State of the Cryosphere 2024

Lost Ice, Global Damage

We cannot negotiate with the melting point of ice.

NOVEMBER 2024

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Cover Photo: Ngozumpa Glacier, Nepal: the longest glacier in the Himalayas, which today is debris covered, with many ice cliffs and lakes, as a result of rapid warming and melting. Photo taken in November 2017. (Credit: James Kirkham, ICCI and Chief Science Advisor, AMI)

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Summary

Global Damages from Cryosphere Melt with Three Different Emissions Choices

Below is a summary of global ecosystem, social and economic impacts from melting cryosphere, as detailed in the Report chapters, based on temperatures and CO_2 levels that will result from our choices today:

- With current climate commitments (Nationally Determined Contributions, or NDCs), which will result in clear overshoot of the higher Paris Agreement 2°C limit.
- If humanity continues **with today's high carbon emissions levels** for the rest of this century, given current lack of fulfillment of even current, inadequate NDCs.
- With **immediate and rapid course correction, back to the lower 1.5°C Paris Agreement limit**, in the next round of NDCs to be presented in 2025.

Current NDCs

2.3°C by 2100, peak CO_2 about 500 ppm

Current NDCs are not sufficient to prevent significant overshoot of 1.5°C, with many governments delaying meaningful mitigation to 2040, 2050, or beyond. While perceived short-term as economically advantageous, for example lowering energy costs today, a slower transition from fossil fuels locks in widespread future loss and damage from the cryosphere for decades and centuries, with adaptation needs far higher and more expensive where still technically feasible.

ICE SHEETS AND SEA-LEVEL RISE: A compelling number of new studies, taking into account ice dynamics, paleo-climate records from Earth's past and recent observations of ice sheet behavior point to thresholds for both Greenland and parts of Antarctica well below 2.2°C. Many ice sheet scientists now believe that exceeding even 1.5°C will be sufficient to melt large parts of Greenland and West Antarctica, and potentially vulnerable portions of East Antarctica; generating inexorable sea-level rise that exceeds 10 meters in the coming centuries, even if air temperatures are later decreased. The pace of this long-term, unstoppable sea-level rise will pose major long-term persistent challenges for all coastal regions; and result in widespread loss and damage of critical infrastructure (about 75% of all cities with >5 million inhabitants exist below 10 meters' elevation), agricultural land, and the livelihoods of all those who depend upon these at-risk regions.

MOUNTAIN GLACIERS AND SNOWPACK: Even 2°C would lead to escalating loss and damage throughout this entire century, well beyond limits of adaptation for many mountain and downstream communities. Nearly all tropical and mid-latitude glaciers would cross thresholds causing their eventual complete loss, with critically important High Mountain Asian glaciers losing around 50% of their ice. Catastrophic hazard events seen already today, such as glacial lake outburst floods and landslides, will increase in frequency and scale. Risks are especially high in Asia, where outburst floods can wash away infrastructure and cities within hours with little warning. Severe and potentially permanent changes to the water cycle, due to loss of snowpack and ice run-off during the warm summer growing season, will impact food, energy and water security.

POLAR OCEANS: Current NDCs, delaying sufficient mitigation of emissions, will lead to CO_2 levels in the atmosphere near 500 ppm, well above the critical 450 ppm level identified decades ago by polar marine scientists. Extreme environmental pressures will affect marine shell-building animals and valuable species in the food chain, such as krill, cod, salmon, lobsters, and king crab. Stress to these polar ecosystems will lead to loss and damage in both commercial and subsistence polar fisheries. These corrosive ocean conditions set by peak atmospheric CO_2 levels are essentially irreversible, lasting tens of thousands of years. Additional losses will come from marine heat waves, with warmer waters and lack of protective sea ice for several months each summer. There is no known way for vulnerable polar marine species to adapt to such changes in time. Disturbances of ocean currents due to incursion of freshwater from both ice sheets appear increasingly likely without urgent improvement of current NDCs.

PERMAFROST: Thaw emissions at this temperature level will increase burdens of mitigation, adaptation, and loss and damage not just locally due to infrastructure damage, but across the planet by decreasing the remaining carbon budget. This is because once thawed, permafrost begins emitting carbon dioxide (CO_2) and methane (CH_4). These emissions are irreversibly set in motion and will not cease for one to two centuries, meaning that future generations must offset them (draw down carbon) at scales the size of major greenhouse gas emitting nations. If current NDCs are not greatly improved, annual total permafrost emissions (as both CO_2 and CH_4) may total the size of the entire European Union's emissions (calculated from 2019 as ≈200 Gt total by 2100) and about twice that by 2300. Since the Arctic is warming 2–4 times faster than the rest of the planet, northern high-latitude permafrost regions will reach 4–8°C on average, with more extreme heat events that can lead to "abrupt thaw" processes where coastlines or hillsides collapse, or lakes form. This exposes much deeper and greater amounts of permafrost to thaw, which means emissions might be greater than projected.

SEA ICE: Global feedbacks from sea ice loss at both poles would increase adaptation and loss-and-damage burdens around the planet. Every year, the Arctic Ocean would be practically sea ice-free for up to four months (July-October). The less reflective open water would absorb more heat from polar 24-hour sunlight conditions. This warmer Arctic will increase coastal permafrost thaw, adding more carbon to the atmosphere and increasing coastal erosion; speed Greenland Ice Sheet melt and resulting sea-level rise; and have unpredictable and potentially extreme impacts on mid-latitude weather patterns. Around Antarctica, near-complete loss of sea ice every summer seems plausible at 2.3°C given current trends at today's 1.2°C. Loss of buttressing sea ice would speed ice shelf collapse, thereby increasing melt from the Antarctic Ice Sheet and resulting sea-level rise. Warmer waters also mean that any recovery of sea ice may take many decades, especially around Antarctica, even with a subsequent return to lower atmospheric temperatures, because the ocean will hold that heat far longer. While some economic analysts see Arctic sea ice loss as a positive due to greater regional economic potential, the extreme levels of loss and damage and increased adaptation needs would almost certainly greatly eclipse any temporary economic gains, even by Arctic nations themselves.

Credit: U.S. Air Force photo by Master Sgt. Mark C. Olsen/Released/Alamy

Flooding in lower Manhattan from Hurricane Sandy, 2012. A 2021 study found that $8.1 billion of Sandy's damage came from sea-level rise caused by anthropogenic global warming.

Current Rise in CO_2 Levels Continues

3–3.5°C and CO_2 about 650 ppm by 2100

If atmospheric CO_2 continues to increase at today's pace, which has not paused despite current mitigation pledges, global temperatures will reach at least 3°C by the end of this century. Loss and damage from cryosphere at this level will be extreme, well beyond limits of adaptation for many communities and nations.

ICE SHEETS AND SEA-LEVEL RISE: Once 3°C is passed, ice loss from Greenland and especially from West Antarctica becomes extremely rapid. Together with extensive ice loss from parts of East Antarctica, the IPCC could not rule out that three meters might be passed early in the 2100s; with five meters passed by 2200 and up to 15 m of sea-level rise possible by 2300. While seemingly in the far future, this massive scale of coastal destruction will have been made inevitable by decisions made in the next few decades, causing temperatures to pass these critical thresholds.

