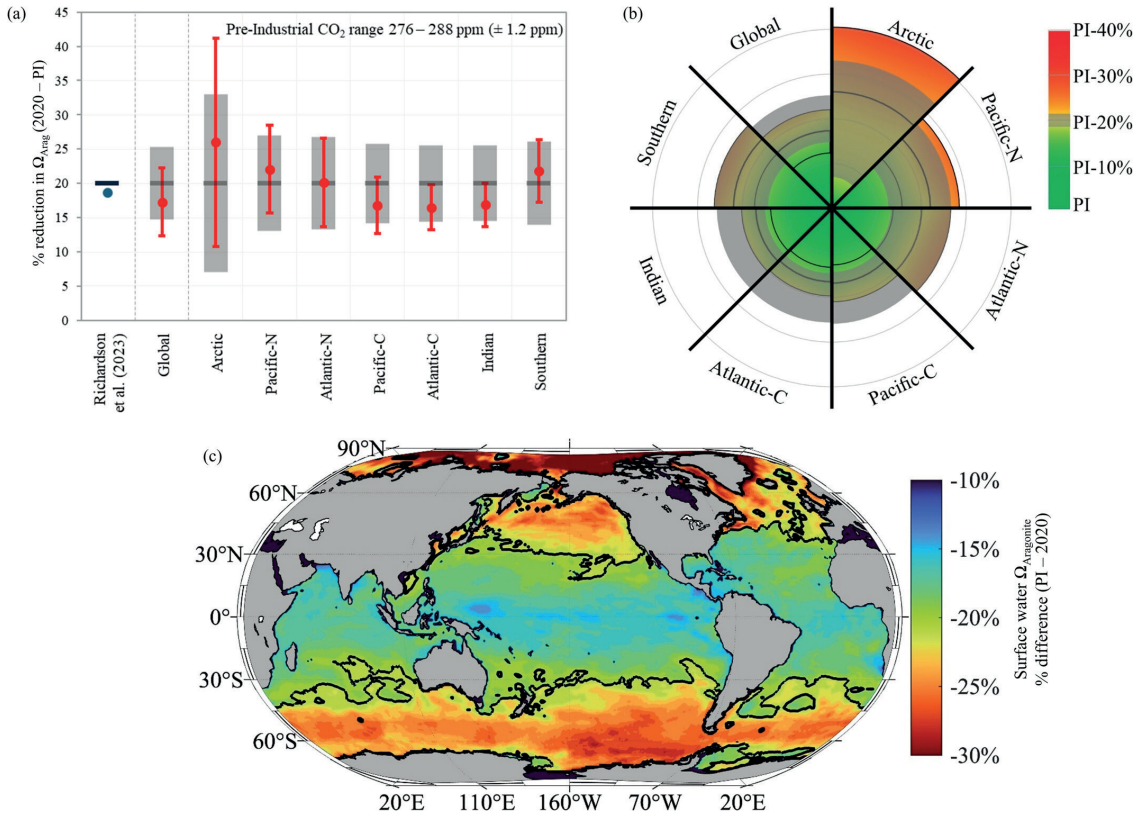
FIGURE 4-2. **Shell Damage from Ocean Acidification**




Pteropods are an important part of the polar ocean food web, with damage from acidification observed in the wild. Healthy pteropod (left), with pteropods showing shell damage from corrosive waters (right) sampled in Antarctic waters around 2006.

Source: N. Bednaršek

FIGURE 4-3. **Observed Ocean Acidification**




The observed rise in ocean acidification compared to pre-industrial (year 1750) marks the transgression of the planetary boundary of ocean acidification in four out of seven ocean basins, all of which lie in the polar regions.

Source: Findlay et al. (2025)

There is currently no viable or scalable practical way to reverse ocean acidification. Natural buffering processes such as rock weathering operate over tens of thousands of years, and so, while $CO_2$ remains in the atmosphere, acidification of the oceans will persist for millennia,[5] making this the "most irreversible" cryosphere dynamic of all.

The only way to slow and eventually halt ocean acidification is through rapid, deep reductions in $CO_2$ emissions and future $CO_2$ removal from the atmosphere. Without these solutions, atmospheric $CO_2$ is expected to surpass 500 ppm, well above the critical level of 450 ppm identified by marine scientists decades ago, and more than doubling ocean acidity in polar regions.[32] Polar marine ecosystems and the people who rely on them will bear the brunt of these changes.

Rising atmospheric $CO_2$ also results in warming of the ocean, most dramatically in the polar regions.[33] This has reduced their capacity to absorb $CO_2$ and limit atmospheric warming in recent years, further amplifying climate change.[34] Arctic summer surface water temperatures have risen by 2°C since 1982, driven by sea ice loss (which exposes darker ocean waters that absorb more solar heat) and inflows of warmer water from lower latitudes. Even at today's ~1.3°C of global warming, Arctic sea ice has thinned and shrunk significantly, and thick multi-year ice – once a year-round feature harboring its own very special ecosystem of which the polar bear and other marine mammals are a part – has nearly disappeared.[35] The duration and frequency of Arctic marine heatwaves are also increasing now and are expected to continue to increase in the future.[36]

The Southern Ocean has also warmed faster than most other regions, particularly along the western Antarctic Peninsula. Record-low sea ice around Antarctica in 2023, with continuing losses through 2025, have added even more stress on marine ecosystems already threatened by acidification and freshening due to glacial melt. Marine heatwaves are now more frequent across Southern Ocean regions, including the Ross, Amundsen-Bellingshausen, and Davis Seas.[37] Furthermore, it is predicted that the Southern Ocean will continue to warm even after net-zero has been reached.[38] These heatwaves

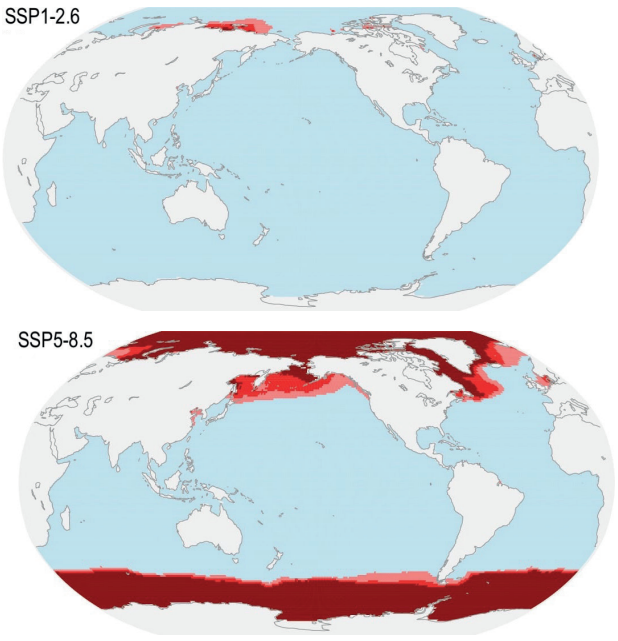
*With 3°C overshoot, reversal of these impacts will not occur on timescales relevant to societies, fisheries, conservation or climate stability.*

FEATURED UPDATE

## Arctic Ocean Far Slower to Recover from Acidification than Any Other Ocean

Acidification of the ocean's interior will persist for hundreds to thousands of years even after a decline of atmospheric $CO_2$ concentrations. While acidification at the ocean surface may in general recover more quickly once atmospheric $CO_2$ levels drop, a study showed that the Arctic Ocean is especially vulnerable to delayed recovery. New model simulations indicated that as $CO_2$ levels fall, Arctic surface waters remain acidic for longer than other ocean regions and require a greater decline in atmospheric $CO_2$ to recover. Indeed, corrosive conditions persist until atmospheric $CO_2$ falls around 120 ppm *below* the level at which acidification first reached the same threshold. Interactions in the Arctic between sea ice, ocean waters and the atmosphere appear responsible for this greater sensitivity.[1]

