State of the Cryosphere 2025

Ice Loss = Global Damage

We cannot negotiate with the melting point of ice.

NOVEMBER 2025

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International Cryosphere Climate Initiative

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We cannot negotiate with the melting point of ice.

Cover

The rate of sea-level rise has doubled over the past three decades, largely from growing ice loss from glaciers and ice sheets in addition to thermal expansion (warmer waters). This makes coastal storms far more damaging in these communities.

Top: iceberg calving from South Sawyer Glacier, Alaska, USA. Photo: Shutterstock/Danita Delimont

Bottom: storm waters pound the coastal town of Dawlish, Devon, United Kingdom. Photo: Shutterstock/Carol Blaker

The jagged line between the photos shows global sea-level rise from 1993–2023, reaching ~4.5mm per year today. Source: Hamlington, B.D., et al. (2024). The rate of global sea level rise has doubled during the past three decades. Communications Earth & Environment, v. 5, no. 1, 601, https://doi.org/10.1038/s43247-024-01761-5

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NDCs for the Cryosphere

There is no negotiating with the melting point of ice.

ICCI was founded as COP15 in Copenhagen collapsed in December 2009, despite clear messages from Arctic scientists and leaders even then of growing ice loss worldwide. In the wake of that political failure, cryosphere scientists needed ways to communicate their growing alarm at the looming global impacts of cryosphere loss – rapidly increasing melt of glaciers, polar ice sheets, ocean ice cover and permafrost, at scales unprecedented in human history. ICCI was created to fill that gap.

The first of these peer-reviewed assessment reports came out ten years ago, ahead of COP21 and the Paris Agreement. They became annual five years ago, simply to keep pace with observations of cryosphere loss and rapidly evolving projections about its future.

The main messages remain the same: losses are accelerating, they are nearly all irreversible, and the great majority of populations impacted by cryosphere loss are not in regions of ice, but well downstream. Coastal flooding today does not come really from the ocean, but from melting glaciers – and going forward, almost entirely from the Greenland and Antarctic ice sheets. Because origins and impacts still seem so disconnected in the minds of policy makers, the 2025 State of the Cryosphere cover shows both.

Such damage to coastal and downstream communities is already tragic, but only the beginning. A child born today and living within 2–3 meters of sea-level rise will almost certainly lose their home within their lifetime if current emissions continue. Within the lifetimes of their own great-great grandchildren – by 2300 – that might rise to 15 meters if we do not course-correct by phasing out fossil fuels.

There are of course other impacts from continued fossil fuel use – deadly heatwaves in cities among them. But only coral reef extinction and (ironically for COP30 in Brazil) transition of the Amazon to dry savannah are as wide-scale, permanent and unforgiving as loss of cryosphere, on the scale of wartime destruction yet constantly dropping down the scale of political priorities. After 10 years of the Paris Agreement, emissions are still climbing. Either global leaders and the public still do not understand the scale of threat from cryosphere loss, or have become resigned to such global destruction.

Neither the panic, nor the resignation are necessary. Ice indeed will continue to be irreversibly lost so long as greenhouse gases continue pouring into our atmosphere. That is a physical fact.

But as the following "Pathways" section outlines, an equally physical fact is that there are feasible pathways that address the root fossil fuel causes of global warming, and halt the current global insanity that would lock in thousands of years of human suffering and species loss.

All involve phaseout of fossil fuel use: first of coal (2040s), then gas (2050s), then oil (2060s). These steps would bring us to net zero greenhouse gas emissions in the 2060's. After that, feasible methods of carbon dioxide removal (CDR) can bring down temperatures to as low as 1.2°C – lower than today's temperatures. By 2150, we can be below the 1°C mark that major findings, published just this year indicated as the true safe planetary boundary for both ice sheets and mountain glaciers.

There will still be great suffering and ecosystem loss over the coming decades. Due to our short-sighted failure to act earlier, we now cannot avoid damaging overshoot of the Paris Agreement 1.5°C temperature mark, peaking as high as 1.7–1.8°C. But with these measures to address the root cause of global warming, a child born today within 3 meters of coastline would be able to raise grandchildren in the same house where they themselves were born. They would be able to show their own children glaciers that after a century or more of retreat, have finally stopped losing ice – and with a view in a far cleaner sky, without fossil fuel pollution browning the horizon and shortening their lives.

Ice loss, and the resulting centuries and millennia of damage and displacement are a choice, not an inevitability. There may be no negotiating with the melting point of ice, but the choice to see and respond to that reality is ours.

Pam Pearson
Director and Founder, ICCI

NDC Cryosphere Pathways

The 2025 UNFCCC NDC Synthesis Report[1] and the UNEP Emissions Gap Report[2] show that the third round of Nationally Determined Contributions (NDCs) remains far off-track to close the ambition gap of limiting warming to 1.5°C by 2100. At current emission levels (~40 $GtCO_2$/year), the global carbon budget could be exhausted in just three years.[3]

Limiting global warming to 1.5°C as outlined by IPCC AR6 pathways[4,5] (which actually included a brief period of overshoot to 1.6°C) appears no longer possible due to our collective failure to slow carbon emissions over the past three decades. Instead, we now must adapt to higher and longer levels of overshoot. Tragically, this will result in greater cryosphere loss and downstream impacts, with greater 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.[6,7]

Every tenth of a degree of temperature rise and year of higher temperatures matters, but there are pathways being developed to limit the damage and supply hope for the cryosphere and the billions who depend on it. Developed by Climate Analytics and the Potsdam Institute,[8] these feasible measures (Highest Possible Ambition, HPA) would return temperatures back down to 1.5°C or below by 2100, even after higher levels of overshoot (1.7–1.8°C). In brief, these would involve:

(1) **Phasing out fossil fuels**, first in power and transport sectors where cost-effective alternatives are readily available, beginning now and with 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, black carbon and other SLCFs

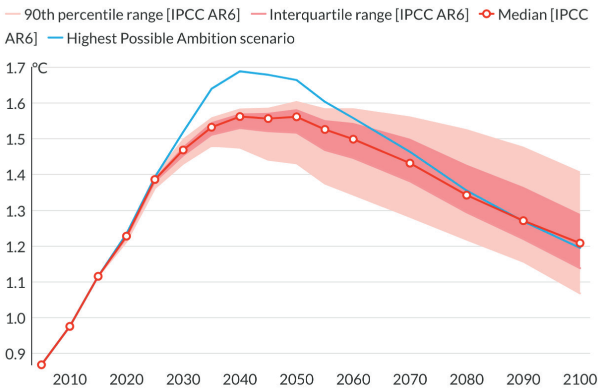
(4) Finally, **scaling up land-based carbon dioxide removal** (CDR) for temperature decline.

These pathways foresee a tripling of energy demand by 2050, met by a tripling of all renewables by 2030, six times by 2035 and 15 times by 2050, on par with the rapid expansion of recent years. Reducing methane and (especially near cryosphere) black carbon emissions from the agriculture, household and waste sectors could help limit overshoot and negative cryosphere feedbacks such as permafrost thaw emissions and reflective sea ice loss.

FIGURE A. **Global average temperatures**

Global average temperatures in the HPA scenario peak at 1.7°C around 2040 before falling towards 1.2°C by the end of the century

This peak is 0.1°C higher than in the median of the IPCC AR6 scenarios.



The course-corrective new HPA pathway, compared with the earlier 1.5C-consistent pathway (C1a) from IPCC AR6

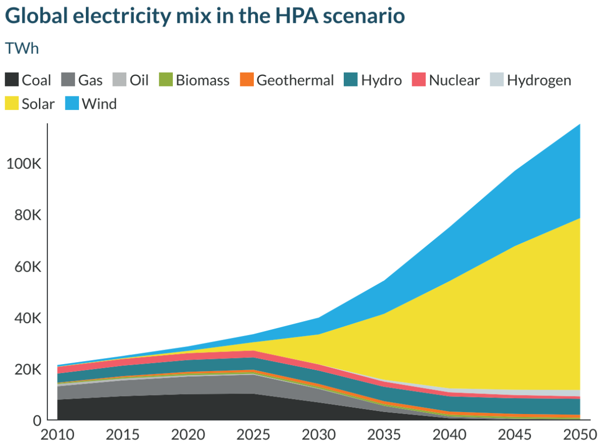
SOURCE: CLIMATE ANALYTICS

This would result in net-zero CO_2 emissions being reached by 2045, and net-zero greenhouse gas (GHG) emissions in the 2060s. Our extra emissions from inaction will then need to be removed from the atmosphere via carbon drawdown to bring temperatures back below 1.5°C by 2100.

Existing and scaled-up CDR measures can achieve this. Contrary to general perception, temperatures actually begin to fall almost as soon as CO_2 concentrations in the atmosphere decline, with around 220 Gt CDR needed to reduce each 0.1°C of temperature overshoot. Existing land-based CDR measures, primarily afforestation/reforestation,[9,10] can already achieve about 2 $GtCO_2$ removal per year, but projections and additional CDR development through technological investment might push this to as high as 8.5 Gt/year by 2100, from direct air capture or bioenergy with carbon capture and storage. Intensive investment is needed here; and it is important to note that 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.*

* 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.

FIGURE B. **Global electricity generation**



The HPA pathway assumes rapid ongoing increases in renewables (yellow, solar; blue, wind) to meet sustainable development needs while transitioning off fossil fuels

SOURCE: CLIMATE ANALYTICS

The new HPA pathway suggests that with aggressive emissions cuts starting in 2025 and effective, sustainable CDR, global warming can still return to below 1.5°C by 2100 after overshoot and below 1°C by 2150, with peak warming levels up to 1.8°C and overshoot lasting for 30–40 years. Significantly, this is achieved without dangerous geo-engineering techniques that involve countering carbon emissions with sulfate pollution, and all the harmful side effects these entail.

The Paris Agreement objective of pursuing efforts to limit the temperature increase to 1.5°C holds regardless of any temporary overshoot.[11,12] However, cryosphere science makes clear that even remaining permanently at 1.5°C can and must be avoided, and every increment of limiting overshoot matters. IPCC reports have unequivocally established that climate-related risks and inequities, as well as adaptation needs and costs, increase with every increment of global warming. Even 1.5°C is not a "safe" limit, especially in light of recent cryosphere research pointing to the need to return below 1°C, which the HPA pathways might achieve by 2150, greatly reducing long-term risks of cryosphere loss.

Limiting global warming to 1.5°C remains the legal, moral, and political imperative to secure a livable planet for present and future generations, especially in light of the recent ICJ advisory opinion.[11,13,14] The Paris Agreement was in itself a political compromise; and many of the impacts of global warming beyond 1.5°C fall disproportionately on the poor and vulnerable.[15]

Under current policies, global warming estimates point to levels close to 2°C by mid-century and 3°C by 2100. The effectiveness of some adaptation strategies will diminish as global warming escalates.[16] 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.

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Summary: The State and Future of the Cryosphere 2025

Ice Sheets and Sea-level Rise

The vast ice sheets covering Greenland and Antarctica play a vital role in regulating Earth's climate, global ocean circulation, and determining the pace and magnitude of sea-level rise. Losses from both ice sheets have quadrupled since the 1990s, bringing them closer to crossing irreversible thresholds that would impact humanity for millennia.

While several meters of sea-level rise from these ice sheets is likely inevitable over the coming centuries, the decisions made by policymakers today on emissions of greenhouse gases will determine how much and how fast seas will rise, as well as wider impacts to the global climate system. With 2025 NDCs consistent with 1.5°C by 2100, and returning below 1°C through carbon dioxide removal in the next century, sea-level rise can likely be slowed to rates that enable feasible adaptation, minimizing loss and damage. In contrast, NDCs that result in temperatures of 2°C or above are very unlikely to prevent the crossing of thresholds for both Greenland and parts of Antarctica that generate inexorable sea-level rise that exceeds 10 meters in the coming centuries, even if air temperatures later decrease. The pace of this long-term, unstoppable sea-level rise will pose major and persistent challenges for all coastal regions, resulting in widespread loss and damage of critical infrastructure, agricultural land, homes and livelihoods.

Polar Oceans

Polar oceans are vital in regulating Earth's climate by absorbing heat and carbon, acting as engines for global ocean circulation and as a basic component of marine food webs. All of these functions are under threat from rising greenhouse gas concentrations and related warming, with thresholds that could trigger widespread and essentially irreversible disruption. At the quarter-century mark, at CO_2 concentrations in the atmosphere sometimes exceeding 430 parts per million (ppm), ocean acidification has reached levels extremely challenging and potentially lethal for shelled marine life in some polar ocean sectors. Two major drivers of ocean currents (the Antarctic Overturning Circulation (AOC) and the Atlantic Meridional Overturning Circulation (AMOC)) have slowed substantially, likely due to a combination of freshwater pouring off Antarctica and Greenland, respectively as well as warming surface waters. Marine heatwaves and compound extreme events, at times including major die-offs of large mammals, fish and bird species, have become far more frequent in Arctic and near-Arctic waters.

The future of polar oceans depends directly on the path of global carbon emissions. Limiting warming close to 1.5°C through quickly reducing carbon emissions will prevent further spread of ocean acidification and reduce the risk of irreversible circulation changes. Every fraction of carbon emissions and associated warming beyond this boundary will intensify ocean acidification and other stressors on polar marine life, pushing polar-driven ocean circulation closer to a tipping point of long-term, essentially irreversible collapse. At 2°C and above (for ocean acidification purposes, equivalent to 500+ ppm CO_2 in the atmosphere), severe and possibly abrupt circulation disruptions alongside widespread acidification become even more likely, with cascading impacts on species survival and global food security.

Mountain Glaciers and Snow

Glacier ice loss around the world is increasing exponentially. Between 2000 and 2023, global 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. Relative glacier loss was greatest in Central Europe and the Caucasus, which lost 39% and 35% of their ice, respectively, during this time. Snowpack has followed a similar trajectory, declining globally in thickness and duration. This loss is especially pronounced at lower mountain altitudes, as well as mid-latitude regions. However, even in the Arctic, spring snow melt has been occurring 1–2 weeks earlier than average; and the 2023–24 snow season in parts of Canada was the shortest in over a quarter-century.