GLACIERS AND SNOWPACK: Catastrophic and cascading impacts from glacier and snow loss are associated with these levels of rapid warming, with some vulnerable mountain and downstream communities experiencing non-survivable conditions already by mid-century due to loss of seasonal water availability, or destructive floods from which they are unable to recover. Over time, even many of the largest glaciers in High Mountain Asia and Alaska are unlikely to survive. Snowpack will become unreliable, with rain falling at higher elevations and more frequently throughout the year when snow would otherwise be expected. Currently fertile agricultural regions such as the Tarim and Colorado River basins may no longer be able to support significant agricultural activities. Losses in mountain biodiversity stemming from cryosphere warming will be extreme across many high-elevation ecosystems.

POLAR OCEANS: If CO_2 continues to accumulate in the atmosphere at today's pace, CO_2 levels will reach at least 600 ppm by the end of this century, with global mean temperature exceeding 3°C and continuing to increase thereafter. Damaging levels of acidification will occur throughout the Arctic and Southern Oceans. At these CO_2 levels, some near-polar seas, especially the Barents, North and Baltic Seas, also would see critical acidification levels rivaling that of the poles. Corrosive conditions will persist for tens of thousands of years (30,000–70,000 years to return to today's pH levels). This will almost certainly result in mass extinctions of polar species, especially when combined with ocean warming and the longevity of heat held within the ocean. Extreme warming from high CO_2 levels will also have severe consequences for today's system of global ocean currents, with highly unpredictable disturbance of Atlantic and Antarctic circulation systems. Loss and damage to ecosystems and human communities will be extreme, and irreversible.

PERMAFROST: If today's rapid warming and permafrost thaw continue, mitigation to maintain net zero emissions from both the "Country of Permafrost" and human activities will become virtually impossible, with permafrost quickly eating up much of the remaining carbon budget to remain within 1.5°C. At such high temperatures, much of Arctic permafrost and nearly all mountain permafrost will thaw, producing annual carbon emissions by the end of this century that are on par with China's annual emissions today, greatly accelerating global heating. Loss and damage from increased emissions globally, as well as pan-Arctic infrastructure damage and catastrophic events such as hillside collapse, will increase, with more economic burden on permafrost communities, moving many well beyond adaptation limits.

SEA ICE: If CO_2 concentrations continue to grow in the atmosphere at today's pace, which has not decreased despite current pledges, global temperatures will reach at least 3°C by the end of this century. At such high temperatures, the Arctic Ocean will be ice-free for nearly 180 days each year, leading to enhanced Arctic warming, increased permafrost degradation, increased Greenland Ice Sheet melt and weather extremes. Though less certain, Antarctic sea ice declines may rival that in the Arctic. Ultimate loss and damage locally and globally will be extreme, well beyond limits of adaptation.

1.5°C Consistent Pathways

PEAK CO_2 ABOUT 430 PPM

Only this pathway can slow cryosphere losses to rates that enable feasible adaptation for many coastal and mountain communities especially, greatly minimizing loss and damage.

ICE SHEETS AND SEA-LEVEL RISE: Rate of sea-level rise would stabilize by 2100 because temperatures, while peaking at 1.6°C, have by then declined to around 1.4°C. This requires urgent action, however, with emergency-scale tightening of mitigation commitments and fossil fuel emissions declining 40% by 2030. Unfortunately, the latest science shows that even 1.5°C may not be sufficient to protect both ice sheets, with a best-case scenario that sea-level rise would slow, but continue. Should the planet remain at 1.5°C for too long (decades to centuries), substantial sea-level rise from Greenland, West Antarctica and possibly even East Antarctica may become locked in for several millennia. This has happened in the geological past when the planet reached +1.5°C due to slow changes in Earth's orbit, with sea levels 6–9 meters above today.

GLACIERS AND SNOWPACK: This level of mitigation is the only chance to preserve at least some minimum glacier ice (15–35%) in some mid-latitude regions, including Scandinavia, the Alps, and Iceland; and maintaining up to 50% of current ice in the Caucasus, New Zealand and much of the Andes. Losses in High Mountain Asia will be far less at this temperature level, with two-thirds preserved glacier ice. Nearby communities must nevertheless prepare for significant adaptation efforts in coming decades, including continued catastrophic floods, especially with extreme rain-on-snow events. However, for most communities, these changes will not move beyond adaptation limits, and rates of glacier melt would slow by mid-century, and stabilize by 2100. Snowpack would also stabilize, though at higher altitudes than today. Some glaciers might even begin to show signs of very slow re-growth in the 2200s, as one of the first possible visible signs of planetary restoration in net-zero pathways.

POLAR OCEANS: Immediate mitigation measures, resulting in temperatures close to the 1.5°C Paris limit, reliably maintain atmospheric CO_2 well below 450 ppm; the most ambitious measures see CO_2 levels peak at 430 ppm. This will limit corrosive stressing conditions to mostly seasonal damage in smaller sections of the Arctic and Southern Oceans, where shell damage and altered vital processes are already observed today. (We are already close to this 430ppm threshold: CO_2 levels in 2024 twice reached 428ppm at Mauna Loa Observatory.) Losses will still occur: destructive compound events of marine heatwaves and extreme acidification have already caused population crashes at today's 1.2°C; and there is growing evidence of some slowing of major ocean currents. Worse can be expected by 1.5°C. However, very low emissions pathways would see temperatures dropping below 1.4°C by 2100, as CO_2 levels in the atmosphere trend downwards.

PERMAFROST: Remaining below 1.5°C still will produce significant permafrost thaw and related emissions, but keeps them on a much smaller scale since temperatures in the Arctic will "only" average 3–4°C higher than today. This means the additional mitigation needed to offset permafrost emissions will be far less, thereby minimizing loss and damage, as well as decreasing adaptation requirements. Infrastructure damage in the "Country of Permafrost" – Russia, Canada and Alaska, as well as the Tibetan Plateau and other mountain regions – will also be much less if global average temperature remains below 1.5°C compared to impacts that will occur if current NDCs (2.2°C) are not strongly improved. Annual permafrost emissions will still need to be offset by future generations but should be 30% less (about 120–150 Gt by 2100) than would occur with current NDCs.

SEA ICE: Studies consistently indicate that Arctic sea ice will still melt almost completely some summers even at 1.5°C, but not each year and only for a brief period (days to a few weeks) when it does. Reducing the frequency of ice-free conditions will greatly decrease impacts and feedbacks both in the Arctic and throughout the planet, decreasing adaptation burdens, though still with some impacts tipping into loss and damage, especially for Arctic Indigenous and coastal communities. Projections of sea ice loss in the Southern Ocean around Antarctica are considerably less certain, but record-low conditions in 2023–24 indicate that its threshold for complete sea ice loss in summer might be even lower than for the Arctic. "Very low" emissions (SSP1-1.6, which peaks at 1.6°C) may lead to some recovery of sea ice at both poles by 2100, when temperatures begin to decline below 1.4°C.

2024 Key Research Updates

Highlights from some of the key 2024 cryosphere developments and research findings, from the 2024 Updates detailed in the following chapters.