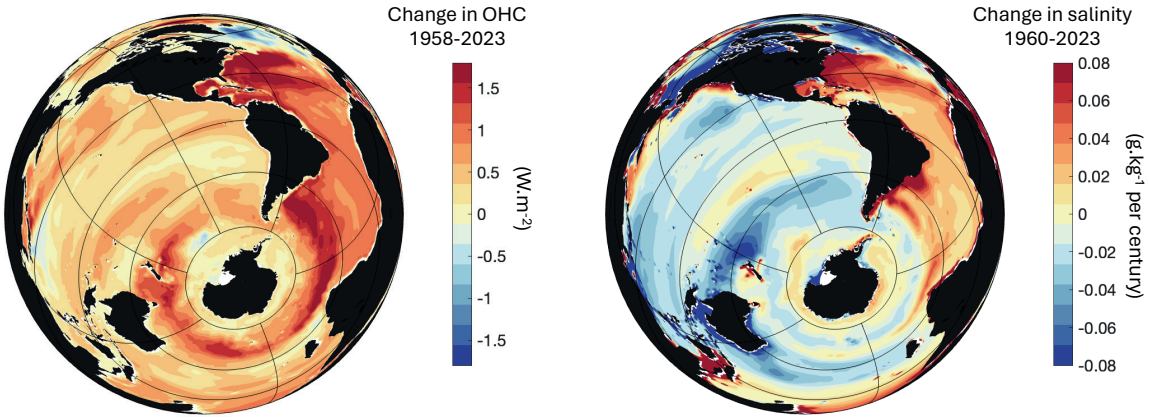
FIGURE 4-4. **Global Ocean Acidification Levels at Minimal vs. Very High Overshoot**




Global ocean acidification levels in pathways with no or minimal versus very high overshoot. Top map shows acidification levels in a 1.5°C world (SSP1-2.6, atmospheric $CO_2$ levels <450 ppm) and bottom map a 3–4°C world (SSP5-8.5, atmospheric levels 700–1000 ppm). Red shows "undersaturated aragonite conditions", a measure of ocean acidification meaning that shelled marine organisms will have difficulty building and maintaining their shells, with loss of biodiversity due to simplified food webs.

Source: IPCC SROCC (2019)

FIGURE 4-5. **Observed Ocean Warming and Freshening**




Regions of the polar oceans are among the fastest-warming waters on the planet, at the same time as ice sheet melt is leading to large injections of freshwater that can impact global ocean currents. Observed increase in ocean temperature ("heat content") between 1958–2023 (left) and observed decrease in salinity (increasing freshwater) from 1960–2023 (right), where blue indicates greater presence of freshwater. In contrast, the increased salinity in the Atlantic and Caribbean is due to less precipitation and greater evaporation, leaving the salt behind.

Source: Meredith et al. (2025)

have pushed some polar species beyond their adaptive limits with damaging, even lethal, temperatures causing severe plankton biomass loss and major disruptions in the Southern Ocean food web.[39] In addition, rising temperatures and the increase in marine heatwaves increase the risk of so-called "bioinvasions": sub-Antarctic marine species such as invertebrates and kelps, which normally cannot survive in the Antarctic environment due to their narrow temperature range, can overcome this physiological barrier during prolonged marine heatwaves, posing an additional stress on local marine species.[40]

**FEATURED UPDATE**

### AMOC May Slow by 50% with Even Intermediate Emissions

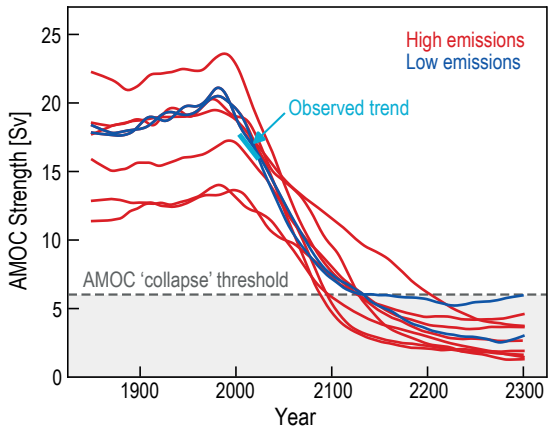
A study using observations of ocean conditions to refine climate model projections predicts that the strength of the AMOC could decline by around 50% by 2100 under an intermediate emissions scenario — substantially larger than average model projections. The stronger weakening is linked to enhanced inclusion of South Atlantic surface salinity, which negatively affects AMOC stability. AMOC weakening would have far-reaching and severe consequences, especially for northern Europe, and these findings suggest that future climate impacts resulting from AMOC changes may be even greater than previously estimated.[2]

As the ocean warms and more temperate marine species in both polar regions struggle to survive, they migrate poleward tracking their thermal niche. This poleward migration increases competition for food resources in areas where polar endemic species essentially become trapped with nowhere else to migrate.[41,42] As the multi-year ice diminishes, sea ice-associated algae and animals are also being lost. Much biological production takes place here, and this production forms the nutritional basis for fish like polar cod, the seals preying on these fish, and ultimately apex predators like the polar bear. Such combined stressors threaten subsistence and commercial fisheries, putting regional economies, Indigenous cultures, and global seafood supplies at risk.[11,17,43]

In the oceans surrounding Antarctica, krill (a keystone species for the Southern Ocean food web) faces severe contractions of suitable habitat at higher emissions levels, driven by ocean warming and acidification, as well as sea ice decline and ocean circulation changes.[44] As krill also plays a critical role in carbon sequestration, a decline in populations threatens not only ecosystems and fisheries, but also a substantial, long-lived carbon sink in the Southern Ocean.[45] The outlook for this critical species and all organisms that rely on it is much better in lower emissions scenarios, with potential partial recovery by 2100.[33]

***Widespread levels of corrosivity have already been observed in the Arctic Ocean.***

FIGURE 4-6. **Projected AMOC Collapse**




Atlantic Meridional Overturning (AMOC) strength under different emissions pathways and models. High emissions pathways (red) caused shutdown (defined as below 6 Sverdrups [Sv], a measure of underwater current flow) in all models. Collapse even occurred under the two models that included low emissions (blue), though more slowly and with potential recovery. Based on these models however, continued AMOC slowdown or even shutdown appears all but inevitable. The short cyan line shows the observed trend from 2005–2023, but with very limited observation data points.

Source: Amended from Drijfhout et al. (2025)

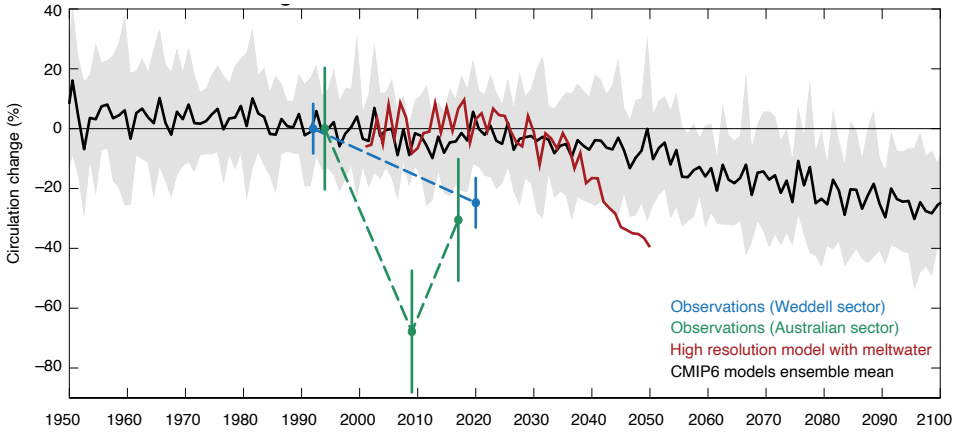
***Temperatures at or below 1°C by 2150 with carbon drawdown would decrease the risk of AMOC and AOC shutdown.***

Melting glaciers, ice sheets, and increased Arctic river runoff are adding large volumes of freshwater to the polar oceans. This reduces the salinity of surface water, creating a cold, lower-density layer on top of the saltier, denser water below. This layering prevents the vertical mixing of nutrients, heat, and carbon through the ocean, with far-reaching implications for global marine ecosystems and the carbon cycle.[46,47]