The future of glaciers and snowpack depends on future carbon emissions. Some areas, such as Scandinavia and western North America, will lose all or nearly all ice already at 2°C; but a 1.5°C emissions trajectory will preserve 20% of today's ice in these regions. Even the higher central and eastern parts of High Mountain Asia are projected to lose 60% of existing ice under a 1.5°C emissions scenario, with only 15% remaining at 3.0°C. The Hindu Kush and Karakoram regions, which in recent decades were near stable, stand to lose 40% of ice mass under a 2°C future but only 15% under a 1.5°C pathway. The impacts of this loss include water, food, economic and political insecurity, and should be considered essentially permanent on human time scales. However, with ambitious emissions cuts, glacier and snow loss can slow and begin to stabilize by the 2060s, and some glacier regions may show signs of regrowth by the 2200s – one of the earliest indications of planetary recovery.

Mount Chimborazo, Ecuador, is the highest point from Earth's center due to the equatorial bulge. Ecuador has lost 50% of its glacier cover, some of which feeds the Amazon basin, over the past few decades. The volcano Carihuairazo, just northeast of Chimborazo, is expected to lose its final glacier ice completely in 2025.

IMAGE BY JAIME NOLIVOS FROM PIXABAY

Sea Ice

Polar sea ice is essential for maintaining a livable global climate, with global risks from its decline ranging from disruption of weather and ocean currents; to accelerated Greenland and Antarctic melt and associated sea-level rise; to extinction of ice-dependent species at the base of the food chain for humans and many polar and marine mammals. Sea ice coverage at both poles has declined by 40–60% since satellite measurements began in 1979, with nearly all Antarctic sea ice decline occurring precipitously since 2016. While most attention is given to the September sea ice minimum in the Arctic, this loss has occurred year-round, in all months of the year including sea ice maximums, when the ice reaches its largest extent. A record-low maximum occurred in the Arctic in March 2025, and Antarctica's record-low maximum was set in September 2023. Global sea-ice coverage, combining both poles, reached a record all-time low in February 2025.

Sea ice has declined not only in extent, but in thickness. Much of the Arctic Ocean used to be covered in thick, multi-year ice that was 4–7 years old. Such "old" ice has virtually disappeared, with even two or three-year-old ice comprising under 10% of today's sea-ice coverage. Antarctic sea ice plays an essential role in several ways, including formation of Antarctic Bottom Water: the densest water mass on the planet, driving the entire global ocean "conveyor belt." 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.

Future sea ice survival is extremely sensitive to current and future human emissions of greenhouse gases. If governments course-correct to 2025 NDCs consistent with 1.5°C of warming or below at 2100, sea ice may slowly begin to recover in the 2070s and beyond. At least one ice-free Arctic summer event seems increasingly likely however before 2050, and the summer ice-free period would increase with additional warming. NDCs that result in global mean temperatures of 2°C or above would lead to ice-free conditions in the Arctic every summer, with high-risk and unpredictable global impacts. Loss of Antarctic sea ice and associated ice shelves is less certain, but holds even greater long-term and non-reversible risks because the sea ice and ice shelves are essential to protecting Antarctica's ice sheet, and holding sea-level rise to adaptable levels in coming decades and centuries.

Permafrost

More than 210,000 km² of frozen permafrost land area has thawed each decade on average since current warming began a century ago, accelerating since the 1990's with every fraction of a degree of warming. This thaw destabilizes infrastructure in Arctic and mountain regions, with global economic impacts from building and road damage projected to exceed $276 billion by mid-century under high emissions. Permafrost thaw also decreases the global carbon budget. Already today, permafrost thaw releases annual carbon emissions equal to those of a top 10 greenhouse gas emitter such as Japan (about 0.3–0.6Gt CO_2-equivalent per year). Emissions will continue at this scale for one to two centuries even with no additional warming; and cannot be halted once initiated, making carbon neutrality more difficult to achieve if temperatures continue to rise.

Permafrost emissions over coming decades and centuries depend on how much carbon countries release into the atmosphere: lower human emissions mean lower permafrost emissions. Growing wildfires and extreme heatwaves leading to abrupt thaw events may increase permafrost emissions even further. NDCs consistent with 1.5°C would lead to annual permafrost emissions around the same level as carbon emissions from India today (about 2.5Gt) for the rest of this century. NDCs causing overshoot to 2°C would increase annual permafrost emissions to the same scale as current emissions from the 38 countries of the OECD Europe (about 3–4Gt). In this scenario, permafrost soils would disappear in extensive regions above the Arctic Circle as well as below, and nearly all existing infrastructure built on permafrost would require stabilization or replacement. NDCs resulting in 3–4°C would lead to annual permafrost emissions similar to the United States or China's annual emissions today (about 5Gt or more) for one to two centuries, burdening the next several generations struggling to keep atmospheric CO_2 concentrations at manageable levels.

CHAPTER 1

Ice Sheets and Sea-level Rise

Current Policies Risk Triggering Long-term Sea-level Rise and Loss of Coastlines on Massive Global Scale

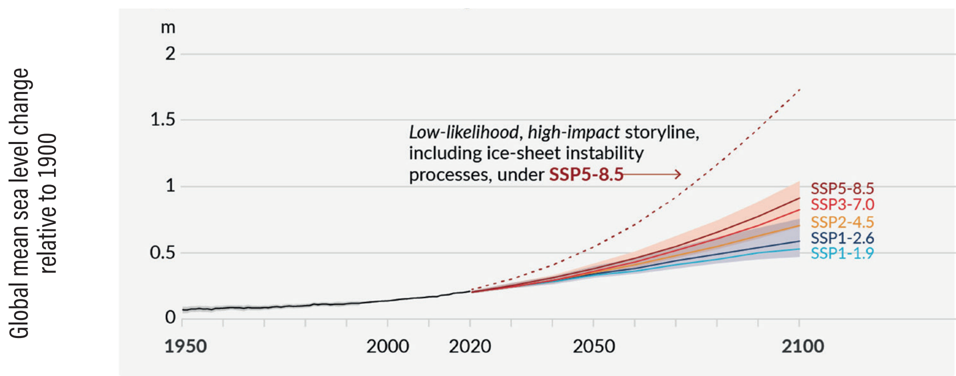
The State and Future of Ice Sheets 2025

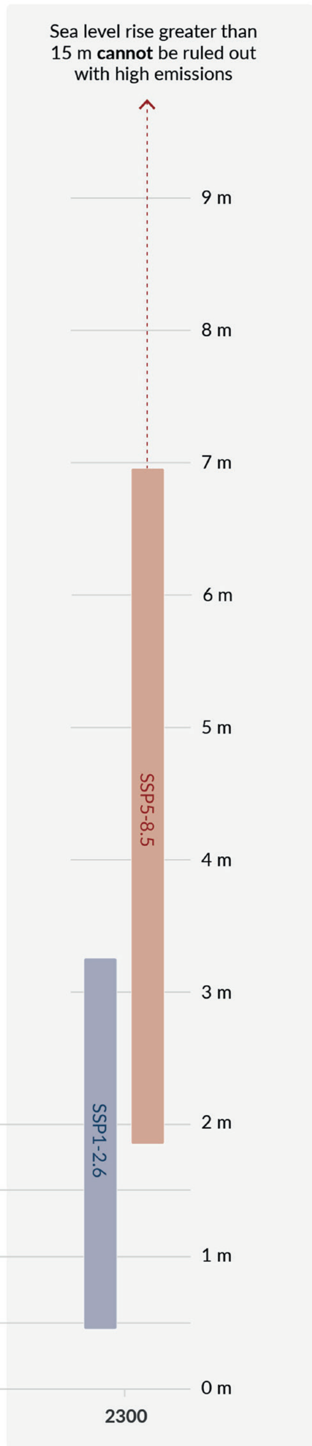
The vast ice sheets covering Greenland and Antarctica play a vital role in regulating Earth's climate, global ocean circulation, and determining the pace and magnitude of sea-level rise. Losses from both ice sheets have quadrupled since the 1990s, bringing them closer to crossing irreversible thresholds that would impact humanity for millennia.

While several meters of sea-level rise from these ice sheets is likely inevitable over the coming centuries, the decisions made by policymakers today on emissions of greenhouse gases will determine how much and how fast seas will rise, as well as wider impacts to the global climate system. With 2025 NDCs consistent with 1.5°C by 2100, and returning below 1°C through carbon dioxide removal in the next century, sea-level rise can likely be slowed to rates that enable feasible adaptation, minimizing loss and damage. In contrast, NDCs that result in temperatures of 2°C or above are very unlikely to prevent the crossing of thresholds for both Greenland and parts of Antarctica that generate inexorable sea-level rise that exceeds 10 meters in the coming centuries, even if air temperatures later decrease. The pace of this long-term, unstoppable sea-level rise will pose major and persistent challenges for all coastal regions, resulting in widespread loss and damage of critical infrastructure, agricultural land, homes and livelihoods.

Decisions made by policymakers today on emissions of greenhouse gases will determine how much and how fast seas will rise.

FIGURE 1-1. **Projections of future sea-level rise under different emissions**





SOURCE: IPCC AR6.

2025 Updates

- Model simulations of Antarctica's response to past warming and cooling cycles shows that a tipping point may be crossed with less than 0.25°C further ocean warming that would trigger the long-term collapse of the West Antarctic Ice Sheet. Substantial irreversible ice loss over the coming centuries, especially from West Antarctica, is therefore likely to be triggered with little or no further climate warming.[4]
- Ice core data from West Antarctica suggest that the Ronne Ice Shelf persisted throughout a substantial portion of the Last Interglacial period (around 125,000 years ago), when global average temperatures were 0.5°C to 1.5°C warmer than preindustrial levels and sea levels were 2 to 9 meters higher than present. The data suggest that most West Antarctic ice loss occurred in the Amundsen Sea sector (the most rapidly changing region of Antarctica today), although how the Ronne Ice Shelf responded to the warmest interval (130–126 thousand years ago) remains uncertain.[5]
- A new model of northwestern Greenland calibrated with satellite observations was able to correct a long-standing bias in the models previously used to inform the IPCC which tend to underestimate the observed mass loss from the Greenland Ice Sheet. The revised model leads to an 8 to 17% greater sea-level rise contribution from this region by 2100.[6]
- A new survey of the shape of seafloor surrounding the Antarctic continent revealed deeper and previously unknown bathymetric troughs that funnel warm ocean water towards Antarctic ice shelves. The greater depths of many of the troughs make many glaciers more vulnerable to subsurface ocean warming than previously thought, which may increase future sea-level rise from Antarctica.[8]
- State-of-the art projections reveal that sea-level rise and changes to groundwater recharge will cause nearly 77% of the global coast to undergo measurable saltwater intrusion by 2100.[9]
- An improved ice sheet model showed that large parts of the West Antarctic Ice Sheet will deglaciate over the coming centuries even if ocean temperatures simply remain at present-day levels. The two largest glaciers in this region, Thwaites Glacier and Pine Island Glacier, collapse in every model scenario.[10]
- An exceptional subglacial lake drainage event temporarily doubled the rate of ocean melting under Thwaites Glacier in 2013. The lake drainage likely contributed to Thwaites' rapid thinning and grounding line retreat during this period. Combined with tidal seawater intrusions into the Antarctic grounding zone,[11] these processes could amplify ocean-driven melting of the Antarctic Ice Sheet.[12]
- More accurately incorporating the movement of water beneath the Antarctic Ice Sheet can increase ice discharge by up to threefold compared to models that do not fully represent this process, potentially contributing an additional 2.2 meters to sea-level rise estimates by 2300. Excluding this process can lead to underestimation of future sea-level rise and delayed prediction of tipping points onset.[13]
- Continuing a very high emissions pathway (SSP5-8.5) could double the amount of freshwater discharged from the Antarctic Ice Sheet by 2100, and quadruple outputs by 2300, in a scenario that risks triggering severe negative global feedbacks, including on ocean currents. If global emissions can be dramatically lowered, the amount of freshwater discharged from Antarctica can be greatly limited in the coming centuries.[14]
- Crevasses in some of the fastest flowing regions of the Greenland Ice Sheet are getting deeper and larger due to rising air and ocean temperatures. This may increase iceberg production as well as water transfer to the base of the ice sheet, potentially resulting in greater ice loss and sea-level rise.[15]
- Including the process of crevasse and rift formation (ice damage) within ice sheet models more than doubles projections of ice loss from Thwaites Glacier by 2300. The results highlight the need to include ice damage processes in ice-sheet models used for forecasting future ice loss and sea-level rise.[16]
- Modelling of a controversial geoengineering proposal to install an artificial underwater curtain in the fjord of one of Greenland's largest glaciers found that this intervention would not prevent further retreat even under low emissions, and comes with a plethora of economic and cultural concerns from local Indigenous People.[17] A further review concluded that such an intervention would severely harm Greenland's regional fisheries.[18]

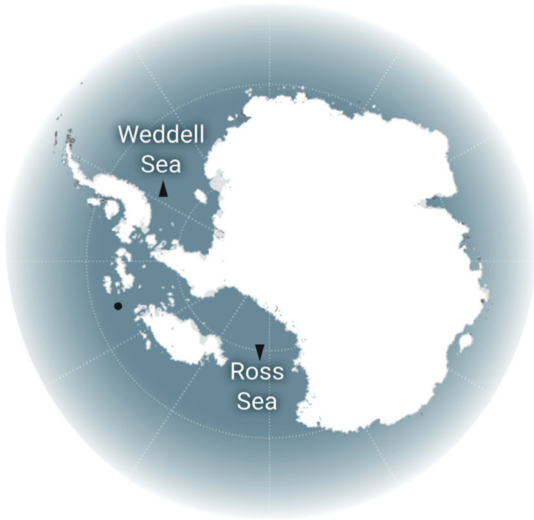
continued on next page

Background

For the Earth's vast polar ice sheets, the risk of triggering runaway melting increases with every tenth of a degree of warming.[1,21] 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.[22,23] 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 it was in the 1990s,[24] and Antarctica's contribution to sea-level rise is now six times greater than it was 30 years ago.[25-27] Given that one billion people live at elevations within 10 meters above current sea level globally, with 230 million living within just 1 meter,[28] 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. The only way to achieve this is by undertaking deep, rapid and sustained emissions reductions.[2]

The Earth's climate record makes clear that, in the past, warming of even 1°C above pre-industrial temperatures dramatically reshaped the Earth's coastlines due to extensive melting of the West Antarctic Ice Sheet (WAIS),[29] the Greenland Ice Sheet[30,31] and by 1.5°C, possibly parts of East Antarctica.[32] 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

FIGURE 1-2. **Antarctica Between 1°C and 2°C in Earth's Past**



How Antarctica looked in Earth's past when temperatures were last between 1°C and 2°C (~125,000 years ago).