CRYOSPHERE THRESHOLDS AND TIPPING POINTS

Any overshoot of the 1.5°C lower Paris temperature limit is extremely risky due to the cryosphere's response: the longer this 1.5°C threshold is breached, and the higher the peak temperature, the greater the risk of crossing tipping points for both polar ice sheets; many land glaciers; and the Atlantic Meridional Overturning Circulation (AMOC).[1]

Permafrost thaw on the other hand increases with every fraction of warming, with no sudden "tipping point": there is no "safety margin" for acceptable permafrost thaw, and warmer temperatures worsen local damage and global feedbacks.[2]

Polar ocean acidification similarly has no discrete tipping point, but lasts for thousands of years: worsening with each rise in atmospheric CO_2, and causing observed damage to shelled organisms already today.[3]

SEA-LEVEL RISE FROM ICE SHEETS AND GLACIERS

- The rate of global sea-level rise has doubled in the last 30 years. If these trends continue, rates would increase to 6.5mm/year by 2050, approaching limits of feasible adaptation.[4,5]
- A study including 16 leading ice sheet models highlighted the risk of triggering a sharp increase in sea-level rise from Antarctica if today's high emissions continue, with up to 6.9m by 2300. 40% of the models predicted West Antarctic Ice Sheet collapse by 2300 with high emissions.[6]
- A new model implies that some degree of unstoppable ice loss from Thwaites and Smith glaciers is now locked in, crossing a tipping point of long-term sea-level rise from the West Antarctic Ice Sheet, though lower temperatures would slow this rise.[7] Another study showed that staying for too long at even current warming, of 1.2°C, is enough to trigger irreversible future ice loss there.[8]
- The ice shelves that surround Antarctica may be more vulnerable to collapse than thought previously. Such ice shelves help stabilize the ice sheet, and their loss may speed ice sheet melt and resulting sea-level rise.[9–13]
- A tidal pumping mechanism may lead to runaway melting under many areas of the Antarctic Ice Sheet and could potentially double sea-level rise from some Antarctic glaciers.[14,15]
- On average, the Greenland Ice Sheet is currently losing 30 million tons of ice per hour,[16] which would make it the largest single contributor to sea-level rise.
- Sediment cores show that the center of Greenland, now covered by 3km of ice was ice-free at least once within the last million years, despite CO_2 levels never exceeding 320ppm. With levels above 420ppm today, this places Greenland well into the risk zone.[17,18]

SEA ICE LOSS

- Only low emissions consistent with 1.5°C will maintain some remnants of year-round Arctic sea ice. Up to three months of sea ice-free conditions would result with global temperatures at 2°C, with more warming in the Arctic and globally as a result.[19]
- Antarctic sea ice coverage dropped below two million square kilometers for the third summer in a row, with low sea ice cover now observed in all sectors around Antarctica.[20,21]
- The reflectivity and global cooling effect of Arctic sea ice decreased by 17–22% from 1980–88, versus 2016–2023 due to loss of ice cover. Cooling from Antarctic sea ice decreased by 9–14% in this same period.[22]
- At least three of the world's 19 remaining polar bear communities, those around the Hudson Bay of Canada, will go locally extinct due to sea ice loss in the next few decades if today's high emissions continue.[23]
- Declining sea ice extent with continued high emissions will expose Arctic Alaskan coastlines to more intense hazards including floods, storm surge and coastal erosion.[24]

PERMAFROST THAW

- The first comprehensive greenhouse gas emission estimate from permafrost thaw, including carbon dioxide, methane, and nitrous oxide shows that the Arctic-boreal permafrost region is now a net source of greenhouse gas warming.[25] These emissions will increase if temperatures continue to rise.[26]
- Continued high emissions will trigger a rapid and irreversible increase of subsea permafrost thaw along Arctic coastlines by 2080, with all coastal permafrost thinner than 100 meters disappearing by 2300, due in part to increased sea ice loss. Only low emissions will allow large areas of Arctic seafloor permafrost to remain frozen for the next thousand years.[27]

POLAR OCEANS

- CO_2 levels in the atmosphere reached 428ppm several times in 2024,[28] and this year's average concentration is expected to near 424ppm,[29] with irreversible acidification of both polar oceans growing as a result. Acidification of Southern Ocean waters around Antarctica has been growing since the 1990s, affecting waters even within Antarctic Marine Protected Areas.[3,30]
- The important Atlantic Meridional Overturning Circulation (AMOC) may be enroute to collapse due to a combination of ice sheet and sea ice melt and warmer waters. Once at the point of collapse, the AMOC would likely not recover for thousands of years.[31]
- AMOC collapse would have far-reaching and dramatic impacts, including rapid cooling of Northern Europe by more than 3°C per decade, with no realistic means of adaptation.[32-35] As a result of growing evidence of such collapse, a group of 40 leading ocean and climate scientists warned leaders of the urgent need to cut carbon emissions.[36]
- In a similar yet less well-known development, the Antarctic Circumpolar Current (ACC) around Antarctica also seems to be slowing, driven by ice sheet meltwater entering the Southern Ocean, potentially slowing not just the ACC, but global ocean circulation.[37]
- The Southern Ocean may continue warming even after net CO_2 emissions reach zero, due to changes in circulation caused by earlier warming, underscoring the need to curb emissions as soon as possible.[38]
- Warmer air temperatures have caused most Arctic sea ice loss to-date, but ocean warming is progressively becoming the most important factor; and will last longer even once air temperatures decline, likely slowing any sea ice recovery.[39]
- Arctic waters have warmed faster than other ocean regions, and the number and duration of marine heatwaves will increase further with continued high emissions and warming, with damage to Arctic fisheries and ecosystems.[40]

MOUNTAIN GLACIERS AND SNOWPACK

- Record glacial melt globally occurred in 2023.[41] Sweden showed the highest melt levels in 80 years of observations,[42] and 2024 melt is also on a record trajectory in Asia.[43]
- Extremely low snowfall combined with extremely high summer temperatures likely contributed to the high 2024 loss in many of these regions, with record-low snowfall in the Hindu Kush Himalaya, causing growing concern for South Asia water supplies.[43]
- Venezuela lost its final glacier, Humboldt, in 2024, joining Slovenia as the first two countries to lose their glaciers in modern times. Indonesia's Puncak Jaya, ironically also known as the "Eternity Glacier" will likely follow within the next two years, as the last tropical glacier in Asia.
- 5,500 glaciers across the Andes have now lost 25% of their ice cover, and Andes tropical glaciers are melting ten times faster than the global average.[44,45]
- Ten million people are currently at risk of catastrophic flooding hazard events from glacial lake outburst floods, especially in Alaska, High Mountain Asia, and Iceland.[46]
- At least one-third of European Alp glacier ice will be lost by 2050, even without further warming; but if current high emissions continue, two-thirds of glacier ice may be lost by 2050.[47] Their survival after 2050 will be at great risk without 1.5°C-consistent emission reductions.