One of the most far-reaching climatic consequences of polar ocean freshening is the weakening of the AMOC. A strong AMOC relies on dense, salty water sinking in the sub-polar North Atlantic, from where it travels southwards deep in the ocean and is replaced by warm water from the tropics, driving a vast Atlantic oceanic conveyer belt. Freshwater from Greenland's melting ice sheet dilutes this salty water, slowing the entire system. Recent evidence suggests the AMOC is weakening more quickly than previously thought, raising serious concerns about an irreversible threshold being crossed which would lead to a new ocean-climate state.[48,49,50] If triggered, this new state would result in a dramatic cooling of northern Europe over just a few decades[51] – likely too fast for large populations to adapt in a sustainable way.[52]

In Antarctica, similar processes are underway. The Antarctic Circumpolar Current, the strongest current in the world, is projected to slow by up to 20% by 2050 due to freshwater input from ice melt, with profound climate and ecological impacts.[53] Meanwhile, the formation of Antarctic Bottom Water (AABW), which helps drive the Antarctic Overturning Circulation (AOC) and thereby the entire global ocean circulation, is decreasing, which will affect global ocean circulation patterns for centuries.[54] Weddell Sea Bottom Water, which makes up nearly half

FIGURE 4-7. **Observed and Projected AOC Slowdown**




Slowdown in Antarctic Overturning Circulation (AOC) can be seen in observations (blue and green lines; starting in the early 1990s), as well as in CMIP6 models (multi-model mean across 18 models in black, with model spread in gray). The slowdown is even more pronounced when including meltwater from the Antarctic Ice Sheet in the simulation (red).

Source: Abram et al. (2025)

of the AABW, has shrunk by 30% since 1992. Its decline is linked to reduced sea ice formation and increasing freshwater from the melting Antarctic Ice Sheet.[40,55]

Changes in ocean currents affect entire ecosystems and food systems. Reduced mixing restricts the delivery of nutrients to the ocean surface, starving surface-dwelling marine life.[56,57] Polar marine ecosystems, already stressed by acidification and warming, may not be able to adapt to this new stratification. Physiological stress, disrupted migration, and collapse of key species are likely outcomes.[58,59] Polar oceans are home to some of the planet's richest fisheries; their destabilization threatens food security, economies and cultures in the polar regions and worldwide.

At 2°C of warming or above, ocean acidification, warming and freshening will transform polar oceans irreversibly, threatening vital ecosystems and fisheries, and undermining the processes that stabilize the climate system to a large degree. Both poles are nearing critical thresholds, and some may already have been breached. Limiting global warming to 1.5°C through deep emissions cuts of 50% by 2035 and net zero by 2050, followed by carbon dioxide removal, is essential to preserve our polar oceans and the critical services they provide to human societies worldwide.

*References begin on page 38.*

FEATURED UPDATE

### Slowdown of Antarctic Bottom Water Increased Four Times after 2015, with Possible Links to Antarctic Sea Ice Loss

Antarctic Bottom Water (AABW), a key driver of global ocean circulation that stores heat and carbon in the deep ocean, has declined markedly over the past two decades. A new observation-based reconstruction shows that its volume decreased by almost 3% over the last two decades, with the rate of decline increasing fourfold after 2015. This accelerated decline coincides with the rapid reduction in Antarctic sea ice observed since 2016, hinting at strong links between sea ice variability and AABW formation. These findings suggest recent Antarctic changes are already affecting the deep ocean, with far-reaching consequences for global ocean circulation and climate.[3]

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CHAPTER 5

# Sea Ice

## *Overshoot Delays Ice Recovery for Decades and Centuries*

Declining **sea ice coverage and thickness** occurred in the Arctic well before global temperatures exceeded 1.0°C of warming; and Antarctic sea ice recently shifted from a highly variable pattern, to one of steep decline that now equals the Arctic in scale. Both regions have now lost about 40% of both their area and volume in the summer, and about 30% in winter, with open dark water absorbing sunlight and accelerating global warming.

### Overshoot to 3°C: Current Emissions Pathway and Policies

#### CMIP 7 High-low Scenario: peak 2.8–3.2°C, 1.5°C in 2250

Sea ice likely remains among the most reversible of Earth's cryosphere elements after overshoot; but current research points to longer delays in ice recovery than previously thought with high overshoot, on the level of decades to even centuries due to warmer ocean waters. Already in the 2°C range, Arctic summer (September) sea ice would disappear for at least some period in September each year. That absence will spread to the spring and especially the fall months by overshoot of 3°C. Projected patterns in Antarctica are far less certain, but losses may be as large. This greatly diminished sea ice, while of some benefit to shipping in the Arctic Ocean, will carry high global economic costs due to accelerated rise in global temperatures, including deadly heatwaves due to the absence of reflective sea ice; potential shutdown of important ocean currents; greater Arctic permafrost thaw, including higher emissions and more land collapse; and greater ice loss from Greenland. Antarctic sea ice loss could accelerate sea-level rise from Antarctica due to collapse of its surrounding ice shelves without the protection sea ice provides. Sea ice-based species, ecosystems and human communities will collapse and not be able to recover on time scales relevant to overall survival. The volume of sea ice after overshoot also is expected to be lower than pre-overshoot levels, even at identical temperature levels.

### Stable 1.5°C without Decline:

Even if temperatures stabilize at 1.5°C, occasional ice-free summers in the Arctic would still occur; while in the Southern Ocean, the thermal inertia of warmer waters may continue to drive Antarctic sea ice loss for some time. Eventually however, sea ice at both poles would stabilize at new and lower levels from today, at times with brief summer ice-free conditions.

### Limited Overshoot to 1.7°C with Rapid Action: 2050 Net Zero

#### Highest Possible Ambition (HPA) Pathway: peak 1.7°C, below 1.5°C by 2100, below 1°C by 2150

Even the most ambitious measures now cannot prevent overshoot to 1.7°C that lasts about two decades, meaning frequent ice-free summers during this overshoot period. However, with decline to well below 1.5°C by 2100, sea ice at both poles should begin to recover relatively quickly given less warming of the polar oceans than with higher and more sustained overshoot; though any slowdown in ocean currents may cause warmer water to remain at the water's surface, delaying recovery on scales of decades or longer. Continued cooling to 1°C under the HPA Pathway however should help to avoid the worst feedbacks of sea ice loss.

# Background

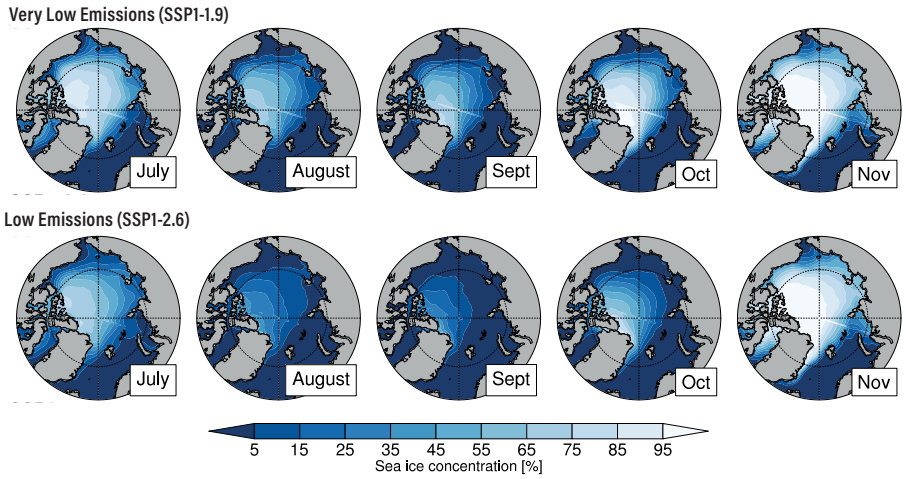
### ARCTIC SEA ICE

Sea ice has served as a "global refrigerator" in the climate system almost continuously for at least the past 125,000 years. Ice in the Arctic Ocean, which covers an area nearly twice the size of the continental U.S., reflects most of the sun's rays back into space during the entire 6-month boreal summer "day," cooling the planet. Yet, multiyear sea ice cover in the Arctic has declined by at least 40% and sea ice volume by 75% since the first satellite measurements in 1979.[15,16] Now the Arctic Ocean is dominated by a thinner covering of first-year ice,[17,18,19,20] which cannot sufficiently thicken in winter and is prone to being carried towards the warmer Atlantic waters, where it melts