FROM LAU ET AL. 2023

Avoiding these impacts requires temperatures cooler than present, closer to 1°C above pre-industrial, or even lower.

2025 UPDATES (CONTINUED)

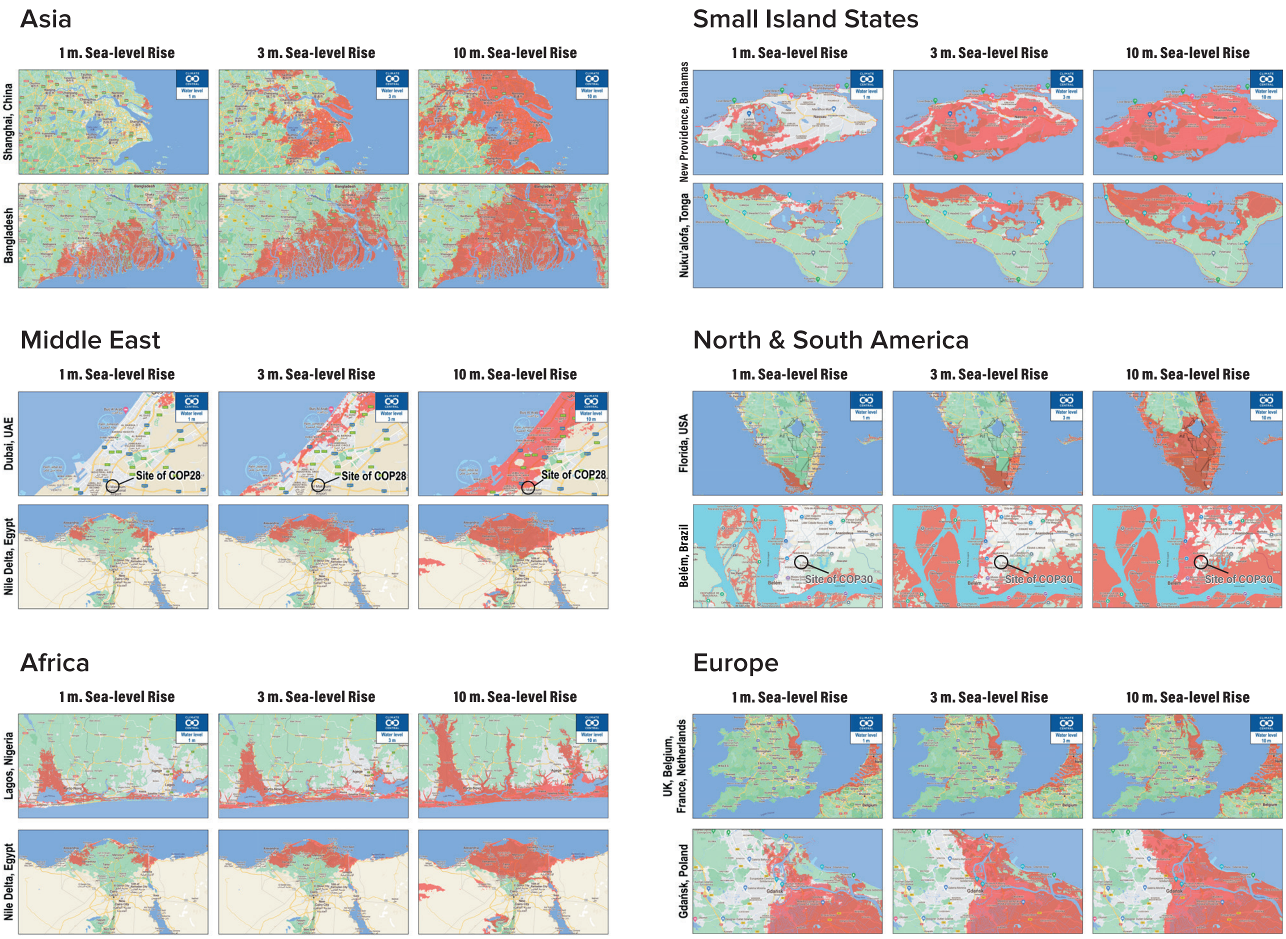
- Researchers noted how Antarctic climate processes are becoming increasingly like those affecting Greenland, an observation they term the "Greenlandification" of Antarctica.[7]
- A 31-year satellite record (1992–2023) reveals that the volume of surface meltwater has significantly increased across the Greenland Ice Sheet in recent decades, while East Antarctica has become a melt hotspot since 2000 due to warm air incursions from the Southern Ocean. Greater meltwater presence along the edges of East Antarctica may lead to greater meltwater ponding and future ice shelf destabilization.[19]
- Evidence for more persistent ice cover over North America during the Last Interglacial Period implies that Greenland and Antarctica melted more than previously thought at this time to reconcile the height of former sea-level records (sea levels were 2–9 meters higher than present). This greater sensitivity suggests that peak sea-level rise estimates from the Last Interglacial may only be a lower bound for the amount of sea-level rise that could be expected from the Greenland and Antarctic ice sheets if current emissions continue.[20]
- Every increment of additional peak emissions and warming this century irreversibly locks in sea-level rise for centuries, this study found in new long-term modelling. Peaking global emissions in the 2020s, by the end of this decade, through ambitious mitigation will prevent around 60 cm of further sea-level rise by 2300 compared to pathways where emissions peak later this century, with the greatest benefits from pre-2030 action for Small Island Developing States.[58]

pre-industrial, geological evidence shows that sea levels were 2 to 9 meters higher than present.[1,33] 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.[1,33-36] 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) due to the collapse of vulnerable ice-sheet sectors.[37] 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 approaching these temperatures at an unprecedented rate.[38]

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 exceeds 1.5°C.[39-43] 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

FIGURE 1-3. **Timing and Extent of Sea-level Rise Depends on Our NDCs**

1 m. Sea-level Rise	3 m. Sea-level Rise	NOT SHOWN: 6 m. Sea-level Rise	10 m. Sea-level Rise
Now long-term inevitable (by mid-2100s), but potentially by 2070 with current emissions	Likely inevitable in 1000–2000 yrs; BUT by early 2100's with current emissions	Early 2200s with current emissions	By 2300 with current emissions



The above maps are only some examples of how ice sheets can cause irreversible sea-level rise to coastal regions. To see more locations, see coastal.climatecentral.org/map/

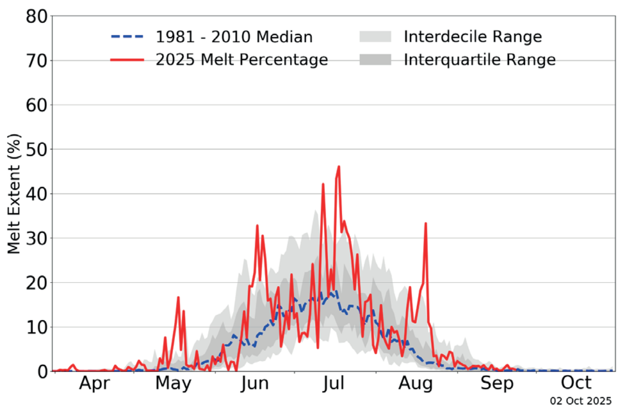
SOURCE: CLIMATE CENTRAL

warming.[4,22,44,45] In the future, extensive melting of West Antarctica's stabilizing ice shelves is predicted to occur even under very low emissions trajectories,[46,47] and modelling suggests that the WAIS could cross a tipping point into unstoppable collapse with less than +0.25°C of further ocean warming.[4] 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.[10,48,49] 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, parts of the much larger East Antarctic Ice Sheet, especially the Wilkes and Aurora Basins (8+ meters of potential sea-level rise), risk crossing a similar threshold around or just beyond 2°C.[32]

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,[50] which is expected to become even more dominant in the future. 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.[51-53] 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, biological activity, and rainfall. Rainfall on the Greenland Ice Sheet has increased by 33% since 1991, and the frequency of extreme deluges is increasing.[54] 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.[30] Similar analysis has recently shown that even the central summit of Greenland was ice free sometime within the last 1 million years,[31] 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;[1] yet, the decadal average for 2015–2024 was 1.24°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

FIGURE 1-4. **Greenland Surface Melt Extent in 2025**



Greenland surface melt in 2025, with unusual melt spikes early in the season (May) and late (August). Researchers on the ice sheet reported extremely dangerous conditions due to the sheer amounts of surface water.

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FEATURED UPDATE

1.5°C is Too High for Polar Ice Sheets

A comprehensive assessment of the stability of Earth's polar ice sheets shows that a temperature target of 1.5°C is too high to prevent widespread global damage from ice loss. Authors reviewed recent observations of Greenland and Antarctic ice sheet melt, also assessing ice sheet response to past warm periods as well as projected future ice loss. They stressed that even the current level of climate forcing (1.2°C), if sustained over decades and centuries, is likely to generate several meters of rapid sea-level rise. This will cause extensive loss and damage to low-lying communities and challenge many coastal adaptation strategies. If the current acceleration of sea-level rise continues, we could see rates of 1 cm per year by 2100, which would present severe challenges to coastal adaptation. Avoiding these impacts would require a global mean temperature that is cooler than present, likely closer to 1°C above pre-industrial levels, or even lower; emphasizing the need for rapid GHG emission reductions to hold peak temperatures as low as possible, allowing for a faster return to safer temperatures.[1]

populations and challenging the effective implementation of adaptation strategies.[1,43] 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. The IPCC[39] 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 realised 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.[40] 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. Sea level lowering will not occur until temperatures go well below pre-industrial levels, initiating a slow ice sheet re-growth.[23] 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.

Ensuring the future rate and amount of sea-level rise from ice sheet loss remains as slow and as low as possible is essential for coastal adaptation to remain feasible.

FEATURED UPDATES

Polar Geoengineering a Dangerous and False Solution to Slow Cryosphere Loss

Over 40 world-leading polar and climate scientists objectively assessed the most prominent polar geoengineering proposals and found that none would provide a responsible and viable means of limiting climate harm to the polar regions. Instead, they found that polar geoengineering concepts are false 'solutions' that would cause severe environmental damage, alongside the likelihood of grave unforeseen consequences. The robust environmental protection and governance frameworks currently in place to protect the polar regions would reject such geoengineering efforts. The authors conclude that minimizing risk and damage from climate change is best achieved by mitigating the cause of climate harm through immediate, rapid and deep decarbonization, rather than attempting speculative interventions in fragile polar environments that likely would not work.[2]

Growing evidence for abrupt environmental changes in Antarctica

A review published in Nature summarized growing evidence of abrupt changes in the Antarctic environment. The authors point to the recent regime shift in Antarctic sea ice extent that has occurred even more rapidly than in the Arctic, and major shifts to habitats and ecosystems on land and in the Southern Ocean that pose an increasing extinction risk. The Antarctic Overturning Circulation is expected to slow down at an accelerating rate this century, and may occur more quickly than the slowdown of the Atlantic Meridional Overturning Circulation in the northern hemisphere. The tipping point for unstoppable ice loss from the West Antarctic Ice Sheet may also be passed even under a low emissions pathway. Redoubling efforts to minimize overshoot of 1.5°C, alongside the implementation of adaptation measures, will be essential to minimize and prepare for the global impacts of abrupt changes to Antarctica and the Southern Ocean.[3]

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Mountain Glaciers and Snow

Amidst Rapid Glacier Loss Worldwide, Evidence of Greater Vulnerability at Lower Temperatures

The State and Future of Mountain Glaciers and Snow 2025

Glacier ice loss around the world is increasing exponentially. Between 2000 and 2023, global 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. Relative glacier loss was greatest in Central Europe and the Caucasus, which lost 39% and 35% of their ice, respectively, during this time. Snowpack has followed a similar trajectory, declining globally in thickness and duration. This loss is especially pronounced at lower mountain altitudes, as well as mid-latitude regions. However, even in the Arctic, spring snow melt has been occurring 1–2 weeks earlier than average; and the 2023–24 snow season in parts of Canada was the shortest in over a quarter-century.

The future of glaciers and snowpack depends on future carbon emissions. Some areas, such as Scandinavia and western North America, will lose all or nearly all ice already at 2°C; but a 1.5°C emissions trajectory will preserve 20% of today's ice in these regions. Even the higher central and eastern parts of High Mountain Asia are projected to lose 60% of existing ice under a 1.5°C emissions scenario, with only 15% remaining at 3.0°C. The Hindu Kush and Karakoram regions, which in recent decades were near stable, stand to lose 40% of ice mass under a 2°C future but only 15% under a 1.5°C pathway. The impacts of this loss include water, food, economic and political insecurity, and should be considered essentially permanent on human time scales. However, with ambitious emissions cuts, glacier and snow loss can slow and begin to stabilize by the 2060s, and some glacier regions may show signs of regrowth by the 2200s – one of the earliest indications of planetary recovery.