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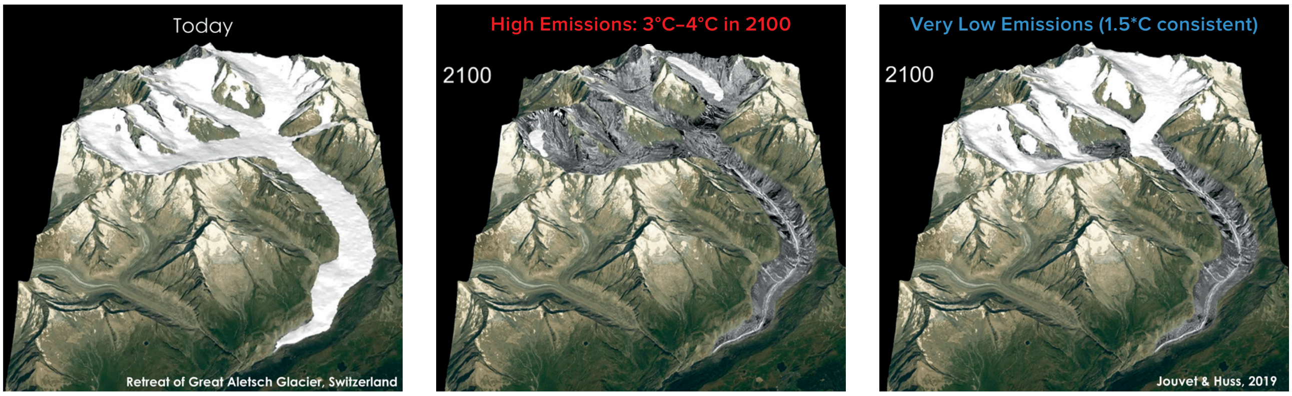


NDC Choices Determine the Future of Great Aletsch Glacier

With so much heat already in the system, a large portion of glacier ice will be lost even with very low emissions; but by 2100, the difference our NDC choices make become clear, with benefits for seasonal downstream water supplies and resilience under 1.5*C-consistent pathways.

COURTESY OF MATTHIAS HUSS

CHAPTER 1

The Cryosphere Can't Wait: Low Emissions Are Critical

Very Low Emissions Can Still Prevent Extreme Loss and Damage, But Window for Action Closing

Summary

HOW TEMPERATURE, CO_2 AND EMISSIONS LEVELS ARE DEFINED IN THE REPORT

Current NDCs – Characterized as 2.3°C by 2100 in the 2024 Report

The latest evaluation of temperature rise by 2100 by the Climate Action Tracker consortium (CAT[1]) ranged from 2.7°C (2.2–3.4°C) for currently implemented policies and measures, to 2.5°C (2.0–3.5°C) based on 2030 Nationally Determined Contributions (NDCs) without long-term "net zero" targets, to 2.1°C when such long-term "net zero" targets are included (for example, China's pledge to reach net zero emissions by 2060). In addition, the CAT consortium has noted an "optimistic scenario" where all announced pledges and commitments are fully implemented, even if not included in any current NDCs or policies, which would result in 1.8°C (1.5–2.3°C) in 2100. For the purposes of the 2024 State of the Cryosphere Report, "Current NDCs" are categorized as the average of 2030 NDCs alone, and NDCs including "net zero" targets; or 2.3°C.

1.5°C Consistent Pathways

In its latest Assessment Report (AR6), the Intergovernmental Panel on Climate Change (IPCC) outlined a number of socio-economic emissions pathways consistent with meeting the lower Paris 1.5°C limit. The most ambitious grouping of these, SSP1-RCP1.9, requires sharp emissions reductions of around 50% by 2030. Such pathways would see temperatures peaking at 1.6°C this century, but declining to 1.4°C by 2100 due to removal of carbon from the atmosphere, alongside "net zero" human emissions. It is noteworthy that the "optimistic scenario" used by CAT (noted above) does include 1.5°C as its lower-end estimate. At the same time, a 2024 re-evaluation using IPCC methods to allow a 50% likelihood of remaining within 1.5°C found that the carbon budget had shrunk from 500Gt at the start of 2020, to 200Gt at the start of 2024.[2] This means that the window to meet the lower Paris target, while still physically possible (and according to the latest Net Zero Roadmap[3] update from the International Energy Agency (IEA), even economically advantageous) is increasingly closing without rapid course-correction, especially by the major emitters of carbon pollution.

Current rise in CO_2 levels continues – Characterized as 3–3.5°C by 2100 in the 2024 Report

Despite some indications that the rate of emissions increase is slowing and may peak sometime this decade,[2] CO_2 concentrations continue to grow in the atmosphere. The year-on-year rise may even have accelerated in 2024, most likely due to warmer oceans this year taking up less carbon, though there are also some indications of growing methane emissions from the oil and gas industry and from permafrost peatlands.[4] If the current rise of 2.5–3.3ppm/year continues however, CO_2 concentrations would reach 600–670ppm by 2100, resulting in 3–3.5°C warming above pre-industrial levels. Such conditions have not existed for at least 15 million years.

1 https://climateactiontracker.org/about/the-consortium/

2 https://essd.copernicus.org/articles/16/2625/2024/

3 https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach/executive-summary

4 https://www.globalcarbonproject.org/methanebudget/24/publications.htm

Background

The cryosphere in the distant past has responded to relatively slow changes in temperature and greenhouse gas concentrations. These were paced by small changes in the Earth's orbit around the sun, leading to a slow rise in temperature, usually over tens of thousands of years, with thaw and loss of many cryosphere elements: ice sheets, glaciers, sea ice and frozen permafrost soils. The cryosphere also has responded to Earth's orientation, where one pole or the other might face the sun more directly, leading to a greater degree of melt on either Greenland, or Antarctica; but not both at the same time.

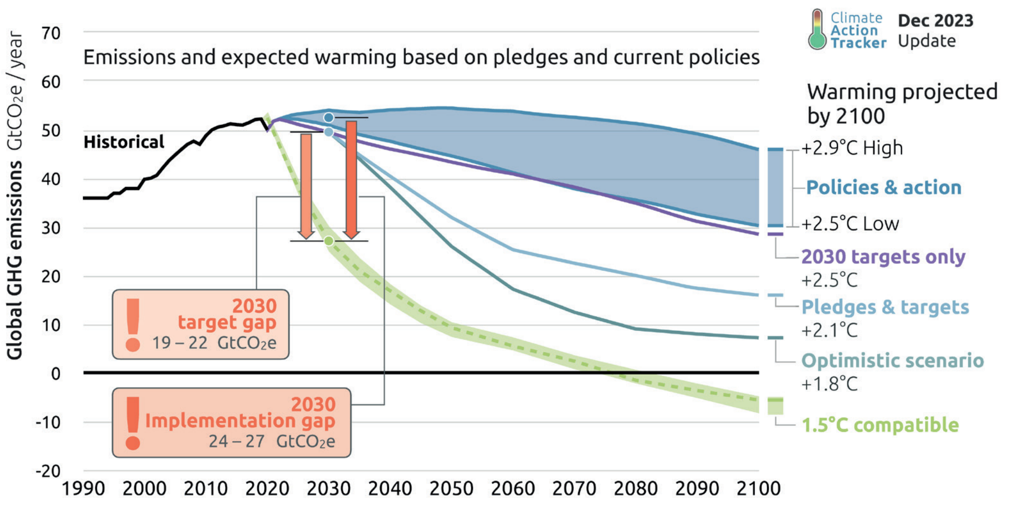
Paleo-climatologists, who study the behavior of Earth's climate, can trace this interaction between temperature, CO_2 concentration, the history of sea-level rise and ice sheets going back many millions of years through studying the geologic recorded in rocks and ancient shorelines. Temperature and CO_2 concentrations can also be followed back tens or even hundreds of thousands of years through small bubbles of gas trapped in ice cores, or through cores of sediment from ancient lakes. It is this combination of evidence that actually gives a fairly clear picture of how the cryosphere has responded in the past as temperatures very slowly rose over hundreds or thousands of years.

It cannot be over-emphasized how much more slowly these shifts in temperature and CO_2 concentrations occurred compared to today's warming from human greenhouse gas emissions. CO_2 levels an Ice Age were around 180 ppm, and 280 ppm during warm periods or "interglacials," including the past 10,000 years. The 2024 CO_2 peak of 428 ppm is completely off-the-charts for the entirety of human existence, going back 3 million years. As of 2023, CO_2 concentrations officially breached 50% above pre-industrial levels.