# 2026 Updates

- Human-caused warming has been the primary driver of winter Arctic sea ice loss since 1980, accounting for most observed decline. Unlike summer sea ice, which has long exhibited a clear response to rising temperatures, winter sea ice was traditionally considered more strongly influenced by natural variability; but this study showed that naturally varying climate patterns, especially in the North Atlantic and parts of the tropical Pacific were of secondary influence on winter sea ice loss.[5]
- Floating slurries of Antarctic sea ice protect the margins of ice shelves from incoming ocean waves, which strike with enough force over time to bend and break ice into the ocean. Months of reduced sea ice preceded three recent major ice shelf calving events, in which large portions of the ice shelves broke away. In final weeks before collapse, each of these ice shelves lost the residual band of sea ice attached to their outer edge, a warning sign of major ice loss soon to occur.[6]
- Arctic sea ice carries far-reaching effects on global climate and weather patterns, including linkages between winter sea ice loss and warmer summer temperatures across much of Europe.[7] Under high emissions, polar sea ice loss is also projected to weaken the winter storm systems known as Western Disturbances this century, reducing winter precipitation and snow accumulation in the Himalayas, which support major river systems across South Asia. These storms bring sudden rain, snow and fog during the winter and pre-monsoon season. They play an essential role in sustaining Himalayan glaciers and winter crops.[8]
- Rough ridges in Arctic sea ice create habitats that sustain diverse microbial communities. These ridges store frozen organic material in the winter and transform into hotspots of algal productivity in summer, holding up to eight times more algae than nearby smooth ice or surface waters. Sea ice loss could reduce algal growth in these habitats and increase the breakdown of organic carbon, with ripple effects across Arctic food webs.[9]
- The amount of sunlight entering the Arctic Ocean will likely increase by over 50% in coming decades as sea ice cover declines, but a high emissions scenario could push this system even further, past a threshold of even more intense warming after 2050 if sea ice levels collapse. With such extreme sea ice loss, increased light reaching greater depths would further speed up ocean warming. Such warming could sharply reduce polar cod egg survival.[10]
- Rapid sea ice loss is driving a fundamental shift in the Arctic Ocean, from a system limited by sunlight to one limited by nitrogen, a nutrient essential for marine life. Nitrate concentrations declined sharply beginning around 2009, shortly after Arctic sea ice underwent major losses. This mechanism has doubled nitrogen decrease in some regions, particularly the Chukchi and East Siberian seas. Changes in ocean circulation have spread these nitrogen-poor waters across the Arctic.[11]
- Recent Antarctic sea ice loss during the emperor penguin molting season has led to sharp decrease in some colonies. Molting is a vulnerable period when penguins regrow their waterproof feathers and cannot enter the ocean to feed until the process is sufficiently complete. Before 2022, over 100 penguin groups were identified in the studied region; in 2025, only 25 small groups remained.[12] On a larger scale, Emperor penguin populations in the Antarctic Peninsula, Weddell Sea, and Bellingshausen Sea have declined by 22% since the turn of the century, two times faster than previously predicted.[13]
- The emperor penguin and Antarctic fur seal were added to the International Union for Conservation of Nature (IUCN) Red List; these species are now classed as Endangered due to climate change.[14]

FIGURE 5-1. **More Arctic Sea Ice with Lower Overshoot**




The AR6 Very Low Emissions (SSP1-1.9) and Low Emissions (SSP1-2.6) pathways both tracked low overshoot scenarios, with peaks of 1.6°C and 1.8°C, respectively but declining to below 1.5°C by 2100. HPA pathways, though starting from a higher total emissions and temperature point would show similar amounts in 2100, though note the far greater sea ice extent in late summer-early fall (September-October) with 1.6°C peak as compared to only 0.2°C higher, underscoring the need to keep overshoot as low and as brief as possible.

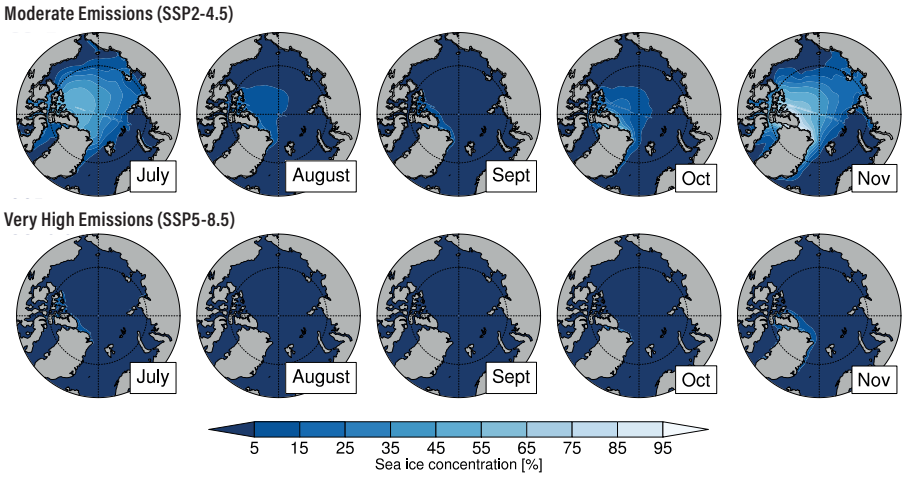
Source: Modified by Alexandra Jahn, from Jahn et al (2024)

entirely.[4] The loss of sea ice exposes a darker ocean, which in contrast to reflective sea ice and snow, absorbs heat, thereby amplifying Arctic and overall global warming. Loss of sea ice has reduced this cooling effect by around 20% since 1979.[21]

Rapid loss of sea ice is one of the leading causes of "Arctic amplification," which refers to the greater rise

*Current research points to longer delays in ice recovery with high overshoot, on the level of decades to even centuries.*

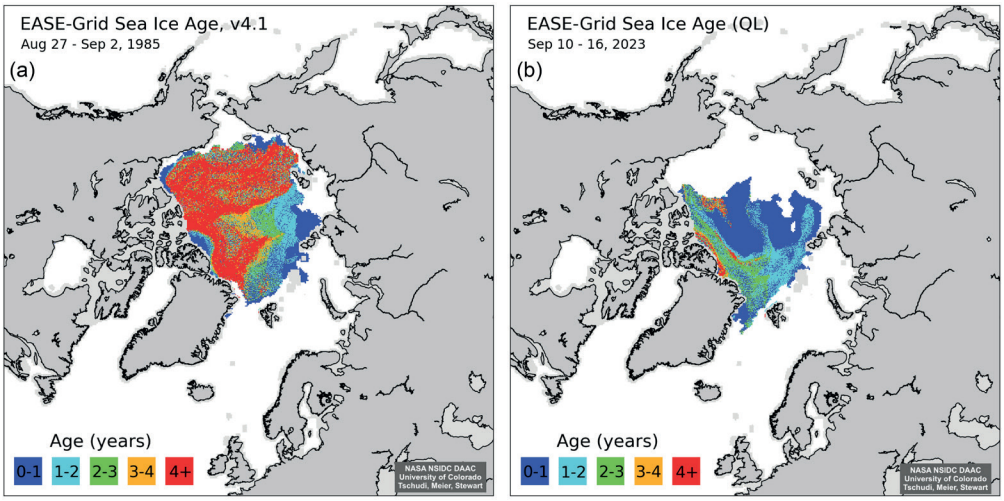
FIGURE 5-2. **Almost No Arctic Summer Sea Ice in a High Overshoot World**




With temperature overshoot towards 3°C or even higher in 2100, summer sea ice would nearly disappear in the Arctic Ocean for a month or even longer, and these conditions might persist for centuries. This would have devastating knock-on impacts around the planet.