FEATURED UPDATE

Melt Rate Far Exceeds Predictions Over Two Decades of Glacier Observations

Two decades of remote and on-site glacier observations compiled by GlaMBIE, the Glacier Mass Balance Intercomparison Exercise, show that glaciers around the world have lost an average of 273 billion metric tons of ice per year between 2000 and 2023, with losses notably accelerating in recent years. GlaMBIE results indicate that the trajectory of past ice loss will continue until adequate climate ambition slows temperature rise. Mountain regions that have smaller glaciers such as the Alps, the Caucasus and Scandinavia are especially vulnerable. This acceleration of melt will require continual re-calculation of adaptation measures for food, water and energy security for billions of people around the world until net zero emissions are reached, including for low-lying and coastal regions experiencing sea-level rise and floodwaters.[1]

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. 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, hence losing mass everywhere, 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 the summer. Their importance varies, with some contributing only a few percent over the course of a year, but even these may become essential during dry seasons, heat waves and droughts.[15,16,17] Loss of water resources from changing glaciers and snowpack has already contributed to increasing tensions and conflicts in some regions. This underscores the global importance of mountain cryosphere, something which the 2025 UN International Year of Glaciers' Preservation has emphasized, despite misperceptions that it is a distant or "niche" issue.[18] 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,

2025 Updates

- The 12 glaciers of the Italian Dolomites have thinned by 30 meters in the past 40 years – one third of which has occurred in the past decade.[3]
- Not only have Indonesia's Puncak Jaya glaciers lost more than 99% of their 1850 surface area, but new satellite imagery from 2023 and 2024 shows the tropical ice masses have lost as much as 64% of the surface area since the most recent survey in 2018.[4]
- New data shows that even temporarily exceeding 1.5°C will have irreversible consequences on ice loss and water scarcity for both glaciated and downstream regions around the world.[5]
- Andean glaciers show greater mass loss during El Niño cycles. Since 1985, one of the largest tropical glaciers, Peru's Quelccaya, has lost 58% of its snow cover and 37% of its total area during periods of accelerated melting during El Niños, despite growth during the cooler La Niñas.[6]
- Since 2020, glaciers in Western Canada and conterminous United States have lost 12% of their mass and those in Switzerland 13%. Lower-than-average snow accumulation and heatwaves, along with unprecedented wildfire seasons (North America) and Saharan dust storms (Switzerland) have contributed to this loss. Light-absorbing particles, such as soot from fires and dust, are usually excluded from climate models looking at glacier mass balance.[7]
- Cosmogenic nuclide dating is helping to identify time periods of past deglaciation, suggesting, for example, that an ice-free Sierra Nevada was unprecedented until now.[8]
- As glaciers recede across southwest Greenland, these newly ice-free regions are transforming into a net source of carbon rather than a carbon sink.[9]
- Warming oceans are driving year-round ice melt in Svalbard. Even the high-latitude winters are not sufficient to protect against runaway ice loss.[10]
- Black carbon is driving significant glacial retreat and snowfall decline in the Tibetan Plateau through increasing heat absorption when it lands on ice as particulate matter and by altering atmospheric circulation patterns.[11]
- 1.9 billion people will be at risk for a once-a-century flood by 2100 with two-thirds of those affected living in areas with the lowest GDPs.[12]
- Two decades of data from the CDC (Centers for Disease Control and Prevention) and NOAA (National Oceanic and Atmospheric Administration) found more than 22,000 deaths in the contiguous United States attributable to floods (partially driven by snow melt) between 2001–2020 with notable consequential spikes in heart disease, respiratory diseases, and injuries. Cryosphere losses contribute to these floods through premature melt of snowpack and ice.[13]
- Snowpack in the Western United States, a critical water source for 100 million people, is set to lose 34% of its seasonal volume by 2100.[14]

FIGURE 2-1. **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 2-2. **How much ice will remain?**

Region	Temperature causing 50% loss	% Remaining at 3°C	% Remaining at 2°C	% Remaining at 1.5°C
Tropics (Central Andes, E. Africa, Indonesia	1.6°C	10%	30%	55%
Caucasus	1.6°C	20%	40%	55%
Alaska	1.7°C	30%	40%	60%
Central Asia	1.9°C	20%	45%	65%
Southern Andes & Patagonia	2.0°C	30%	50%	55%
Western Himalaya, Karakorum & Hindu Kush	2.2°C	30%	60%	85%

Even in more resilient glacier systems, 1.5°C preserves far more ice and related water resources. Percentages are in comparison to 2020 ice mass levels.

SOURCE: GLACIERMIP3 (ZEKOLLARI, SCHUSTER ET AL., *SCIENCE*, 2025)

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.[19]

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."[20,21] Adaptation

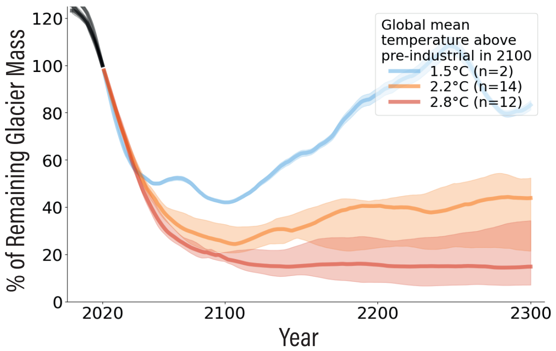
Some glacier regions [will lose] at least half their ice at or even below 1°C, showing the increasing vulnerability of glacier ice.

FEATURED UPDATE

1.5°C May Be the Difference Between Ice and No Ice in Key Regions – Even Compared to 2°C

Current policies have temperatures reaching 2.7°C by century's end, which means that only 24% of today's glacier ice will survive if we remain at that temperature over multi-centennial timescales. Glaciers that are central sources of freshwater to the world's human population, as well as the very large polar glaciers of Alaska and Canada will lose high percentages of their ice. At just 2°C, only 25% of ice in the giant glaciers of the Hindu Kush Himalaya – an area that supports nearly two billion people – will survive. In Scandinavia, no glacier ice will remain at 2°C; and in the European Alps, North American Rockies, and Iceland, a mere 10–15% of the 2020 ice mass will remain at this temperature. Each of these regions is committed to losing at least half their ice at or even below 1°C, further demonstrating the increasing vulnerability of glacier ice. The good news is that globally, keeping global temperatures to the 1.5°C lower limit of the Paris Agreement can save twice as much glacier ice as temperatures at 2.7°C. This study stresses the increasing urgency to keep global temperatures to the 1.5°C lower limit of the Paris Agreement.[2]

FIGURE 2-3. **Caucasus and Middle East**



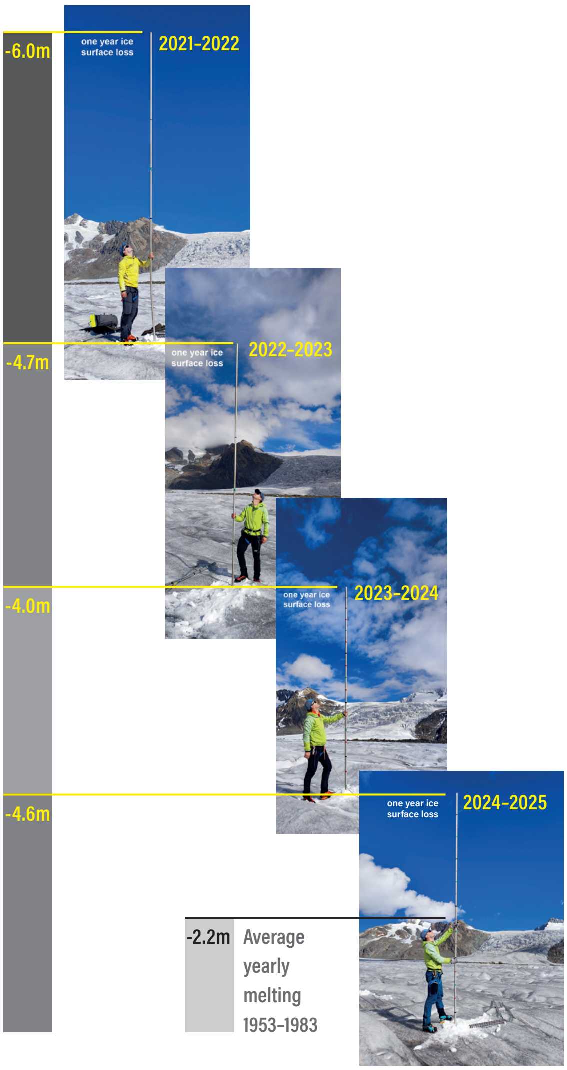
At 1.5°C, not only do models show the glaciers in the Caucasus preserving more of their mass, models indicate glacier regrowth under a very low emissions pathway.

SOURCE: SCHUSTER ET AL. (2024)

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.[22,23]

Many glaciers of the northern Andes, East Africa and Indonesia, especially those close to the Equator, are disappearing too rapidly to be saved even in the present 1.2°C climate.[24] These glaciers have mostly been shrinking since the end of the Little Ice Age, but global warming greatly accelerated their melting.[25]

FIGURE 2-4. **2022–25 Ice Loss at "the Top of Europe": Great Aletsch Glacier, Switzerland**



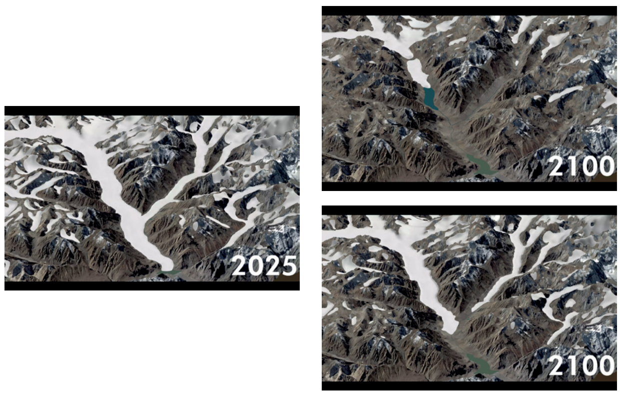
Extreme record rates of ice loss in 2022, 2023, 2024 and 2025 as measured at Konkordiaplatz, Switzerland. 2025 melt was 4.6 meters.

PHOTO: MATTHIAS HUSS.

Severe losses also are 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, 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.[26,27] Others, such as those in the Hindu Kush Himalaya (HKH), may experience up to 80% of ice loss.[28] However, 1.5°C-aligned policies can save at least some portion of ice even in the most vulnerable regions, such as the Alps, Rockies, Iceland and Scandinavia, and would lead to some stabilization around 2060, according to latest models.[27] Any other emissions path will eventually result in almost complete loss of all mid-latitude glaciers by 2300, many as earlier as 2050.

Glaciers can shrink and even disappear completely over the space of just decades to a century. When Glacier National Park in the U.S. was created in 1910, it had around 150 glaciers; today, fewer than 30 remain, and those have shrunk by about two-thirds in surface area.[29] In contrast, projections show that significant ice mass re-growth 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.[30] Therefore, on human timescales, the disappearance of today's glaciers is an essentially

FIGURE 2-5. **The Future of Vanch-Yakh Glacier, Tajikistan**



Vanch-Yakh today (left); and in 2100 with high emissions (upper right), and with far more ice remaining at low emissions (lower right), especially in the right-hand valley. Vanch-Yakh is the world's largest land glacier outside the poles, yet is still highly vulnerable to climate change. Animations comparing glacier loss at high and low emissions for Vanch-Yakh, as well as Chhota Shigri (India), Great Aletsch (Switzerland) and Athabasca (Canada) glaciers, see iccinet.org/statecryo25/glaciers.

FROM ANIMATION BY ENRICO MATTEA.

permanent change to the mountain landscape. Very low emissions are key to ensuring as little ice as possible is lost during this current period of rapid decline.

A very low emissions pathway is 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 that accompany loss of mountain glaciers.[28,31,32,33,34,35] 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.[36]

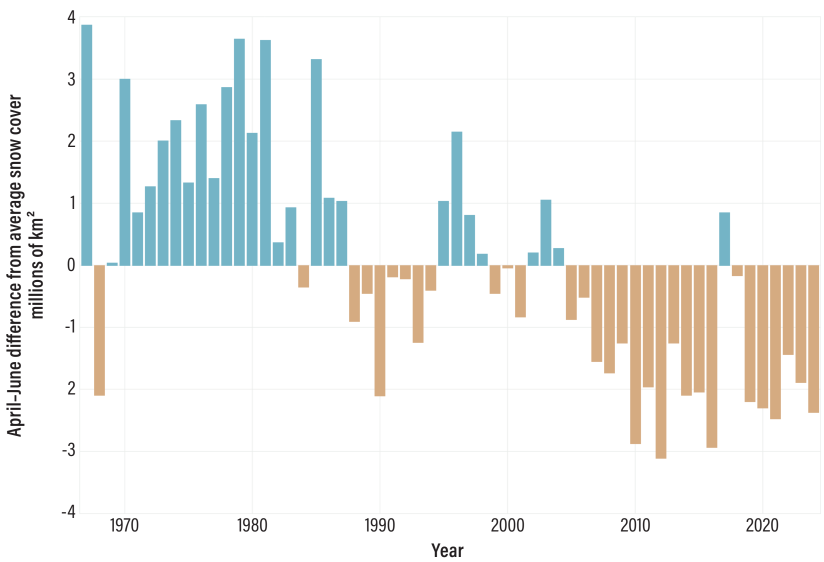
With high emissions, and global mean temperature rise exceeding 4°C by 2100, any substantial seasonal snowpack will become rare outside the polar regions and very high mountains.[37] Snowfall already has become less reliable in many mountain watersheds, with extreme snow droughts alternating with extreme snowpack, which increasing the risks of avalanche and flood, such as in California, USA (2023) and the Hindu Kush Himalaya (2023–2024).[17,37,38] 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.[39]

With rising temperatures due to high emissions, at lower elevations and latitudes, snow will become less frequent at lower elevations and latitudes, and the winter season will shorten.[40,41] Even in the high-latitude Arctic, spring snow melt has been occurring 1–2 weeks earlier over the past fifteen years.[42] Water stored in the snow and snow-fed underground aquifers will decrease, as already reported in many mountain areas.[43,44] Continued declines in annual snowpack will result in negative economic impacts for many sectors, especially agriculture, hydropower, and tourism; and threaten the availability of sufficient water supplies for major downstream population centers, from Los Angeles and Bangladesh to Marrakech and Delhi.[45,46,47]

In both the Arctic and mountain regions, the well-being of people and many species depend on seasonal snow cover. For reindeer-based Arctic Indigenous cultures, more animals are lost to starvation when winter rain falls on snow, forming thick layers of ice that makes it impossible for reindeer to forage through the ice cover.[48] Lack of snow cover also increases the risk of wildfires, as well as natural disasters such as mudslides or drought in the wake of fires.