Most worryingly, CO_2 continues to rise in the atmosphere by around 2.5 ppm each year, and was 3.36 ppm higher in 2023. Indeed, 2023 set a new record for greenhouse gas emissions, according to the 2024 UNEP Emissions Gaps Report released in October, with 2023 emissions 1.3% higher than 2022, during a decade when the IPCC has identified a need for around 7% reductions needed each year to keep the lower 1.5°C goal within reach. The UNEP Emissions Gap Report also noted that among the G20 countries, which represent around 80% of emissions globally, none appear likely to meet their 2030 NDC emission reductions targets. These developments stand in stark contrast with needed reductions in accordance with the 2015 Paris Agreement aiming to peak and stabilize CO_2 concentrations, with that peak occurring before 2025 especially in 1.5°C-consistent emissions scenarios.

By continuing to emit CO_2 and other greenhouse gases without pause, the world's nations and industrial sectors have pushed the planet into a clear cryosphere danger zone. Today's 1.2°C above pre-industrial already has caused massive drops in Arctic and Antarctic sea ice; loss of glacier ice in all regions across the planet; accelerating loss from both the Greenland and Antarctic ice sheets; extensive permafrost thaw; and rising polar ocean acidification. The global impacts of these cryosphere losses at today's 1.2°C include floods, landslides and loss of snow and ice water resources; accelerated sea-level rise; infrastructure damage from permafrost thaw, as well as permafrost greenhouse gas emissions; and seasonal damage to shelled polar organisms. Impacts may also include extreme weather and disturbed ocean currents.

FIGURE 1-1. **2100 Warming Projections**



SOURCE: CLIMATE ACTION TRACKER GLOBAL UPDATE, DECEMBER 2023

TABLE. **IPCC AR6 Emissions Pathways**

Emissions Pathway	Scenario Name (Prior scenario)	Median temperature projected for 2100	CO_2 in 2100
Very Low	SSP1–1.9	1.4°C (after brief 1.5° overshoot)	440
Low	SSP1–2.6 (≈RCP2.6)	1.8°C (and declining)	450
Intermediate	SSP2–4.5 (≈RCP4.5)	2.7°C (and rising)	650
High	SSP3–7.0	3.6°C (and rising)	800
Very High	SSP5–8.5 (≈RCP8.5)	4.4°C (and rising)	1000+

Nearly all of these changes cannot be reversed on human timescales, and they will grow with each additional fraction of a degree of warming and CO_2 concentrations in the atmosphere. Well before 2°C, they would become devastating due to the physical reality of the cryosphere's response.

This is not however a pre-determined outcome. A variety of reports and independent analyses have shown the way to a 1.5°C future, beginning with the IPCC's Special Report on 1.5°C of Warming (SR1.5) from 2018. The IPCC Sixth Assessment, with its Synthesis Report released in March 2023, updated these findings, and outlined an even greater variety of pathways (see Table below). Other expert groups, especially the International Energy Agency (IEA), Climate Analytics, and initiatives from UN Secretary General Guterres have outlined how 1.5°C can be achieved. The 2024 UNEP Emissions Gap report concluded that despite today's yawning gap between Paris goals and current policies, there is sufficient technical potential still for emissions cuts by 2030 and 2035 to bridge the gap to 1.5°C in both of these benchmark years, and at a cost below US$200 per ton of CO_2 equivalent.

All these 1.5°C-consistent solutions however involve very sharp cuts in fossil fuel emissions within the next few years, so that CO_2 emissions peak before 2030 and no later.

Scenarios that would keep temperatures within or very close to 1.5°C remain physically, technologically, and economically feasible and even advantageous to both human populations and ecosystems, especially because many of their elements greatly improve human health outcomes. Most of the early emissions decline would take place in the transport and power sectors. In particular, nearly all use of fossil fuels – especially coal, with oil and natural gas clearly declining – must be phased out, and certainly not expanded. Non-OECD countries especially must receive support to develop in a carbon-neutral manner. After 2050, "negative emissions" – pulling carbon out of the atmosphere through

Low Emissions for the Cryosphere

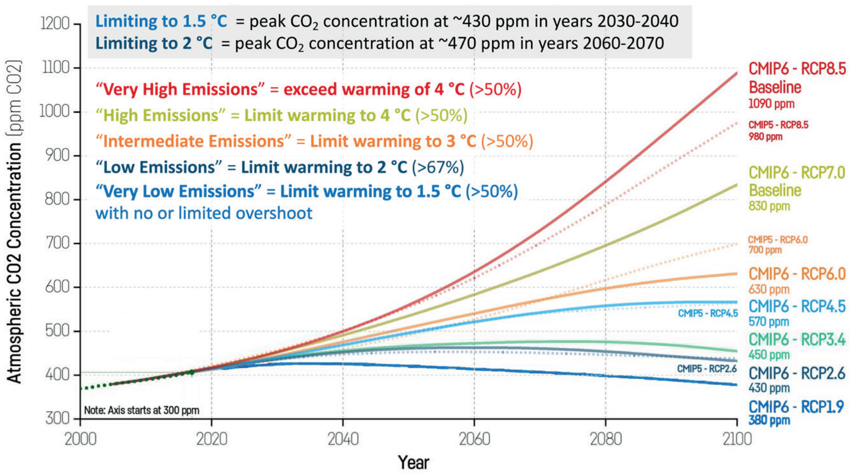
SSP1–1.9, Very Low Emissions (peak temperature 1.6° and declining to 1.4°C by 2100) requires:

1. at least 42% greenhouse gas reductions globally from 2019 levels by 2030, and 57% by 2035, primarily from steep declines in fossil fuel use;
2. carbon neutrality (net zero CO2 emissions) by 2050, and
3. net negative emissions (carbon drawdown) afterwards.

With these still-technically and economically feasible reductions and measures, cryosphere generally begins to stabilize in 2040–2080. Slow CO2 and methane emissions from permafrost continue for one-two centuries, then cease. Snowpack stabilizes, though at lower levels than today. Steep glacier loss continues for several decades, but slows by 2100; some glaciers still will be lost, but others begin to show re-growth. Arctic sea ice stabilizes slightly above complete summer loss. Year-round corrosive waters for shelled life are limited to scattered polar and near-polar regions for several thousand years. Ice sheet loss and sea-level rise will continue for several hundred, to thousands of years due to ocean warming, but likely would not exceed 3 meters globally and take centuries to occur.

All other emissions pathways – even "low emissions" peaking at 1.8°C – result in far greater committed global loss and damage from cryosphere, continuing over centuries and millennia.

FIGURE 1-2. **For the Cryosphere, Peak Temperature and CO_2 is What Matters: Overshoot is Unacceptable**



SOURCES: IIASA SSP DATABASE V2 (2018 RELEASE); NOAA ESRL MAUNA LOA CO2 ANNUAL MEAN DATA; IIASA RCP DATABASE; LIVEMAGICC

changes in agricultural practices or mechanical carbon removal technologies – will help CO_2 levels decline more rapidly, with temperatures beginning to lower by the end of this century. Some benefits – such as slight decreases in extreme weather – may begin to be felt as soon as temperatures trend downwards.