Source: Modified by Alexandra Jahn, from Jahn et al (2024)

FIGURE 5-3. **Loss of Thick Multi-Year Arctic Sea Ice**



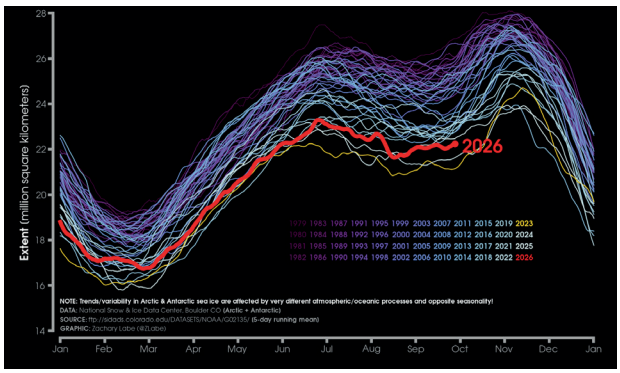

**The previous ecosystem of thick multi-year ice (red) is essentially gone today. Left: 1983, Right: 2023.**

Source: NSIDC

in temperature observed in the high latitudes of the Northern Hemisphere compared with the rest of the globe.[17,22,23] It also carries wide-ranging ecological and atmospheric consequences. For this reason, it is considered a bellwether of climate change. Many Arctic marine organisms evolved with an ice "ceiling" (or sea ice cover) for much of the year, and populations of these keystone species are dwindling in areas without persistent ice coverage.[17,24] Large predators such as walrus and polar bears that evolved with a "floor" of sea ice (to haul out onto or hunt on) will similarly struggle to survive.[25] A reduction in sea ice is projected to influence mid-latitude weather systems, as exemplified by the persistent cold snaps, heat domes, prolonged precipitation and drought in recent years stemming from abnormally large north-south undulations in the jet stream.[26,27,28,29,30,31,32,33,34,35,36,37]

Moreover, an ice-free summer Arctic will bring high economic costs to most people, even if it provides a short-term economic opportunity to a few. Traditional livelihoods for Arctic Indigenous people are already impacted as they depend on stable sea ice platforms for hunting, fishing and travel. Warming associated with summer ice-free conditions will allow exploitation of resources and will amplify risks and societal disruptions noted elsewhere in this report, such as 6–20 meters committed long-term sea-level rise, fisheries loss from acidification, and extensive coastal damage from more intense storms and coastal permafrost thaw, including in the coastal Russian High North.[27,37,38,39,40] Such profound adverse impacts almost

FIGURE 5-4. **Record 2025 Low for Global Sea Ice**




**Both Arctic and Antarctic sea ice extent have held at near-record monthly lows for much of the past three years. In April 2025, the extent of planetary sea ice (in other words, combined area at both poles) reached a new record low.**

Source data: NSIDC/University of Colorado Boulder. Graphic: Z. Labe.

FEATURED UPDATE

## Record-Low Winter Maximum (Again) for Arctic Sea Ice

The 2026 Arctic maximum sea ice extent tied the previous low set in 2025, reaching 14.29 million square kilometers ($km^2$) on March 15. This is technically the smallest maximum in the 48-year satellite record, falling 20,000 $km^2$ lower than 2025. However, since the margin of error for these satellite records is 30,000 $km^2$, 2025 and 2026 were declared statistically tied for this troubling record low.[1]

FIGURE 5-5. **Wildfires and Sea Ice Loss? France, 2026**



Some scientists believe that low levels of sea ice in the Arctic create conditions for extreme weather events, not only because of higher global mean temperatures due to loss of reflective sea ice, but also by disturbing the jet stream: causing it to remain in place for weeks at a time. The extreme heat and wildfires in Europe in summer 2026, and current drought conditions in the American West, may therefore be only a foretaste of a world with no Arctic summer sea ice at all.

Image: Alamy / Abaca Press

**FEATURED UPDATE**

### Decreased Arctic Ice in Laptev Sea Increased Wildfires in Eastern Siberia

Wildfires in Eastern Siberia have increased significantly in recent decades. Lower levels of sea ice in the Laptev Sea in the Russian Arctic have resulted in changed atmospheric circulation patterns over Eastern Siberia since 2004, leading to decreased precipitation and drier soil conditions there, which in turn increase wildfire risk. Wildfires in this region also lead to greater permafrost thaw, including potential abrupt thaw and additional emissions; alongside higher wildfire black carbon emissions that can deposit on Laptev sea ice. The Laptev Sea is known as the "birthplace" of Arctic sea ice, and black carbon deposition there can slow ice formation, further decreasing overall ice loss; all in a potential feedback mechanism driven by decreasing sea ice.[4]

certainly will eclipse any temporary economic benefits brought by an ice-free summer Arctic.

The occurrence of the first sea-ice-free Arctic summer (defined as less than 15% of the Arctic Ocean's area or 1 million km² of ice) is difficult to predict, but scientists now show it is inevitable even with low emissions and is likely to occur at least once before 2050 even under a very low emissions scenario.[16,41,42,43,44] On our current emissions trajectory, the Arctic may become ice-free in the summer by the 2030s when global mean temperatures reach about 1.7°C.[45] If global temperatures continue to rise past this threshold, ice-free conditions will become the norm for some portion of each summer, ultimately extending into spring and autumn.[46,47,48,49]

The last time the Arctic had an ice-free summer may have been during the Eemian period 125,000 years ago.[50] Today's temperatures now almost equal those of the Eemian, when much of Greenland may have been ice-free in part due to feedback from the warmer Arctic Ocean, and when sea levels were 5–10 meters higher than today.[51,52] This is the current trajectory of the Earth's climate: $CO_2$ levels from human emissions today are already higher than at any point in at least the last 3 million years. However, under low and very low emissions scenarios, summer sea ice extent would likely stabilize. Eventually, as warming drops again below 1.5°C after substantial net atmospheric greenhouse gas removal, greater amounts of sea ice may reform, but multiyear ice will likely take decades to recover owing to residual heat in the Arctic Ocean that will need to dissipate.[53]

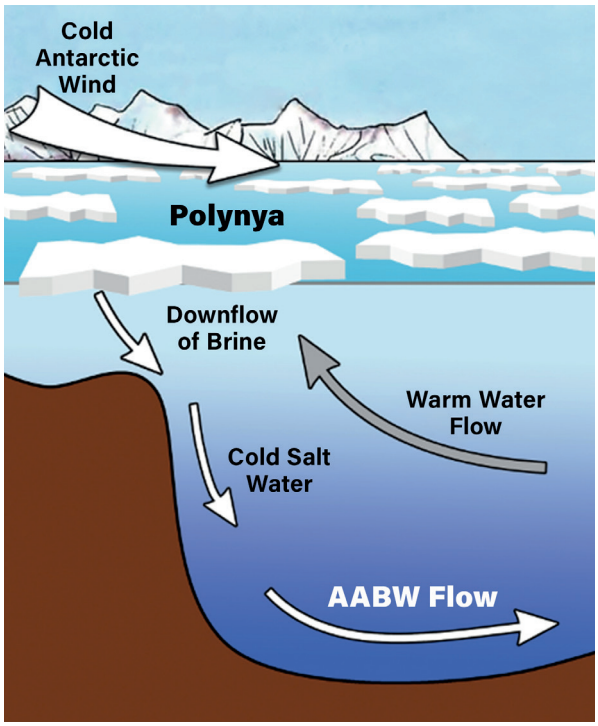
The Arctic Ocean has never been ice-free in modern human existence. With the determination by the IPCC that at least one ice-free summer is now inevitable owing to human $CO_2$ emissions,[54] the first cryosphere "threshold" of collapse has essentially been breached. This collapse will worsen rapidly unless emissions are curtailed to keep global warming close to 1.5°C or below.

## ANTARCTIC SEA ICE

*Declining sea ice...occurred in the Arctic well before...1.0°C of warming.*

Although sea ice extent around Antarctica was stable or even increased slightly during 1979–2016, observations over the past decade document a very sharp decline beginning in 2016. The size of this loss is equal to or exceeds that in the Arctic but has occurred much more rapidly.[55] This sharp decline was underscored in 2022 when the summer minimum sea ice extent dropped below 2 million km²,[56] for the first time, reaching a record-breaking minimum extent of 1.79 million km² in 2023. Failing to recover during the southern winter of 2023, 2.77 million km² of ice were 'missing' by July compared to the 1981–2010 average, which represents an area the size of Argentina. That year's maximum, reached on September 10, 2023, was fully 1 million km² below the previous record low. This trend is now seen as a part of a

FIGURE 5-6. **Antarctic Bottom Water (AABW)**




AABW formation drives the entire ocean circulation system, but seems to be slowing today due to a combination of warming and freshening of Antarctic waters. It originates in "polynyas" (stretches of open water surrounded by ice) as Antarctic sea ice forms each winter.

Source: Morozov et al. 2021.