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 also will significantly benefit economies dependent on snowpack for power generation, agriculture and revenue from snow

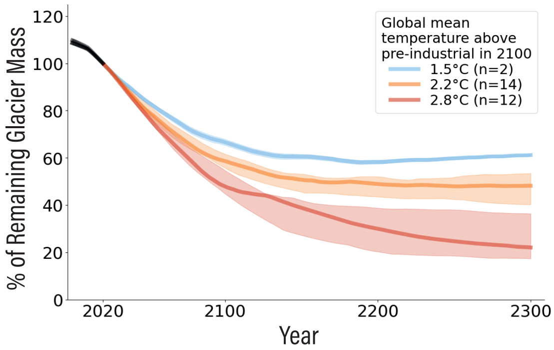
FIGURE 2-6. **Snow Cover Disappearing across the Northern Hemisphere**



Records from the last five decades show that spring snow cover is disappearing earlier, declining most rapidly in June when Siberia, Alaska, and northern Canada used to retain some snow. Across the entire Northern Hemisphere, the total area covered by snow during March and April also has shrunk over time.

SOURCE: GRAPH BY NOAA CLIMATE.GOV, BASED ON RUTGERS SNOW LAB DATA

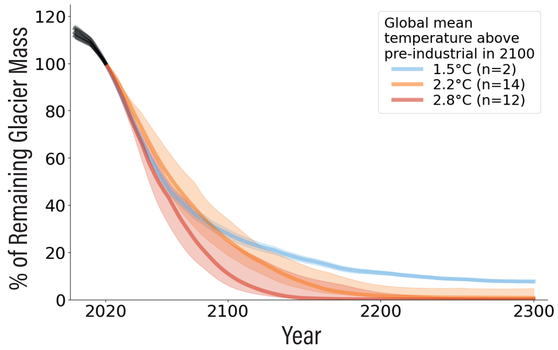
FIGURE 2-7. **Patagonia and the Southern Andes**



Glaciers in Patagonia are especially sensitive to emissions. At +2°C, these models show the slowing of ice loss and the preservation of about 50% of their current ice by 2300; losses much greater at +3°C.

SOURCE: SCHUSTER ET AL. (2024)

FIGURE 2-8. **Scandinavia**



Ice loss in Scandinavia is accelerating. Only keeping temperatures to 1.5°C will preserve some ice in this region; nearly all ice will be gone at 2°C.

SOURCE: SCHUSTER ET AL. (2024)

tourism.[49] Low 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.[27,43,50] New research highlights ongoing overconfidence in sufficiently drawing down temperatures with any overshoot of the lower 1.5°C Paris limit, reinforcing the need for drastic emissions cuts.[39] 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 with adequate adaptation and disaster prevention measures.

A sharp strengthening of climate action towards the 1.5°C limit will determine the future after that mid-century timeframe, 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.[51]

The good news is that globally, keeping global temperatures to the 1.5°C lower limit [by 2100] can save twice as much glacier ice as temperatures at 2.7°C.

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CHAPTER 3

Polar Oceans

Growing Signs of Acidification and Risks of Ocean Current Shutdown

The State and Future of Polar Oceans 2025

Polar oceans are vital in regulating Earth's climate by absorbing heat and carbon, acting as engines for global ocean circulation and as a basic component of marine food webs. All of these functions are under threat from rising greenhouse gas concentrations and related warming, with thresholds that could trigger widespread and essentially irreversible disruption. At the quarter-century mark, at CO_2 concentrations in the atmosphere sometimes exceeding 430 parts per million (ppm), ocean acidification has reached levels extremely challenging and potentially lethal for shelled marine life in some polar ocean sectors. Two major drivers of ocean currents (the Antarctic Overturning Circulation (AOC) and the Atlantic Meridional Overturning Circulation (AMOC)) have slowed substantially, likely due to a combination of freshwater pouring off Antarctica and Greenland, respectively as well as warming surface waters. Marine heatwaves and compound extreme events, at times including major die-offs of large mammals, fish and bird species, have become far more frequent in Arctic and near-Arctic waters.

The future of polar oceans depends directly on the path of global carbon emissions. Limiting warming close to 1.5°C through quickly reducing carbon emissions will prevent further spread of ocean acidification and reduce the risk of irreversible circulation changes. Every fraction of carbon emissions and associated warming beyond this boundary will intensify ocean acidification and other stressors on polar marine life, pushing polar-driven ocean circulation closer to a tipping point of long-term, essentially irreversible collapse. At 2°C and above (for ocean acidification purposes, equivalent to 500+ ppm CO_2 in the atmosphere), severe and possibly abrupt circulation disruptions alongside widespread acidification become even more likely, with cascading impacts on species survival and global food security.

FEATURED UPDATE

Arctic and North Atlantic Ocean Acidification Has Reached Critical Levels

Ocean acidity has reached critical levels, especially in the Arctic and North Atlantic Oceans. A new assessment, based on updated oceanographic and marine biological data combined with advanced computer models, has confirmed that ocean conditions in these polar and near-polar regions have passed a planetary boundary.[1] Ocean acidification is also spreading from surface waters to deeper levels. As a result, there has been a loss of suitable habitat for keystone shell-building species by about 60% for polar pteropods and about 40% for coral reefs – both vital components of marine food webs.[1] Escalating ocean acidification has also occurred in the near-polar oceans of Northwest Europe, particularly the UK and Ireland.[2] If current emissions continue, ocean acidification could also begin to damage shelled creatures in parts of the Northwest European Shelf seas, threatening the broader food web in this region, and by extension, local and regional economies.

2025 Updates

- Rising atmospheric temperatures are increasing extreme ocean warming events globally. The Arctic is particularly vulnerable due to declining sea ice, which, historically, acted as a buffer against such events. High-resolution climate models predict more frequent and intense Arctic marine heatwaves as sea ice decreases.[7] This will lead to a more stratified Arctic Ocean, with a warmer surface layer preventing nutrient mixing with colder, denser waters below. This disruption threatens the foundation of the Arctic ecosystem.
- The North Atlantic Ocean faced an unprecedented marine heatwave in summer 2023, caused by weak winds that slowed heat redistribution, warming the surface at a rate equivalent to two decades of typical warming.[8] Low wind speeds led to the shallow upper ocean absorbing solar heat without mixing with cooler waters below, intensifying extreme weather, coral bleaching, and hurricanes like Idalia, causing significant damage in the southeastern U.S. Long-term warming reduces surface water density, inhibiting mixing and increasing temperature spikes, impacting fisheries and weather stability.
- Warming coastal waters are expected to increase harmful algal blooms in high-latitude regions, particularly during spring and autumn, threatening seafood safety and wildlife. For example, a 3°C temperature rise along the Norwegian coast could lead to a 50% increase in diarrheic toxins and a 40% decrease in paralytic toxins.[9] This shift alters risks to marine ecosystems and public health, potentially exposing both humans and marine life to more poisoning incidents.
- New evidence from bivalve shell records reveals that the subpolar North Atlantic has undergone two major destabilization episodes over the past 150 years, signaling potential loss of stability in its key circulation elements.[10] The first episode preceded the 1920s North Atlantic regime shift, suggesting an early 20th-century tipping event. The second, beginning around 1950 and continuing today, indicates ongoing weakening of both the North Atlantic subpolar gyre and the AMOC. These findings provide independent, high-resolution evidence that the North Atlantic may be approaching a critical tipping point under continued climate change.
- New climate simulations show that an AMOC collapse could trigger strong cooling in Northwestern Europe, especially in winter, even under moderate global warming.[6] With intermediate warming at or below 2°C, a weakened AMOC leads to several degrees of cooling, more intense cold extremes, and larger day-to-day temperature variability. These effects are closely linked to expanded North Atlantic sea ice and enhanced storm track activity. The results highlight that Europe's future climate depends on both global emissions pathways and AMOC stability, with potential for disruptive regional cooling despite overall global warming.
- By analyzing 34 climate models of the AMOC under high emissions and freshening scenarios, researchers found that – despite a significant reduction in its strength – the AMOC was unlikely to fully cease by 2100, though increased emissions and Greenland meltwater could severely weaken it[11] (and other studies[6] beyond 2100 show collapse soon thereafter). Reflecting the connection between the AMOC and the Southern Ocean around Antarctica, stronger winds there could counterbalance some of AMOC's decline and prevent complete stalling.
- Melting Antarctic ice releases freshwater into the Southern Ocean, and a new study projects freshwater discharge from ice shelf subsurface melting, iceberg calving, and surface runoff through 2300.[12] A very-high emissions scenario (SSP5-8.5) could double meltwater discharge by 2100 from today, and quadruple discharge by 2300, potentially triggering severe climate and ocean feedbacks. In a low emissions pathway (SSP1-2.6), the increase in meltwater discharge remains limited.
- Southern Ocean stratification has shifted unexpectedly in the last decade. Despite enhanced freshwater input from the Antarctic continent, satellite data show a sharp rise in Southern Ocean surface-water salinity since 2015, coinciding with a significant decline in Antarctic sea ice; an area the size of Greenland lost in a decade.[13] This unexpected trend, not predicted by models, suggests saltier waters promote mixing and thus enable deep ocean heat to rise, melting ice from below. Possible causes include wind shifts, precipitation changes, or warm Circumpolar Deep Water intrusion. These findings highlight the need for improved ocean observations and modelling to better predict and prepare for future changes around Antarctica and their global impacts.

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 25% of human CO_2 emissions every year.[14,15] 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 global oceanic carbon, making them disproportionately affected by acidification.[1,16]

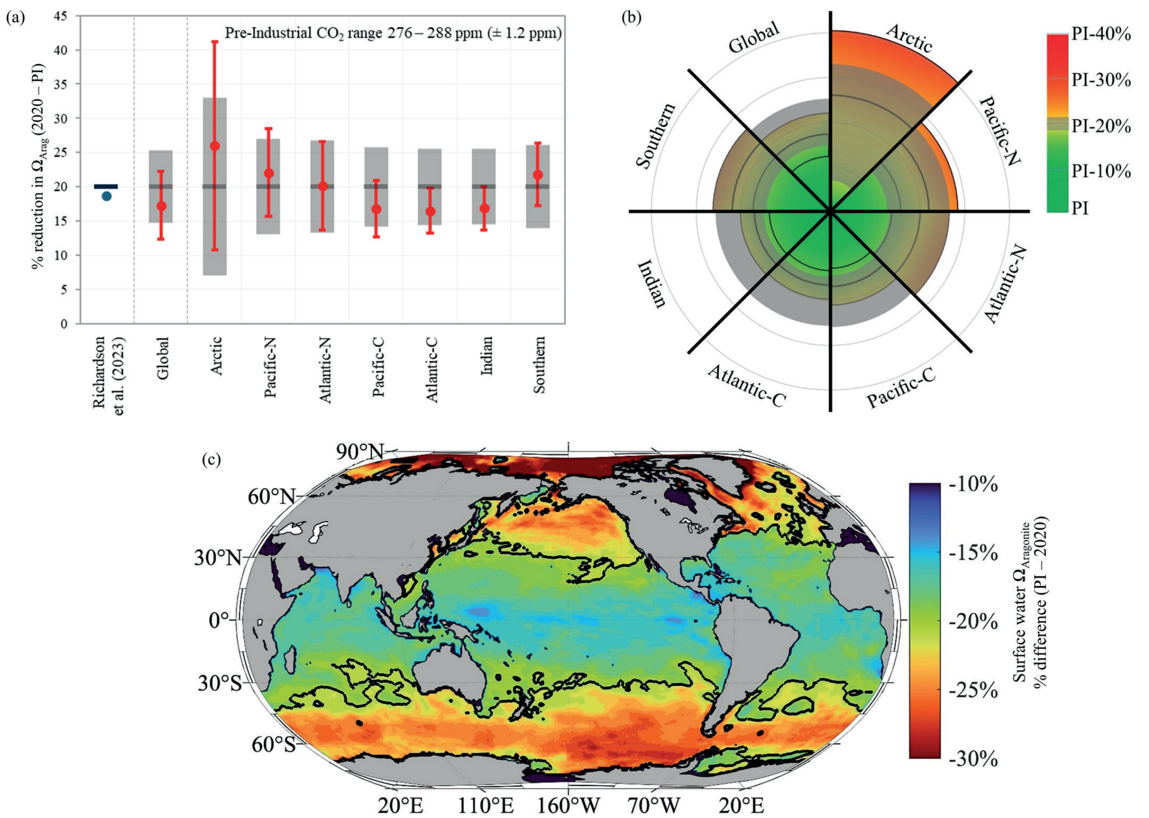
Over the past several million years, ocean acidity has been relatively stable. While polar oceans have undergone changes in the Earth's past, these shifts occurred far more slowly. Even so, these previous changes to ocean chemistry and acidification were accompanied by mass extinctions.[17] Today's ocean acidification is occurring faster than at any point in at least the past 300 million years.[18] 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.[19,20]

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.[21,22,23] 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.[24,25]

Widespread levels of corrosivity have already been observed in the Arctic Ocean,[26,27] alongside declines in pH over several decades in the Southern Ocean, including in Antarctic Marine Protected Areas.[28,29] Damage to vital marine invertebrates such as pteropods has been observed in both the Arctic Ocean[30,31] and Southern Ocean.[32]

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,[18] making this the most "irreversible" cryosphere dynamic of all.