The issue therefore is not that global leaders do not have 1.5°C solutions available. The issue is that those leaders, and humanity collectively, must decide to implement them. The most recent 2024 analysis show that the remaining carbon budget has shrunk to around 200 Gt, from around 500 Gt in 2020. As a result, the window to act and minimize cryosphere-related global loss and damage has become very small. Indeed, some of the very lowest emission pathways from IPCC no longer remain possible. Only a strong, emergency scale course-correction towards 1.5°C – emissions following the remaining "very low" pathways – can avert higher temperatures, to slow and eventually halt these cryosphere impacts within adaptable levels.

As the chapters in this Report describe, each fraction of a degree above today matters. The various parts of the cryosphere will respond in future to our decisions today, based on the simple physical reality of the melting point of ice.

Nearly all of these changes cannot be reversed on human timescales, and they will grow with each additional fraction of a degree of warming and CO_2 concentrations in the atmosphere.

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CHAPTER 2

Ice Sheets and Sea-level Rise

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

Current NDCs (2.3°C by 2100): Current NDCs are not sufficient to prevent significant overshoot of 1.5°C, with many governments delaying meaningful mitigation to 2040, 2050, or beyond. While perceived as lowering energy costs today, a slower transition from fossil fuels locks in widespread future loss and damage, with adaptation needs far higher and more expensive where still technically feasible. A compelling number of new studies, taking into account ice dynamics, paleo-climate records from Earth's past and recent observations of ice sheet behavior point to thresholds for both Greenland and parts of Antarctica well below 2.2°C. Many ice sheet scientists now believe that exceeding even 1.5°C will be sufficient to melt large parts of Greenland and West Antarctica, and potentially vulnerable portions of East Antarctica; generating inexorable sea-level rise that exceeds 10 meters in the coming centuries, even if air temperatures are later decreased. The pace of this long-term, unstoppable sea-level rise will pose major long-term persistent challenges for all coastal regions; and result in widespread loss and damage of critical infrastructure (about 75% of all cities with >5 million inhabitants exist below 10 meters' elevation), agricultural land, and the livelihoods of all those who depend upon these at-risk regions.

1.5°C Consistent Pathways: Only this pathway can slow sea-level rise to rates that enable feasible adaptation for many coastal communities, minimizing loss and damage. The rate of sea-level rise stabilizes by 2100 because temperatures, while peaking at 1.6°C, have by then declined to around 1.4°C. This requires urgent action, however, with emergency-scale tightening of mitigation commitments and fossil fuel emissions declining 40% by 2030. Unfortunately, the latest science shows that even 1.5°C may not be sufficient to protect both ice sheets, with a best-case scenario that sea- level rise would slow. Should the planet remain at 1.5°C for too long (decades to centuries), substantial sea-level rise from Greenland, West Antarctica and possibly even East Antarctica may become locked in for several millennia. This has happened in the geological past when the planet reached +1.5°C due to orbital changes, and resulted in sea levels 6–9 meters above today.

Current rise in CO_2 levels continues (3–3.5°C by 2100): If atmospheric CO_2 continues to increase at today's pace, which has not paused despite current mitigation pledges, global temperatures will reach at least 3°C by the end of this century. Loss and damage from ice sheet melt at this level will be extreme, well beyond limits of adaptation for many coastal communities. This is because, once 3°C is passed, ice loss from Greenland and especially from West Antarctica becomes extremely rapid. Together with extensive ice loss from parts of East Antarctica, the IPCC could not rule out that three meters might be passed early in the 2100s; with five meters passed by 2200 and up to 15 m of sea-level rise possible by 2300. While seemingly in the far future, this massive scale of coastal destruction will have been made inevitable by decisions made in the next few decades, causing temperatures to pass these critical thresholds.

2024 Updates

- The global rate of sea-level rise has doubled in the last 30 years. Between 1993 and 2024, sea levels rose by over 11 cm at an accelerating rate of 2.1 mm/year in 1993 to 4.5mm/year in 2023. If these trends continue, rates would increase to 5.0 mm/year by 2030, 5.8 mm/year by 2040 and 6.5 mm/year by 2050, presenting a widespread challenge for adaptation efforts along coastlines worldwide.[1]
- Genetic analysis of Octopus DNA that live in the seas surrounding Antarctica demonstrated that the West Antarctic Ice Sheet (WAIS) collapsed completely during the last interglacial period, when global average temperatures were only about 1°C warmer than pre-industrial. WAIS collapse during this period led to global sea levels more than 3 meters higher than today.[2]
- Satellite data show that seawater is being flushed beneath the grounding zone of Thwaites Glacier (West Antarctica) by the tides, perhaps as far as 12 km, triggering vigorous melting.[3] As ocean temperatures increase, this tidal pumping mechanism may lead to runaway melting under many areas of the Antarctic Ice Sheet.[4] This recently-highlighted process could potentially double sea-level rise from Antarctica.[5] Current models used to generate global projections of sea-level rise, such as those that informed the last IPCC report (2022), do not adequately represent this process, meaning that future sea-level rise from Antarctica may be substantially underestimated.[3,4]
- A new ice–ocean model of the Amundsen Sea region of West Antarctica showed that even without further basal melting, some degree of unstoppable ice loss from Thwaites and Smith glaciers is now locked in. This implies that a tipping point has now been crossed and we are now committed to long-term sea-level rise from the West Antarctic Ice Sheet.[6] This is consistent with a new stability analysis of Antarctica, which indicates that if the current global mean temperature of +1.2°C above pre-industrial is sustained, this is enough to trigger irreversible retreat in future – referred to as "committed tipping".[7]
- A comparison of 16 leading ice-sheet models highlighted the sharp risk of triggering a large acceleration in Antarctic ice loss rates after 2100 if the world continues on a high emissions pathway. The models suggest that Antarctica alone could contribute up to 28 centimeters of sea-level rise by 2100 under a high emissions pathway, and up to 1.7 m by 2200 and 6.9 m by 2300 if its peripheral ice shelves collapse. 40% of the models predict that the West Antarctic Ice Sheet will collapse by 2300.[8]
- New models show that under high emissions, ocean circulation driven by transport of freshwater from beneath parts of the East Antarctic Ice Sheet will increase the melting of its peripheral glaciers, making them contribute up to 30% more to sea-level rise by 2100 compared to models that do not include this process. This 'missing' mechanism would mean that some East Antarctic glaciers will retreat 25 years sooner, meaning that previous projections may have underestimated Antarctica's nearer-term contribution to sea-level rise.[9,10]
- A new freshwater-driven feedback loop was also discovered for the floating ice shelves that surround Antarctica, arising from melting that causes a stronger ocean undercurrent to pull more warm water under the ice shelf, further increasing its melting.[11] Ice shelf pinning points (where the ice shelf touches the seabed) hold back ice as it flows towards the ocean, but new analysis shows that almost 40% of Antarctic pinning points have decreased in size since the year 2000.[12] Greater ice shelf melting, especially when this leads to total shelf collapse, may further destabilize the West Antarctic Ice Sheet.
- A state-of-the-art ice sheet model predicting future sea-level rise showed that rapid emissions reductions may allow the uplift of land to slow further ice loss in Antarctica. The study showed that under low emissions, such uplift may be able to reduce Antarctica's long-term contribution to sea-level rise by up to 40% after the year 2100. This effect is lost however under high emissions, because uplift cannot occur fast enough to slow ice loss at higher warming levels.[13]