FEATURED UPDATE

## Warmer Waters from Antarctic Sea Ice Loss May Lead to More Permanent Loss Conditions

Antarctic sea ice has remained at historically low levels since 2015, driven by shifts in Southern Ocean winds that pulled heat from the deep ocean to the surface and weakened the separation between ocean layers. In East Antarctica, sea ice loss has been driven by heat rising from deep ocean waters, while in West Antarctica it has been linked to increased cloud cover and heat trapped near the surface of the ocean.[2] While unusual winds drove the 2015 record-breaking low, the sustained lack of sea ice since then indicates that the cold winter water layer – which previously protected sea ice from melting – remains too thin to insulate it from the billowing warmer deep ocean waters below. These factors point to a more permanent loss in the Antarctic sea ice, with recovery to higher levels unlikely at current temperatures.[3]

"new normal" of Antarctic sea ice decline, driven by ocean warming due to anthropogenic fossil fuel emissions.[57,58] The last five years have marked the lowest minima in the satellite record.

Reductions in Antarctic sea ice extent in recent years have negatively impacted ice sheet stability, ocean circulation, and ecosystems in a similar manner to ongoing changes in the Arctic. Antarctic sea ice also plays an essential role in producing Antarctic Bottom Water. This is the densest water mass on the planet and drives the entire global ocean "conveyor belt," transporting carbon and heat deep into the ocean. Heat transport to deeper water levels decreases overall global warming, and the carbon remains stored there for centuries to millennia. Yet, a 40% decline in sea ice in the Weddell Sea has reduced the production of Antarctic Bottom Water in this region by almost a third over the last three decades.[59] A slowdown in Antarctic sea ice production could therefore harm the Southern Ocean's ability to take $CO_2$ out of the atmosphere, accelerating the pace of global temperature rise.

Dramatic declines in Antarctic sea ice extent have also had a catastrophic impact on the region's fauna, such as Emperor penguins, which rely on stable sea ice platforms between April and December to breed. The low spring sea ice extent in 2022 led to the highest rates of breeding failure ever recorded, with 80% of penguin colonies in some regions suffering total loss of penguin chicks.[60]

For decades, Antarctic sea ice seemed almost immune to global warming, showing an overall average change of 1–2% while Arctic sea ice declined precipitously by 40–60% during the same period. This apparent immunity has entirely dissipated in the last decade. Given the long-term impacts of this loss on ice sheet stability and global sea-level rise, the human consequences of Antarctic sea ice loss ultimately may prove equal to, or even greater than, those of its more well-publicized Arctic cousin.

*References begin on page 38.*

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# Permafrost

## *Far Greater Infrastructure Loss and Emissions with High Overshoot*

The thawing of permafrost – perennially frozen ground in the Arctic including near-Arctic coastal seabed, as well as high mountain regions – began well below 1°C. At today's temperatures, this thaw now releases greenhouse gases annually on the scale of a large industrialized nation; and can destabilize the foundations of infrastructure, change local and regional water cycles, and impact vegetation including the intensity and frequency of wildfires.

### Overshoot to 3°C: Current Emissions Pathway and Policies

#### CMIP 7 High-low Scenario: peak 2.8–3.2°C, 1.5°C in 2150

High overshoot to 3°C would thaw nearly all near-surface permafrost, and trigger more frequent and widespread "abrupt thaw" process that rapidly expose deeper permafrost to above-freezing temperatures. These processes, which can be accelerated by wildfires, include hillside collapse, and sudden lake formation where the lakebed progressively thaws. Permafrost emissions would climb to annual levels of about that of the U.S. today, continuing for 1–2 centuries. As temperatures decline after overshoot, thawed soils will begin to refreeze, but continue to release high carbon levels, increasing global warming even as human emissions reach net zero. During the peak of overshoot, wildfire frequency, intensity and severity are expected to increase, with longer fire seasons and deeper burning of organic soils. Subsequent cooling following peak overshoot will create less favorable conditions for vegetation growth, reducing the amount of carbon that can be reabsorbed from the atmosphere. 3°C overshoot will fundamentally reshape soils and hydrology in these regions for decades to centuries.

### Stable 1.5°C without Decline

Every fraction of a degree of warming causes more widespread and deeper permafrost thaw. In addition to damaging roads and buildings built on previously frozen ground, permafrost thaw releases emissions of both $CO_2$ (under dry conditions) and methane (under wet conditions). Long-term 1.5°C stabilization without overshoot would eventually see permafrost soils reach a new equilibrium, although emissions from thawed permafrost typically continue for a few hundred years before petering out once all organic matter – which took thousands of years to accrue – has decomposed. While carbon can again be drawn down into these soils, the process of replacing it will take centuries to millennia. These extra emissions therefore need to be considered as part of the global carbon budget needed to stabilize the climate.

### Limited Overshoot to 1.7°C with Rapid Action: 2050 Net Zero

#### Highest Possible Ambition (HPA) Pathway: peak 1.7°C, below 1.5°C by 2100, below 1°C by 2150

Even the most ambitious measures now cannot prevent overshoot to around 1.7°C for about two decades, with today's levels of permafrost thaw continuing. Emissions and infrastructure damage would likely be greater along this pathway than under a stable 1.5°C without overshoot. However, once temperatures decline below 1.5°C – and especially below 1°C – the frequency of heatwaves, lightning strikes and wildfires that trigger abrupt thaw would decrease in the latter half of this century. As a result, this pathway could produce less carbon emissions than a stable 1.5°C.

## Background

Permafrost is ground that remains frozen for at least two consecutive years. It consists of a mixture of soil, rocks, sand, and organic matter and varying amounts of ice, extending from one meter to over a thousand meters deep. Permafrost contains vast amounts of ancient organic carbon stored in the form of plant, animal, and microbe remains that have accumulated over thousands of years. This carbon is locked in the ground until it thaws.

Permafrost thaw on dry land primarily releases carbon dioxide ($CO_2$), but it also produces smaller yet significant levels of methane ($CH_4$) in waterlogged or submerged regions. Permafrost holds about twice the amount of carbon than currently exists in the Earth's atmosphere, establishing it as a major contributor to future emissions on the same scale as large industrial countries, especially if temperatures rise further.[12,13]

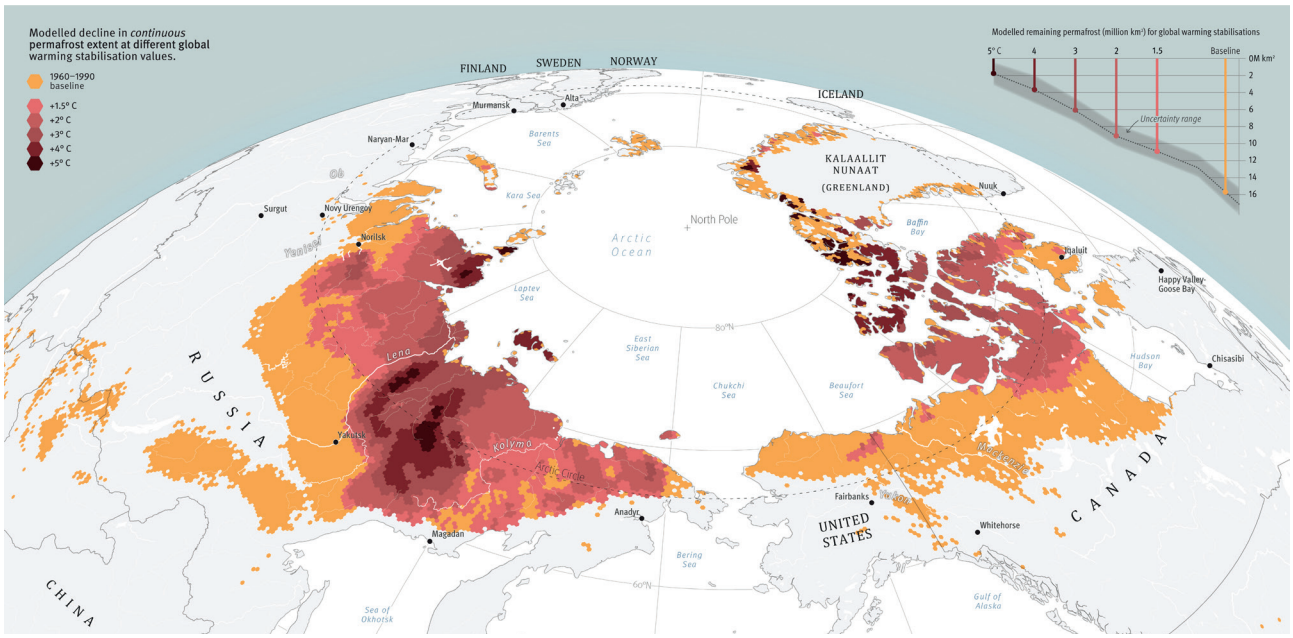
Permafrost can be found on land as well as in lake and near-coastal seabeds. It is widespread across the Arctic – including Alaska, Canada and Siberia – and high mountain regions, especially the Tibetan Plateau, underlying ~15% of land area in the Northern Hemisphere.[14,15] In the Southern Hemisphere, it can be found in Antarctica as well as the South American Andes and New Zealand's Southern Alps. Permafrost also occurs in shallow Arctic Ocean regions flooded after the last Ice Age.