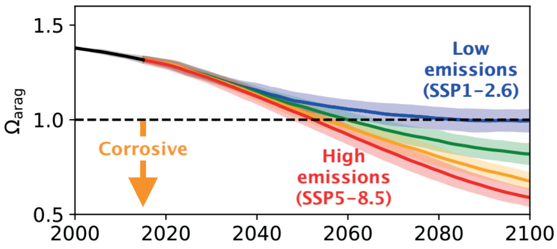
FIGURE 3-1. **Observed Ocean Acidification**



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

SOURCE: FINDLAY ET AL. (2025)

FIGURE 3-2. **Projected future trends in Arctic Ocean acidification at different emissions pathways**

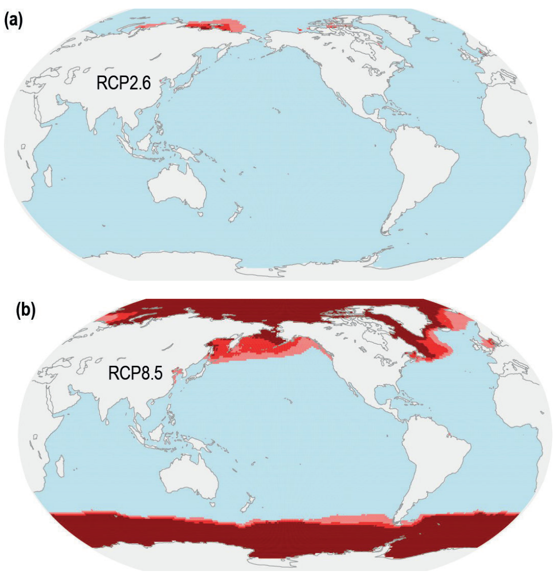


Acidification (eg aragonite or calcium carbonate saturation) trends in the Arctic Ocean over the 21st century following different future emissions scenarios. Values below 1.0 correspond to corrosive ocean water conditions.

ADAPTED FROM TERHAAR ET AL. (2021)

At 2°C of warming or above, ocean acidification, warming and freshening will transform polar oceans irreversibly.

FIGURE 3-3. **Global Ocean Acidification Levels at Low v. High Emissions Pathways**



Difference between acidification levels in a 1.5°C world (RCP2.6) (upper map), and a 3–4°C world (RCP8.5) (lower map) by 2100. Red shows "undersaturated aragonite conditions", a measure of ocean acidification meaning that shelled organisms will have difficulty building or maintaining their shells, leading to potential decline of populations and dietary sources for fish, with loss of biodiversity towards simplified food webs.

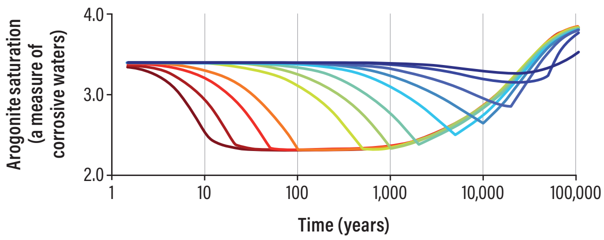
SOURCE: IPCC SROCC (2019)

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 (parts per million), well above the critical level of 450 ppm identified by marine scientists decades ago, and more than doubling ocean acidity in polar regions, leading to widespread corrosive waters.[33] 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.[34] This has reduced their capacity to absorb CO_2 and limit atmospheric warming in recent years, further amplifying climate change.[35] 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 ~1.2°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.[36] The duration and frequency of Arctic marine heatwaves are also increasing now and are expected to continue to increase in the future.[37]

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.[38] Furthermore, it is

FIGURE 3-4. **Time to buffer (restore to normal) acidification levels at different emissions pathways**



Ocean acidification recovery time, ranging from high emissions (red) to low emissions (blue). Note logarithmic timescale: for marine species, ocean acidification is essentially permanent, with full recovery taking 30,000–50,000 years.

ADAPTED FROM HONISCH ET AL (2012)

predicted that the Southern Ocean will continue to warm even after net-zero has been reached.[39] These heatwaves 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.[40] In addition, 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 window of thermotolerance, can overcome this physiological barrier during prolonged marine heatwaves, posing an additional stress on local marine species.[41]

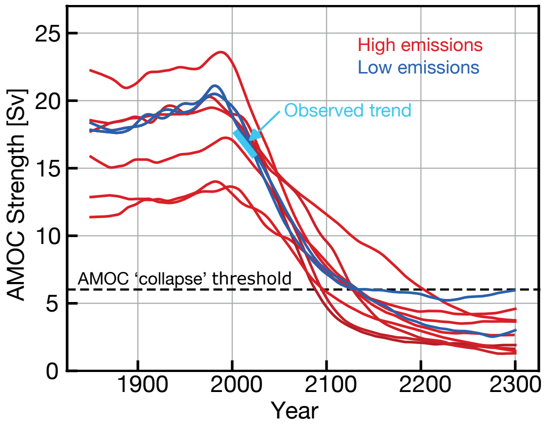
As the ocean warms and more temperate marine species in both hemispheres struggle to survive, they migrate poleward tracking their thermal niche. This poleward migration increases competition for food resources in areas, where polar endemic species essentially become trapped with nowhere else to migrate.[42,43] 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. Ocean pollution adds further stress to these environments.[44] Such combined stressors threaten subsistence and commercial fisheries, putting regional economies, Indigenous cultures, and global seafood supplies at risk.[24,30,45]

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.[46] As krill also play a critical role in carbon sequestration, a decline in populations not only threatens ecosystems and fisheries, but also a substantial, long-lived carbon sink in the Southern Ocean.[47] 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.[46]

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.[48,49]

One of the most far-reaching climatic consequences of polar ocean freshening is the weakening of the Atlantic Meridional Overturning Circulation (AMOC). A strong AMOC relies on dense, salty water sinking in the sub-polar North Atlantic, from where it travels south deep in the ocean and is replaced by warm water from

FIGURE 3-5. **AMOC Projections Through 2300**



AMOC strength under different emissions pathway model runs in which shutdown occurs ("shutdown" defined as flow at or below 6 Sverdrups (Sv), a measure of current strength; today's flow is around 16 Sv). Shutdown occurs by 2300 in about 70% of model runs for high emissions pathways, but for only around 25% of the low emissions model runs. The short cyan line shows the observed trend from 2005–2023.

AMENDED FROM DRIJFHOUT ET AL. (2025)

Weakening of the Antarctic Circumpolar Current would reverberate through global ocean systems for centuries.

FEATURED UPDATE

Risk of AMOC Shutdown Seems Increasingly High

A study analyzing long-term climate projections beyond the end of this century now suggests that the AMOC could enter an extremely weak state after 2100, even under intermediate or low emissions.[5] In this AMOC state, heat release to the atmosphere north of 45°N drops to less than 20% of present levels in some models, causing strong cooling in the North Atlantic and Northwest Europe.[6] Observational data show downward trends in mixing of ocean water layers over the past 5–10 years, which is consistent with model projections, though may also reflect natural variability. These findings underscore the importance of monitoring the AMOC and North Atlantic ocean circulation systems to anticipate potentially severe cooling and other regional climate impacts.

FEATURED UPDATE

Continued High Emissions Could Drastically Alter Vital Antarctic Ocean Circulation

Researchers forecast a 20% weakening of the Antarctic Circumpolar Current (ACC) already by 2050 if today's high emissions continue.[3] The ACC is crucial for global heat and nutrient transport, for atmospheric carbon uptake, and for connecting ocean basins. Because the ACC is linked to the Atlantic Meridional Overturning Circulation (AMOC), a weakening of this current would reverberate through global ocean current systems for centuries. This trend appears largely driven by Antarctic Ice Sheet melt.[3] Models now also predict a nearly 50% intensification of the Antarctic Slope Current (ASC) along the Antarctic continental shelf from 2025 to 2050 with high emissions.[4] A strengthened ASC could trigger instabilities that allow warm eddies to further erode Antarctic ice shelves, accelerating ice loss and – in a potential feedback mechanism – weakening the ACC even further.

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.[50,51] If triggered, this new state would result in a dramatic cooling of northern Europe over just a few decades[6] – likely too fast for large populations to adapt adequately.[52]

In Antarctica, similar processes are underway. The Antarctic Circumpolar Current (ACC), 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.[3] Meanwhile, the formation of Antarctic Bottom Water (AABW), which helps drive the entire global ocean circulation as well as carbon storage, is decreasing, which will affect global ocean circulation patterns for centuries.[53] Weddell Sea Bottom Water, which makes up nearly half 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.[53,54]

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.[55,56] 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.[57,58] Polar oceans are home to some of the planet's richest fisheries; their destabilization threatens food security, economies and cultures.

At 2°C of warming or above, ocean acidification, warming and freshening will transform polar oceans irreversibly, threatening vital ecosystems and fisheries. 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 humans worldwide.

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CHAPTER 4

Sea Ice

Losses Year-Round at Both Poles, with Far-Ranging Impacts from Food Webs to Ocean Currents

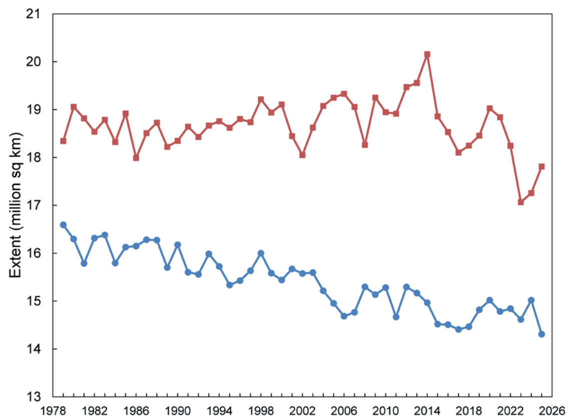
The State and Future of Sea Ice 2025

Polar sea ice is essential for maintaining a livable global climate, with global risks from its decline ranging from disruption of weather and ocean currents; to accelerated Greenland and Antarctic melt and associated sea-level rise; to extinction of ice-dependent species at the base of the food chain for humans and many polar and marine mammals. Sea ice coverage at both poles has declined by 40–60% since satellite measurements began in 1979, with nearly all Antarctic sea ice decline occurring precipitously since 2016. While most attention is given to the September sea ice minimum in the Arctic, this loss has occurred year-round, in all months of the year including sea ice maximums, when the ice reaches its largest extent. A record-low maximum occurred in the Arctic in March 2025, and Antarctica's record-low maximum was set in September 2023. Global sea-ice coverage, combining both poles, reached a record all-time low in February 2025.

Sea ice has declined not only in extent, but in thickness. Much of the Arctic Ocean used to be covered in thick, multi-year ice that was 4–7 years old. Such "old" ice has virtually disappeared, with even two or three-year-old ice comprising under 10% of today's sea-ice coverage. Antarctic sea ice plays an essential role in several ways, including formation of Antarctic Bottom Water: the densest water mass on the planet, driving the entire global ocean "conveyor belt." 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.

Future sea ice survival is extremely sensitive to current and future human emissions of greenhouse gases. If governments course-correct to 2025 NDCs consistent with 1.5°C of warming or below at 2100, sea ice may slowly begin to recover in the 2070s and beyond. At least one ice-free Arctic summer event seems increasingly likely however before 2050, and the summer ice-free period would increase with additional warming. NDCs that result in global mean temperatures of 2°C or above would lead to ice-free conditions in the Arctic every summer, with high-risk and unpredictable global impacts. Loss of Antarctic sea ice and associated ice shelves is less certain, but holds even greater long-term and non-reversible risks because the sea ice and ice shelves are essential to protecting Antarctica's ice sheet, and holding sea-level rise to adaptable levels in coming decades and centuries.

FIGURE 4-1. **Maximum Sea Ice Extent in the Arctic and Antarctica, 1979–2025**



Arctic and Antarctic sea ice extent has been at record lows for many months out of the year, showing declines year-round. A new record was set for the Arctic sea ice "maximum" (when the sea ice reaches maximum growth) in March 2025 (blue line); and for Antarctica in September 2023 (red line). In February 2025, the extent of sea ice globally (combining both poles) reached a new record low.

CREDIT: WALT MEIER, BASED ON DATA FROM THE NATIONAL SNOW AND ICE DATA CENTER (NSIDC), U.S.