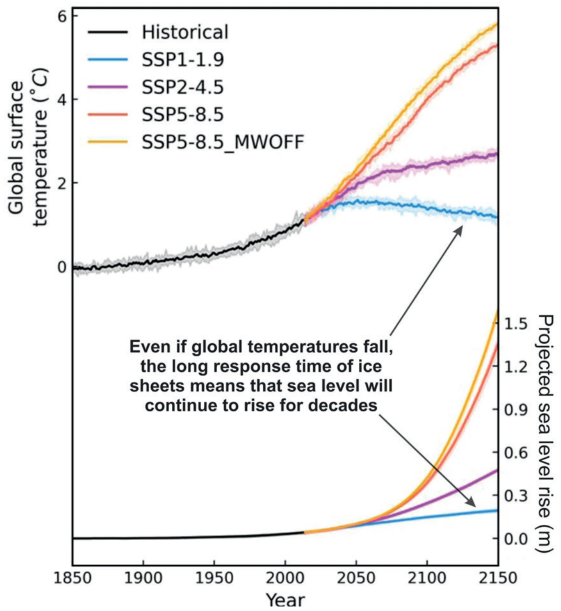
continued on next page

Background

For the Earth's polar ice sheets on Greenland and Antarctica, which together hold enough ice to raise sea level by 65 meters, risks of non-reversible melting increase as temperature and rates of warming rise, with every tenth of a degree increasing that risk.[18] The Earth's climate record makes clear that warming above even 1°C over preindustrial has reshaped the Earth's coastlines in the past due to extensive melting of the West Antarctic Ice Sheet (WAIS),[2] Greenland[19,20] and by 1.5°C, possibly parts of East Antarctica.[21] While some of these changes occurred very slowly in the past, over thousands of years, there have also been periods of extremely rapid sea-level rise (around 3.5 to 4 meters per century) due to ice-sheet collapse. Termed "meltwater pulses," the last of these events took place around 14,500 years ago when vulnerable sectors of Antarctica and the ice sheets which used to cover North America and Scandinavia collapsed, causing global sea levels to rise by 12–18 meters in about 350 years.[22,23]

The observed human-induced global temperature increase over the past few decades is much faster than anything documented in Earth's past, which was driven by slow changes in the Earth's orbital cycles. The rate of CO_2 increase in the last 50 years is 200 times faster than during the end of the last Ice Age. This means that future rates of ice sheet loss and sea-level rise (SLR) could increase even further beyond the acceleration that has already been observed over the last few decades, and

FIGURE 2-1. **Projected Sea-level rise by 2150 with Different Emissions Pathways**



Even under "low emissions," where global temperatures peak at 1.8°C and then fall (purple line, SSP2), sea-level rise continues accelerating. Only "very low" fossil fuel emissions that peak before 2030 (blue line, peak temperature 1.6°C, SSP1) would slow and stabilize sea-level rise, preserving many coastal communities and giving others time to adapt.

SOURCE: PARK ET AL. (2023)

2024 UPDATES (CONTINUED)

- The Greenland Ice Sheet is currently losing 30 million tons of ice per hour.[14] Ice shelves in northern Greenland have lost 35% of their total volume since 1978, and three ice shelves have now collapsed completely.[15]
- A new model shows that increased melting of the Greenland Ice Sheet will cause Europe to become hotter and drier in coming decades. This is because meltwater pouring from Greenland into the North Atlantic affects the polar jet stream, with periods of rapid melting triggering unusually hot, dry summers that last several years. The model predicts that rapid ice loss observed in 2023 will likely drive heatwaves in southern Europe in 2024 and 2025.[16]
- Ice drilling records confirm that the center of the Greenland Ice Sheet was ice-free sometime within the last 1 million years, even when CO_2 concentrations were far lower than today. This significant loss of ice, even when the causes of warming (slight orbital changes) were much less extreme than that caused by today's high CO_2 levels, demonstrates how sensitive Greenland's ice sheet may be to even relatively low levels of warming.[17]
- Current climate policies are not ambitious enough to prevent tipping points from being crossed, even if long-term temperatures return to 1.5°C by 2300 via an overshoot pathway. A new study shows that the longer the 1.5°C threshold is breached, and the higher the peak temperature, the greater the risk of crossing tipping points for the West Antarctic and Greenland ice sheets, the Atlantic Meridional Overturning Circulation (AMOC), and the Amazon Rainforest.[18]

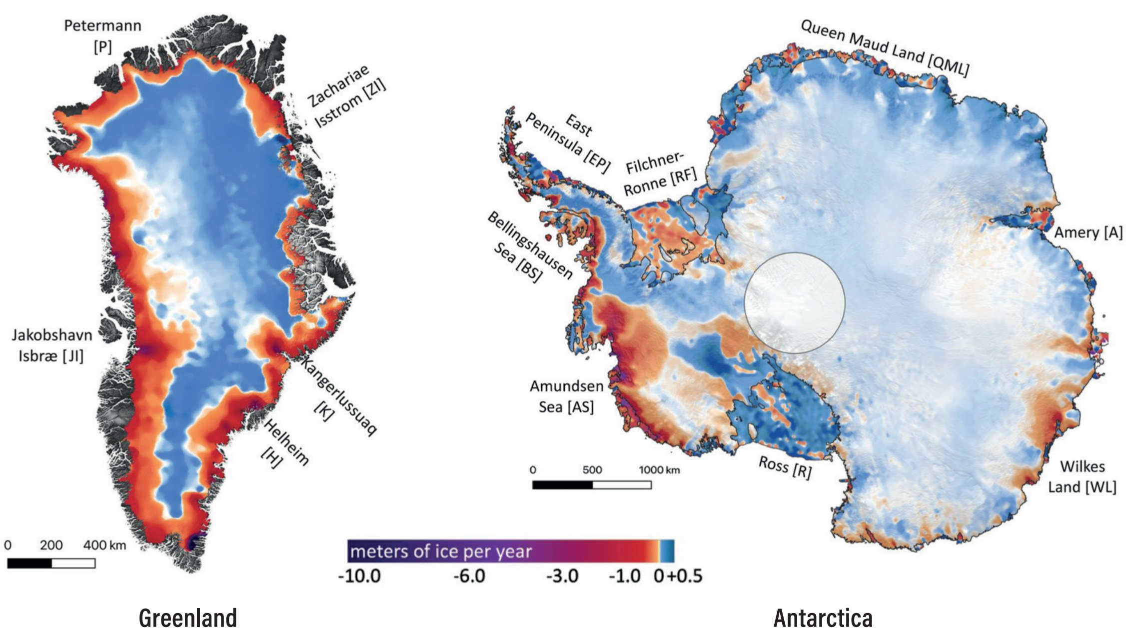
could potentially be more rapid than at any other time in the past 130,000 years.[24] The latest investigations of ice sheet behavior, especially interactions between the ice and the warming oceans that surround them, inform us that ice sheet collapse and rapid sea-level rise cannot be ruled out[4,25–29] especially if peak warming exceeds 1.5°C. This is especially the case for the WAIS, where some studies show that the threshold for eventual collapse may already have been passed at around 0.8°C above pre-industrial.[30–32] Even if ice sheet loss is inevitable once thresholds are crossed, this can be slowed to take place over longer timescales if temperatures remain close to 1.5°C, with an aim to return below that level as soon as possible. This would give coastal communities greater time to adapt to rising sea levels.