Arctic and high mountain regions are warming at 2–4 times the global average, making permafrost highly vulnerable to rising temperatures.[16] Once it begins to

## 2026 Updates

- Northern high latitudes could become a net source of emissions even at or below 2°C of warming.[4]
- Methane emissions, including that produced by permafrost thaw beneath sub-Arctic wetlands and lakes will increase by one third by 2100 with even moderate warming. Under high emissions, permafrost thaw will also contribute to lake expansion, further increasing the amount of carbon released as methane (which occurs under wet conditions, as opposed to $CO_2$ release which occurs under dry conditions). Methane warms for a shorter period, but far more intensely than $CO_2$.[5]
- Arctic river delta soils currently contain 58 gigatons of carbon and 4 gigatons of nitrogen, despite covering less than 1% of the Arctic's permafrost area. About two-thirds of these stores remain frozen in permafrost, but rising temperatures are making them increasingly vulnerable to thaw and subsequent greenhouse gas emissions release.[6]
- Ground collapse driven by Arctic permafrost thaw can rapidly strip vegetation and destabilize terrain. Vegetation is slow to recover, with recovery times ranging from 5–10 years in low latitude Arctic ecosystems to multiple decades in high latitude and high elevation regions. Plant community composition often remains altered even after green growth returns, indicating that a return of plant life does not equate to full ecological recovery.[7]
- 40% of permafrost land area above 40°N was at high or very high susceptibility to ground collapse between 2000–2020, with an additional 14% at medium susceptibility. Currently, more than 2.7 million people, 200 $km^2$ of buildings, and 110,000 km of roads in the circumpolar Arctic are at risk for infrastructure damage from permafrost thaw.[8]
- Reducing greenhouse gas emissions could nearly halve the permafrost area in the Qinghai-Tibet Plateau experiencing high or very high ground instability by 2090, from about 85% under high emissions to around 50% under low emissions. Infrastructure maintenance costs under very high emissions could reach $16.2 billion by 2090, equivalent to 9% of the region's GDP. Nearly three-fourths of these costs are expected to fall on the Plateau's most socio-economically disadvantaged regions.[9]
- Extreme rainfall in permafrost regions generally cools near-surface soils while warming deeper layers, leading to faster thaw. These effects vary with regional climate, vegetation, and soil conditions: rainfall tends to cool permafrost in humid landscapes, but lead to stronger ground warming in arid regions and shrublands.[10]
- As Arctic permafrost thaws, its seasonally thawed layer deepens, triggering changes that make northern landscapes more prone to wildfires. Deeper thaw reduces soil moisture, creating warmer, drier conditions while also increasing vegetation growth and burnable material. These thaw-driven changes were estimated to contribute to 16% of the observed increase in summer fire weather over recent decades, contributing to greater burned area and fire emissions.[11]

FIGURE 6-1. **Permafrost Loss at Higher Temperatures**




Decline in continuous permafrost extent under various emissions scenarios. Darker shades correspond with higher peak temperatures and greater loss.

Credit: Levi Westerveld/GRID-Arendal https://www.grida.no/resources/16284

thaw, microbes begin decomposing previously frozen organic matter, releasing carbon into the atmosphere. These microbial processes can continue emitting for centuries after initial thaw.[17,18] This growing stream of carbon emissions will add as much global warming as a large country this century, depending how much permafrost thaws; the only way to limit these emissions is to prevent more areas from thawing by holding global temperatures as low as possible.[19] Rebuilding new permafrost and soil carbon pools takes hundreds to thousands of years.[20]

Annual permafrost region emissions today are already a source of carbon emissions, on the scale of a large industrialized nation.[21-23] While there is a wide range of future permafrost emissions, the amount of carbon these soils release depends on the actions of decision makers today:

- If warming is limited close to 1.5°C, permafrost emissions this century will total around 25Gt combined $CO_2$ and $CH_4$ (methane) emissions (or $CO_2$-equivalent ($CO_2$eq), which combines $CO_2$ and $CH_4$ emissions.
- At 2°C, annual permafrost emissions will total an additional 55Gt $CO_2$eq by 2100.
- Overshoot to 3–4°C, however, will most likely add the equivalent of another United States or China to the global carbon budget, resulting in up to 230Gt $CO_2$eq by 2100.[1,24-27]

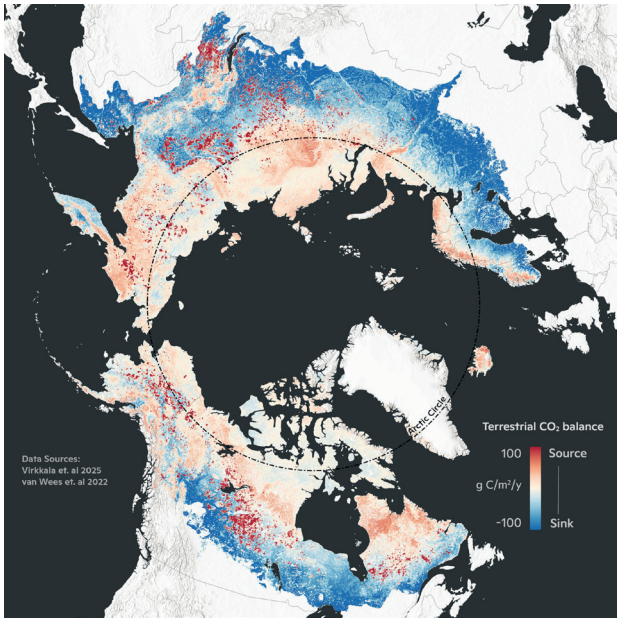
***During the peak of overshoot, wildfire frequency, intensity and severity are expected to increase.***

**FEATURED UPDATE**

## Peak Overshoot Largely Determines Scale of Permafrost Emissions

Permafrost emissions directly increase as warming increases, so both the magnitude and duration of warming determine how much carbon is irreversibly lost during overshoot. While factors such as temporary regional cooling driven by Atlantic Meridional Overturning Circulation (AMOC) slowdown can reduce permafrost carbon emissions, it would not prevent continued emissions from permafrost thaw during a temperature-overshoot period. Minimizing the peak temperature and duration of any overshoot is therefore key to limiting permafrost carbon emissions.[2]

FIGURE 6-2. **Permafrost Lands Confirmed as a New Net Source of Carbon Emissions**




Mapping carbon sinks and sources in Arctic land ecosystems from 2001–2020.

Credit: Greg Fiske / Woodwell Climate Research Center https://phys.org/news/2025-01-millennia-arctic-boreal-region-source.html

These greenhouse gas emissions with high overshoot are on the scale of today's largest emitting nations, ranging from India (which emitted 1.23 $GtCO_2eq$ in 2025) to the United States or China (1.64 and 4.35 $GtCO_2eq$ in 2025, respectively).[28] Calculations of the remaining global carbon budget must take into account these indirect human-caused emissions from permafrost to accurately determine when and how emissions reach carbon neutrality – and not just through 2100, but well into the future.