Background

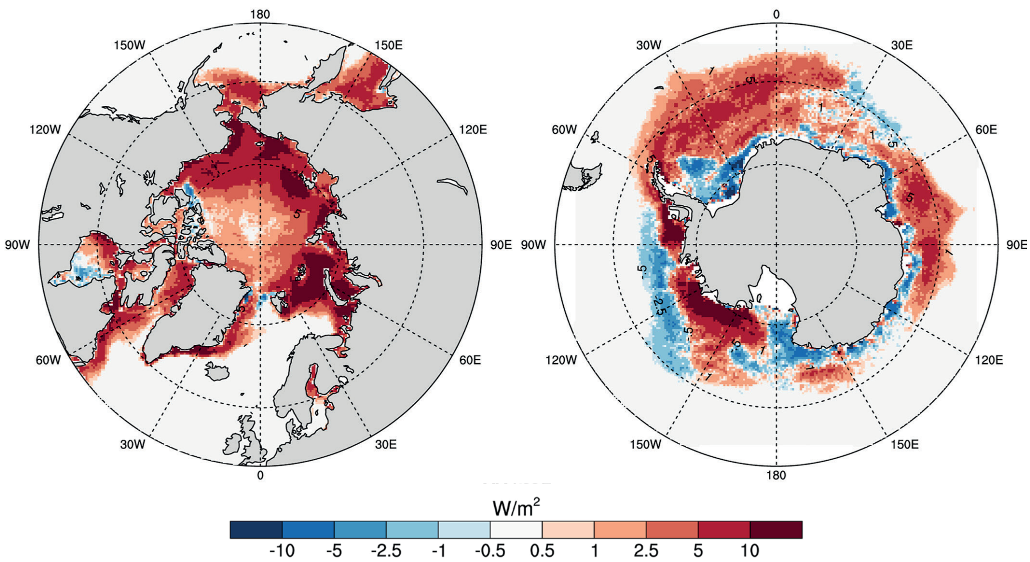
ARCTIC SEA ICE

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 – 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.[12,13] Now the Arctic Ocean is dominated by a thinner covering of seasonal ice,[14,15,16,17] which cannot recover in the winter[18] and is prone to being carried towards the warmer Atlantic waters, which further accelerate melt.[15] 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. Consequently, the loss of sea ice has reduced this cooling effect by around 20% in this time.[19]

Rapid loss of sea ice is one of the leading causes of "Arctic amplification," which refers to the greater rise in temperature observed in the high latitudes of the Northern Hemisphere compared with the rest of the globe.[14,20,21] 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.[14,22] 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.[23] A reduction in sea ice is projected to influence mid-latitude weather systems, as exemplified by the persistent cold snaps, heatdomes, prolonged precipitation and drought in recent years stemming from abnormally large north-south undulations in the jet stream.[24,25,26,27,28,29,30,31,32,33,34,38]

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.[35,36,37,38,25] Such profound adverse impacts almost certainly will eclipse any temporary economic benefits brought by an ice-free summer Arctic.

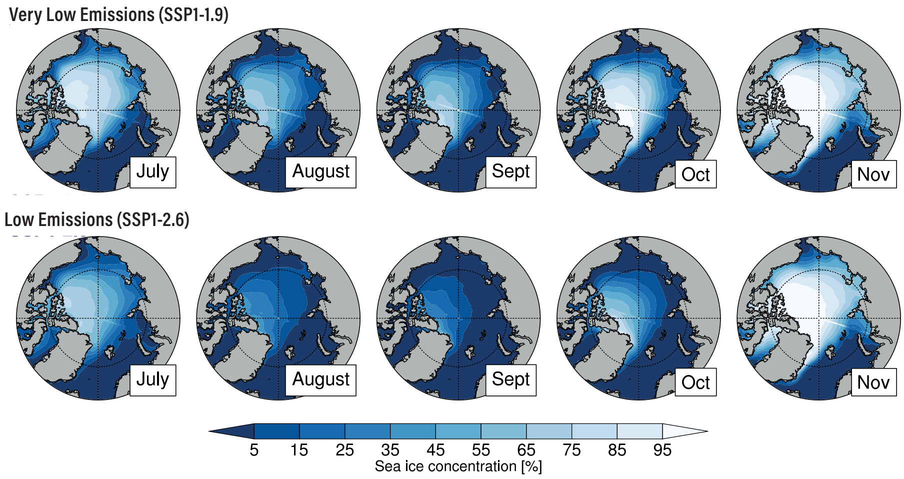
FIGURE 4-2. **Loss of Sea Ice Albedo (Reflectivity) from Warming To-date**



This 2024 study demonstrated that the decline in sea ice caused by CO_2 emissions even today has decreased the reflective ability of both Arctic and Antarctic sea ice, with greater radiative forcing (warming) at both poles as a result of the sun's rays being absorbed by more open water.

SOURCE: DUSPAYEV ET AL, 2024

FIGURE 4-3. **1.5°C-Consistent Emissions Pathways Can Lead to Sea Ice Recovery**



With a 1.5°C-consistent (very low) emissions pathway, global mean temperature has declined to between 1.2–1.4°C by 2100 due to extensive carbon drawdown (in contrast to common perception, global temperatures would begin to fall relatively quickly as CO_2 concentrations in the atmosphere decline); and some level of summer sea ice coverage has returned (top). In contrast, even a "low" emissions pathway, peaking at 1.8°C and remaining above the 1.5°C mark in 2100 (bottom), would see very little summer sea ice return.

SOURCE: MODIFIED BY ALEXANDRA JAHN, FROM JAHN ET AL (2024)

The occurrence of the first sea-ice-free Arctic summer (defined as less than 15% of the Arctic Ocean's area or 1 million km^2 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.[13,39,40,41,42] 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.[43] 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.[44,45,46,47]

The last time the Arctic had an ice-free summer may have been during the Eemian period 125,000 years ago.[48] 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.[49,50] 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.[51]

FEATURED UPDATE

How the First Ice-free Arctic Ocean Event Could Occur Before 2030

The Arctic Ocean is expected to experience at least occasional "ice free" summer conditions within the next 25 years, even with low emissions pathways. However, some model runs show this potentially occurring before 2030, with conditions that include strong Arctic atmospheric warming in winter and spring, combined with storms passing across the Arctic in the days leading to the first ice-free period. The highest probability of the first ice-free occurrence, however, lies within a 7-to-20-year time frame. Holding emissions close to pathways consistent with the Paris 1.5°C limit could minimize the occurrence of such ice-free periods, since all model runs leading to an ice-free Arctic Ocean showed a five-year temperature average above 1.5°C. Although the first singular ice-free day (defined as less than 1 million km^2 of sea ice) will largely be symbolic, it will signal a transition to an Arctic where seasonal ice loss becomes increasingly likely and consequential.[1]

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,[52] 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.

ANTARCTIC SEA ICE

Although the 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.[53] This sharp decline was underscored in 2022 when the summer minimum sea-ice extent dropped below 2 million km^2,[54] for the first time, reaching a record-breaking minimum extent of 1.79 million km^2 in 2023. Failing to recover during the southern winter of 2023, 2.77 million km^2 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 km^2 below the previous record low. This trend may be a new "normal" era of decline driven by ocean warming caused by anthropogenic fossil fuel emissions[55,56] for Antarctic sea ice: the last four 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, where it is stored

2025 Updates

- In March 2025, Arctic sea ice reached 4.33 million km^2 – the lowest-ever maximum extent in the 47 years of satellite data. The five lowest maxima have all occurred since 2015.[3]
- Sea ice loss in the Arctic can lead to shifts in weather patterns around the world, such as winters that are wetter in the Mediterranean and drier in the southwestern United States.[4]
- The rapid decline in Arctic sea ice is driving stronger and more frequent marine heatwaves, and will continue to do so. Consequences include further loss in sea ice, redistribution of key animals such as fish, and disruption to nutrients and algae that form the base of one of the planet's most prolific food chains.[5]
- In areas with already thinning sea ice, Arctic cyclones can accelerate ice break up and loss over very short time frames through upper ocean mixing and wave action. Arctic cyclones are not resolved in most models, which means the impact they have on sea ice is not well captured.[6]
- Antarctic sea ice has undergone a regime change in sea-ice patterns over the past decade. Extreme low-ice conditions are becoming the norm in an area previously dominated by long-term stability. This shift impacts the reliability of climate models and affects marine ecosystems and coastal communities worldwide.[7]
- Massive disruptions in krill and phytoplankton populations appear to have occurred in the Southern Ocean due to the rapid decline of Antarctic sea ice since 2016. This shift could decrease the dominance of the krill-centric food web, with severe impacts on Southern Ocean species. It could also lessen the biological transport of carbon into the deep ocean, with implications for the global ocean carbon sink, in which the Southern Ocean currently absorbs more carbon than any other ocean region.[8]
- A newly identified feedback loop is melting Antarctic sea ice from below. Satellite observations now indicate increased surface salinity over the past decade in the Southern Ocean, which makes sea ice harder to form and may redistribute ocean heat from depth to the surface, where it can directly and negatively impact sea ice.[9]
- Antarctic Emperor penguin populations are declining at twice the predicted rate, shrinking by 22% between 2009 and 2023. The loss of sea ice has reduced their habitat, ability to find food and breed.[10] Penguins have recently been identified as an important influence on the climate through cloud-producing guano particles, emphasizing the critical interconnection between ecosystems and climate.[11]

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 in the last three decades.[57]

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 reductions 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.[58]

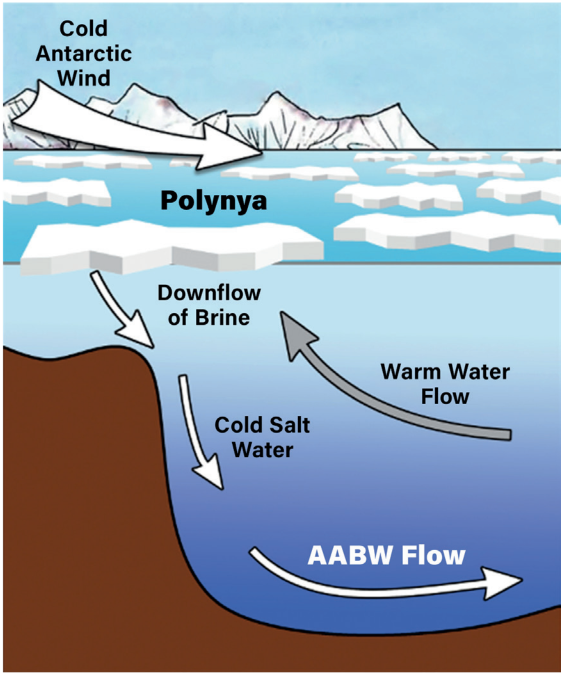
For decades, Antarctic sea ice seemed almost immune to global warming, showing an overall average change of 1–2% while Arctic sea ice declined precipitously by 40–60% during the same period. This apparent immunity has entirely dissipated in the last decade. Given the long-term impacts of this loss on 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.

FEATURED UPDATE

Antarctic Sea Ice May Hold Back Extreme Sea-level rise

The sea ice around Antarctica may be preventing more extreme glacier calving – and related sea-level rise – by protecting ice shelves, blocking ocean waves and shielding the ocean from heat input and mixing by wind. With less sea ice to protect them, ice shelves are more vulnerable to the impacts of ocean swells, which decay their edges. Such ocean erosion may have a greater impact on ice-shelf loss than the warming temperatures currently leading to direct melting. Nevertheless, the direct connection between ice-shelf disintegration and sea-ice loss is not included in most models used to analyze future ice sheet loss, and Antarctic sea ice has demonstrably declined in extent over the past decade. For this and other reasons, huge risks and uncertainties exist in future sea-level rise predictions on which coastal communities and economies depend.[2]

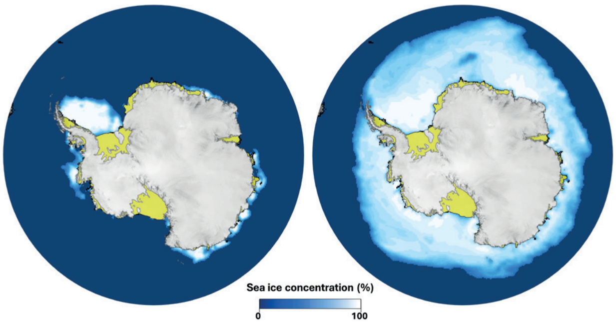
FIGURE 4-4. **Antarctic Bottom Water (AABW)**



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.

FIGURE 4-5. **Sea Ice and Antarctica's Ice Shelves**



Ice shelves (yellow in these maps) ring almost the entire Antarctic continent, and are stabilized by sea ice which expands greatly into the Southern Ocean during the Antarctic winter. The ice shelves in turn help slow ice sheet loss and related sea-level rise. Antarctic sea ice began steep losses in 2016, leaving more ice shelves exposed in summer to open ocean, making them more vulnerable to collapse; which could lead to more rapid ice sheet melt and sea-level rise. Left: Antarctic summer sea ice minimum; Right: Antarctic winter sea ice maximum; in 2017.

CREDIT: JAMES KIRKHAM AFTER NSIDC DATA

In February 2025, the extent of sea ice globally reached a new record low.

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CHAPTER 5

Permafrost

New Evidence of Net Carbon Dioxide and Methane Emissions from Arctic Permafrost, Even in Winter

The State and Future of Permafrost 2025

More than 210,000 km² of frozen permafrost land area has thawed each decade on average since current warming began a century ago, accelerating since the 1990's with every fraction of a degree of warming.[1] This thaw destabilizes infrastructure in Arctic and mountain regions, with global economic impacts from building and road damage projected to exceed $276 billion by mid-century under high emissions.[2] Permafrost thaw also decreases the global carbon budget. Already today, permafrost thaw releases annual carbon emissions equal to those of a top 10 greenhouse gas emitter such as Japan (about 0.3–0.6Gt CO_2-equivalent per year). Emissions will continue at this scale for one to two centuries even with no additional warming; and cannot be halted once initiated, making carbon neutrality more difficult to achieve if temperatures continue to rise.

Permafrost emissions over coming decades and centuries depend on how much carbon countries release into the atmosphere: lower human emissions mean lower permafrost emissions. Growing wildfires and extreme heatwaves leading to abrupt thaw events may increase permafrost emissions even further. NDCs consistent with 1.5°C would lead to annual permafrost emissions around the same level as carbon emissions from India today (about 2.5Gt) for the rest of this century. NDCs causing overshoot to 2°C would increase annual permafrost emissions to the same scale as current emissions from the 38 countries of the OECD Europe (about 3–4Gt). In this scenario, permafrost soils would disappear in extensive regions above the Arctic Circle as well as below, and nearly all existing infrastructure built on permafrost would require stabilization or replacement. NDCs resulting in 3–4°C would lead to annual permafrost emissions similar to the United States or China's annual emissions today (about 5Gt or more) for one to two centuries, burdening the next several generations struggling to keep atmospheric CO_2 concentrations at manageable levels.

2025 Updates

- Record-warm conditions in permafrost lands have become increasingly common, with the 2023–2024 winter (September–April) documented as the warmest on record for the Arctic region. For the first time, near real-time data was available to document carbon dioxide and methane emissions from 19 tower sites across the Arctic even during this winter period (nearly all measurements have occurred in summer). The new measurements revealed record net carbon dioxide and methane emissions occurring in winter, coinciding with warm conditions. Despite increasing recognition of the importance of winter permafrost emissions, their measurement remains a challenge.[4,5]
- An interdisciplinary risk assessment of Arctic coastal threats consolidated data on erosion, sea-level rise, and permafrost thaw to find that nearly half of all coastal settlements will be impacted by sea-level rise and one fourth by erosion by 2100, with three-fourths of present-day coastal infrastructure resting on permafrost at risk of thawing.[6]
- In fact, the overlapping impacts of sea-level rise, permafrost thaw, sea ice loss, and storm-prone seas will likely lead to eight times more land lost along northern Alaskan coastlines this century compared to the impact of coastal erosion alone. Without strong adaptation measures, these losses could damage 40–65% of present-day coastal infrastructure in this region by 2100.[7]

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Background

Permafrost is ground that remains frozen for at least two years. It consists of a mixture of soil, rocks, sand, and organic matter bound together by 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.[3] 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 three times more 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.[11,12]

Permafrost can be found on land as well as in lakes and near-coastal seabeds. It is widespread across the Arctic – including Alaska, Canada and Siberia – and high mountain regions, especially the Tibetan Plateau, underlying 22% of land area in the Northern Hemisphere.[13,14] 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.

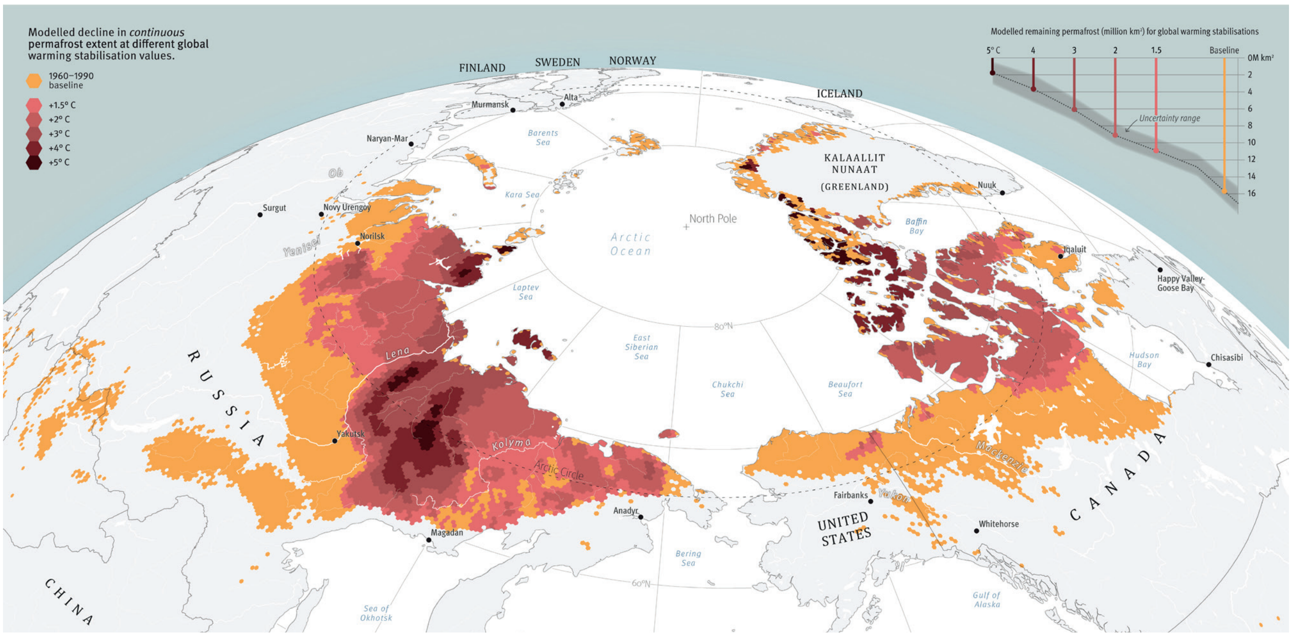
Arctic and high mountain regions are warming at 2–4 times the global average, making permafrost highly

2025 UPDATES (CONTINUED)

- Permafrost-related damage to Alaskan buildings and roads could cost $37 billion by mid-century under moderate emissions and $51 billion under very high emissions; these latest cost estimates are two times higher than previously predicted.[8]
- High emissions will also generate more intense heat waves in Arctic permafrost regions by mid-century, increasing the likelihood of abrupt thaw events which expose much deeper layers of permafrost to thaw. Low and moderate emissions would prevent this distinct mid-century spike in heatwave growth and potentially enable a downturn in intensity if global temperatures remain low enough.[9]
- Multiple permafrost areas in European mountains including the Alps, Scandinavia, Iceland, the Sierra Nevada of Spain, and Svalbard are now warming by more than 1°C per decade, matching rates commonly found in Arctic lowlands.[10]

There is no "safety margin" for acceptable permafrost thaw.

FIGURE 5-1. **Loss of Permafrost Extent Increases at Higher Temperatures**



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/16284 vulnerable to rising temperatures.[15] Once it begins to thaw, microbes begin decomposing previously frozen organic matter, releasing carbon into the atmosphere. These microbial processes can continue emitting for centuries after initial thaw.[16] 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.[17] Rebuilding new permafrost and soil carbon pools takes hundreds to thousands of years.[18]

Today at 1.2°C of warming above pre-industrial, annual permafrost emissions are already about the same as Japan's, currently one of the top 10 greenhouse gas emitters.[19] 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 to 1.5°C, annual permafrost emissions this century will be about as large as those from India today (2.5Gt per year), totaling around 150Gt CO_2-equivalent (CO_2-eq) by 2100.
- At 2°C, annual permafrost emissions will about equal those of OECD Europe (3–4Gt per year), resulting in an additional 200Gt CO_2-eq by 2100.
- Exceeding 3–4°C will most likely add the equivalent of another United States or China (currently 5–10Gt per year) to the global carbon budget, resulting in up to 400Gt CO_2-eq by 2100.[20,21,22]

FIGURE 5-2. **Permafrost Emissions Today at 1.2°C**

Committed annual permafrost emissions through 2100 will be about the scale of Japan's annual emissions today, about 0.3–0.6Gt/year, even with no further rise in temperature.

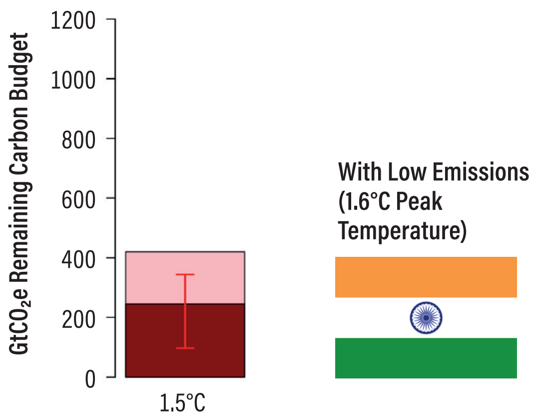
DATA SOURCES: IPCC SR15, GASSER ET AL. (2018), TURETSKY ET AL. (2019)

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. Permafrost thaw, wildfires, and wetland emissions have increasingly offset its natural ability to sequester carbon through plant growth,[3] and it is now releasing more carbon into the atmosphere than it absorbs.[23,24] This net warming will raise global temperatures for decades in a feedback loop that deepens permafrost thaw during the summer, progressively overwhelming its ability to naturally balance emissions with carbon sequestration.[25]

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

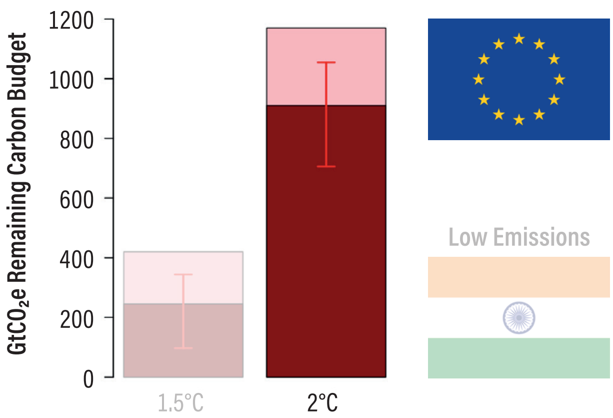
FIGURE 5-3. **Permafrost Emissions Decrease Our Carbon Budget at 1.5°C...**



Committed annual permafrost emissions to 2100 on scale of India's annual emissions today, about 2.5Gt/year, total ≈150–200GtCO_2e

DATA SOURCES: IPCC SR15, GASSER ET AL. (2018), TURETSKY ET AL. (2019)

FIGURE 5-4. **...But Reduce/Restrict It Much More at 2°C**



Committed annual permafrost emissions to 2100 on scale of the EU's annual emissions today, about 3–4Gt/year, total ≈220–300GtCO_2e

DATA SOURCES: IPCC SR15, GASSER ET AL. (2018), TURETSKY ET AL. (2019)

Abrupt permafrost thaw on the Peel Plateau in Canada. Thawing of ice-rich permafrost can cause abrupt ground collapse, which can further accelerate thaw and increase permafrost carbon emissions. For scale, the lake length parallel to the headwall of the thaw feature is 150m. CREDIT: SCOTT ZOLKOS

peatlands will no longer be able to sustain permafrost by the 2060s.[26] Already at today's temperatures, climate conditions in Norway, Sweden, Finland, and parts of Russia might no longer be able to support peatland permafrost.[26]

Subsea permafrost below the Arctic Ocean is rapidly thawing and releasing methane, particularly along the coast of Eastern Siberia.[27] Continued high emissions will likely trigger rapid and irreversible decline in subsea permafrost along Arctic coastlines by 2080, with all coastal permafrost thinner than 100 meters disappearing by 2300.[28] Only low emissions will allow large areas of subsea permafrost to remain frozen for the next thousand years.[28]

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.[29] Permafrost thaw creates unstable ground prone to flooding, threatens cultural and subsistence resources, and damages infrastructure such as roads, pipelines, and houses.[30] In Alaska, for example, experts estimate that permafrost thaw will increase cumulative maintenance costs of public infrastructure by $5.5 billion USD by 2100.[31] Permafrost thaw has contributed to thousands of kilometers of coastal erosion across the Arctic, requiring entire communities to relocate.[32]

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 2100.[33] Even under moderate emissions, nearly two-thirds of the permafrost area in the Tibetan Plateau could become a "high-hazard" zone this century.[34]

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.[35,36] 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.[37]

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.[38] 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.[39] Aligning 2025 NDCs with 1.5°C would greatly decrease the scale of permafrost emissions in coming centuries, and minimize the long-term burden laid on future generations.

FEATURED UPDATE

Permafrost Lands Confirmed as a New Net Source of Carbon Emissions

At least one third of the Arctic's land ecosystems are now confirmed as a net source of greenhouse gas emissions in the form of both carbon dioxide and methane. Permafrost across Arctic tundra, boreal forests, and wetland regions stores vast quantities of carbon, and a new study confirms that large regions of Canada, Alaska, Russia and Scandinavia now release more carbon into the atmosphere than they absorb. Rising temperatures worsen wildfires and trigger deeper permafrost thaw, emitting large amounts of carbon. Natural carbon sequestration through Arctic vegetation has been thought to balance the release of thawed permafrost carbon each year, but this study raises a warning flag that current levels of warming have now pushed these cycles from carbon sinks into sources.[3]

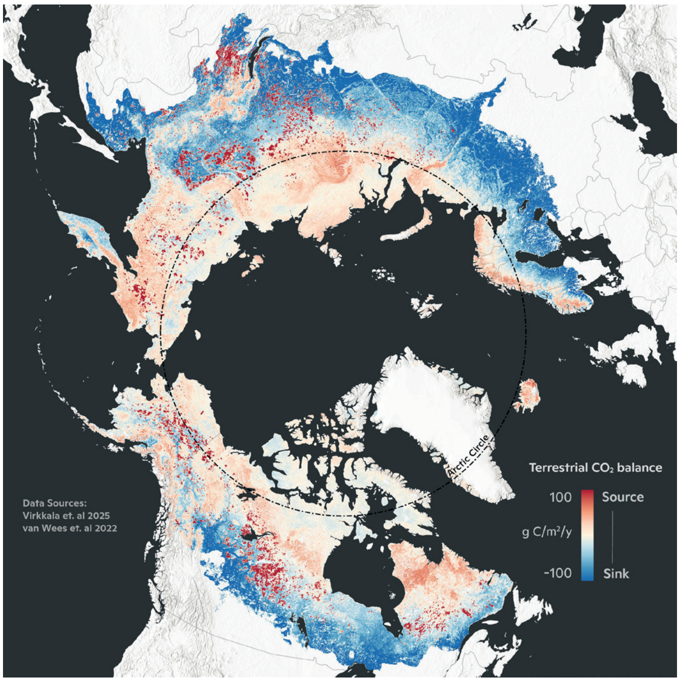


FIGURE 5-5. **Map of carbon sinks (blue) and sources (red) in Arctic land ecosystems from 2001–2020. These findings confirmed that as a whole, Arctic permafrost regions are now contributing more carbon emissions to the atmosphere from thawed permafrost soils than plants in these regions take up during the growing season.**

CREDIT: GREG FISKE / WOODWELL CLIMATE RESEARCH CENTER

Permafrost thaw contributes to rapid erosion and land destabilization beneath critical community infrastructure in the Alaska Native Village of Cev'aq (Chevak). A massive storm devastated some communities standing on coastal permafrost in southwest Alaska in October 2025.

CREDIT: SUE NATALI / WOODWELL CLIMATE RESEARCH CENTER

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