The Arctic has historically acted as a significant carbon sink for thousands of years, storing vast amounts of carbon in frozen permafrost and tundra. Today, its carbon uptake from plant growth is increasingly offset by wildfires, emissions from lakes and rivers, and methane from wetlands. This means that the Arctic region is at best close to carbon neutral, with tundra areas already a net source of $CO_2$,[23] Given methane release from the permafrost region, however, over shorter timescales it is already a net source of warming today.[22,29,30] This net warming will raise global temperatures for decades in a feedback loop that deepens permafrost thaw during the summer,[31] progressively overwhelming its ability to naturally balance emissions with carbon sequestration.

Some permafrost can also be found under lakes, peatlands, and wetlands. If temperatures rise above 2°C, three-fourths of northern European and western Siberian peatlands will no longer be able to sustain permafrost by the 2060s.[32] Already at today's temperatures, climate conditions in Norway, Sweden, Finland, and parts of Russia might no longer be able to support peatland permafrost.[32] Northern peatlands will act as a net positive feedback if temperatures exceed 1.5°C, reducing the global carbon budget by roughly 37 $GtCO_2eq$ per 1°C of peak overshoot warming.[33]

*The process of replacing permafrost carbon [after overshoot] will take centuries to millennia.*

Subsea permafrost is degrading, but its response is generally slower and more uncertain than that of terrestrial permafrost.[34] Under high emissions, models project rapid thaw of flooded coastal permafrost once ocean-bottom temperatures exceed 0°C, potentially around 2080.[35] In one model, coastal permafrost thinner than 100 meters in 1850 disappears before 2300.[35] Expert assessments estimate substantial but highly uncertain subsea emissions, with much methane oxidized before reaching the atmosphere.[34]

Coastal permafrost erosion decreases the Arctic Ocean's capacity to absorb atmospheric carbon dioxide, which could lead to a 14% reduction in uptake by 2100 under a worst-case scenario.[36] This erosion has the potential to increase carbon emissions by 1.1–2.2 million tons per year for every 1°C of global warming.[36]

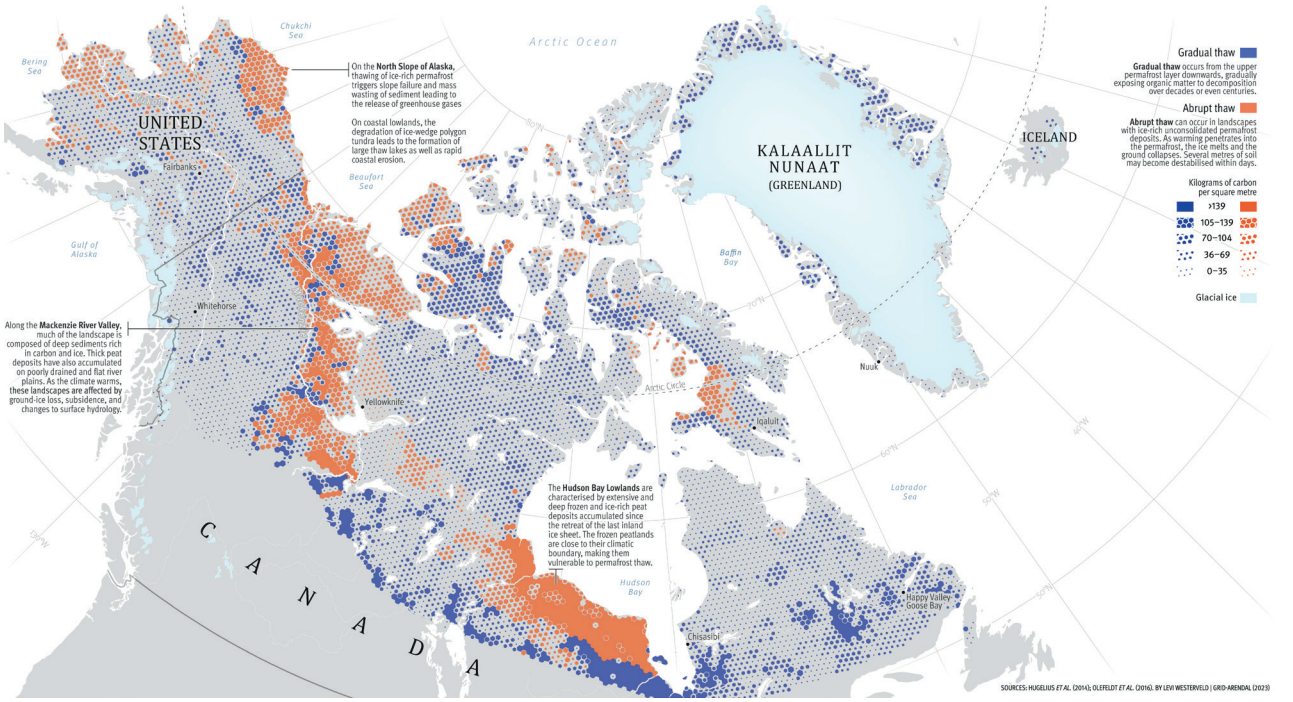
In addition to its impact on the global carbon budget, permafrost thaw directly impacts Arctic and high mountain people, lands, and economies. More than 66% of Arctic settlements are located on permafrost.[37] Permafrost thaw creates unstable ground prone to flooding, threatens cultural and subsistence resources, and

FEATURED UPDATE

### Permafrost Feedback Loops Increase Tipping Point Risks

Including feedback loops generated by permafrost thaw and global warming increases the probability of crossing one or more tipping points in the Earth system by up to 50%, including the Greenland and West Antarctic ice sheets, the AMOC, and the Amazon rainforest. This feedback can also bring the timing at which these thresholds are crossed forwards by hundreds of years.[3]

FIGURE 6-3. **Speed of Gradual and Abrupt Permafrost Thaw across North America**




**Projected decline in Arctic permafrost extent. Darker red shades correspond with higher peak temperatures and loss.**

Credit: Levi Westerveld/GRID-Arendal https://www.grida.no/resources/16290



**Abrupt permafrost thaw on the Peel Plateau in Canada. This can cause sudden ground collapse, further accelerating thaw and permafrost carbon emissions.**

Credit: Scott Zolkos



Buildings in Nunapitchuk, Alaska, are sinking due to thawing permafrost that has underpinned the Arctic tundra for millennia. This thawing ground produces sinkholes and collapse already at today's temperatures.

Credit: Sue Natali / Woodwell Climate Research Center

damages infrastructure such as roads, pipelines, and houses.[38,39] In Alaska, for example, experts estimate that permafrost thaw and other stressors from global warming will increase cumulative maintenance costs of public infrastructure by $5.5 billion USD by 2100.[40] Permafrost thaw has contributed to thousands of kilometers of coastal erosion across the Arctic, requiring entire communities to relocate.[39]

For high-altitude mountain regions such as the Tibetan Plateau, limiting warming to 1.5°C instead of 2°C will reduce the cost of infrastructure damage from permafrost thaw by $1.32 billion by 2090. Even under moderate emissions, nearly two-thirds of the permafrost area in the Tibetan Plateau could become a high-hazard zone this century.[41,42]

Permafrost thaw often occurs gradually but is vulnerable to abrupt thaw events that can lead to rapid erosion and collapse, releasing large amounts of carbon previously considered immune from thawing for many more centuries.[43,44] Globally, the total land area covered by near-surface permafrost (within the first few meters of soil) has declined by 7% over the past five decades alone.[45]

Permafrost responds to every local increment of warming, rather than destabilizing as a whole at certain temperature thresholds or tipping points. This means that there is no "safety margin" for acceptable permafrost thaw.[46,47] The most effective means available to minimize these growing risks is to keep as much permafrost as possible in its current frozen state, by keeping global temperature increase as low as possible.[48] Limiting overshoot to return temperatures back to 1.5°C and below would greatly decrease the scale of permafrost emissions in coming centuries and minimize the long-term burden laid on future generations.

*References begin on page 38.*

## SCIENTIFIC REVIEWERS

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FEATURED UPDATE

### Decreased Carbon Budget with Permafrost Thaw and Wildfires

Adding fast and disruptive landscape events such as abrupt permafrost thaw and wildfires to climate models, as well as more gradual permafrost thaw emissions, lowers the remaining carbon budget by 25% from 2025-onwards even if governments follow a 1.5°C pathway. The 2°C budget would shrink by an additional 17%, emphasizing the importance of every tenth of a degree of warming.[1]

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