There is strong consensus that the risk of extensive melting from ice sheets increases as both the peak in global temperatures and the rate of warming rise.[18] The massive Greenland and Antarctic ice sheets consist of compressed snow that fell, in the oldest sections, over a million years ago.[33,34] In equilibrium, the calving of icebergs and outflow of meltwater into the ocean are balanced by mass gain via snowfall. Observations now confirm that this equilibrium has been lost in Greenland, the WAIS, and the Antarctic Peninsula; and potentially for portions of the tentimes-larger East Antarctic Ice Sheet. Combined, the Earth's ice sheets lost 7,560 billion tons of ice between 1992 and 2022.[35] For Greenland, this equates to a loss of approximately 30 million tons of ice per hour,[14] and if this ice sheet's recent acceleration in ice loss continues, it will track above the upper range predicted by the IPCC[36] for this decade.[35]

All changes in the total mass of 'land ice' bound within the Earth's ice sheets have direct consequences for global sea level. During Ice Age periods, when the ice sheets expanded significantly, sea level was around 130 meters lower than it is today. During periods of warming, when the ice sheets lost mass, sea level rose accordingly, with clear evidence of meltwater pulses (noted above) largely as a result of relatively rapid collapse of the Laurentide Ice Sheet over North America.[23,37]

Floating ice shelves in Antarctica also play an important role in ice loss because they hold back, or "buttress," the ice upstream by resting on isolated bedrock highs termed 'pinning points', and by generating friction when ice shears past their sides. Loss of this buttressing effect through ice shelf thinning and break-up accelerates the rate of ice flow from the land into the sea.[38] From 1997 to 2021, Antarctic ice shelves experienced a net loss of 36,701 ± 1,465 km^2 – equal to the size of the country Guinea-Bissau[39] – and almost 40% of Antarctic pinning points have reduced in size since the year 2000.[12] Antarctic ice shelf thinning has accelerated over recent decades, driven by the intrusion of warmer ocean currents beneath them.[40–42] Reduced ice-shelf buttressing driven by warm ocean currents accounts for a significant portion of

FIGURE 2-2. **Current Ice Loss Regions – Greenland and Antarctica**



The rate of ice loss is now 5 times higher in Greenland and 25% higher in Antarctica compared to the early 1990s.

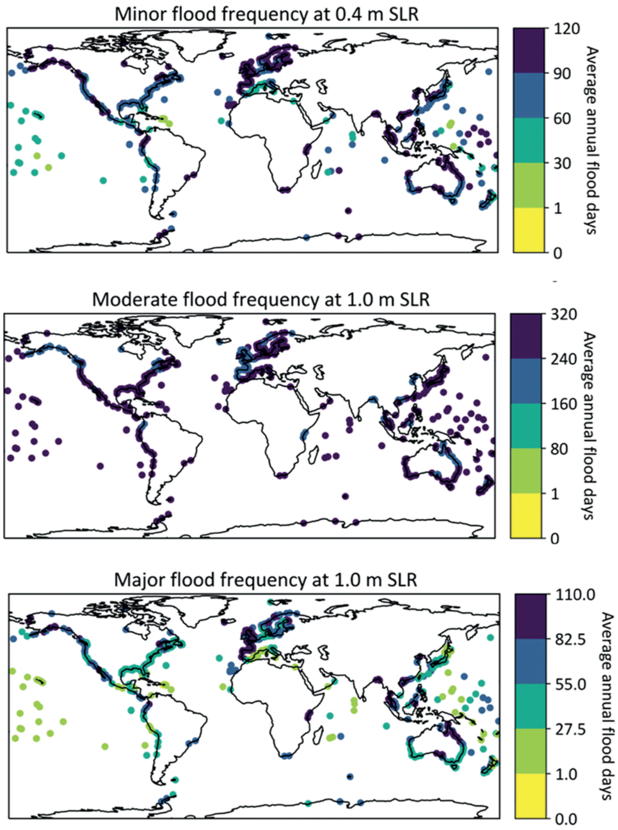
SOURCE: SMITH ET AL. (2020)

Antarctic ice loss[43,44] and could drive increasingly significant sea-level rise in the future.[32,38,39,45]

Greenland and (parts of) Antarctica have certain thresholds beyond which irreversible melt becomes inevitable and potentially rapid.[2,29,46–48] In Earth's past, several of these thresholds have occurred somewhere between 1 and 2 degrees of warming above pre-industrial: likely about 1°C for the WAIS and Antarctic Peninsula (containing about 5 meters SLR); and between 1.5°C and 2°C for Greenland (approximately 7 meters SLR).[2,49] (It should be noted that changes around past thresholds were paced by slow changes in Earth's orbit – unlike today's rapid warming that is driven by greenhouse gas emissions from human activities). Some of the most advanced ocean and ice-sheet models available now suggest that because of ocean warming caused by fossil fuel emissions to date (and the amount locked in for the future), extensive West Antarctic ice shelf melting, including in regions crucial for maintaining ice sheet stability, has now become inevitable. This means that the opportunity to preserve much of the West Antarctic Ice Sheet, with its potential 3.5 meters of sea-level rise, has now probably passed even with very low emissions trajectories.[6,7,32] Its loss can be slowed, but not prevented entirely. Elsewhere, parts of East Antarctica, especially the massive Wilkes and Aurora Basins (at least 8 meters of potential SLR), may also have a threshold around or just beyond 2°C.[21,50,51] Wilkes Land has been referred to as the 'weak underbelly' of the East Antarctic Ice Sheet[52] and has been losing mass for at least three decades,[21] increasing ten-fold between the 2000s and 2010s,[53] and driven by significant ocean warming.[54]

Because of the existence of these thresholds, when temperatures reached 2°C above pre-industrial in the Earth's past, sea levels peaked at around 12–20 meters higher than present-day levels. During the height of the Pliocene 3 million years ago, when CO_2 levels were comparable to today and temperatures stabilized at 2–3°C higher than pre-industrial, sea levels may have peaked at around 20+ meters higher than today's, implying a

FIGURE 2-3. **Increased Coastal Flooding**



Flood terminology

Minor: minimal property damage, some public threat

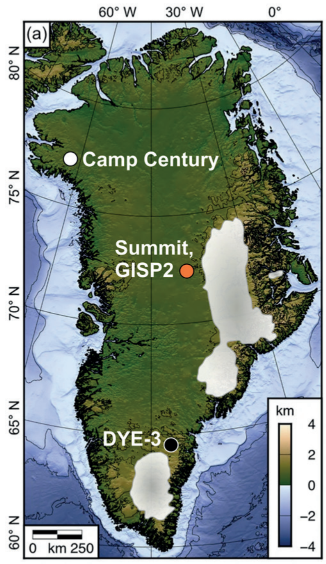
Moderate: Structures inundated; evacuation needed

Major: Extensive inundation and damage; widespread evacuation needed

The impact of 0.4 and 1 m sea-level rise on coastal flood frequency along the world's coastlines. Even relatively low levels of sea-level rise massively increases the occurrence of damaging and dangerous coastal floods.

FROM HAGUE ET AL. (2023).

FIGURE 2-4. **New Findings of an Ice-Free Greenland**



Ice drilling records now confirm that the center of the Greenland Ice Sheet was ice-free sometime within the last 1 million years, even when CO_2 concentrations were far lower than today. This significant loss of ice, even when the causes of warming were much less extreme than that caused by today's high CO_2 levels, demonstrates how sensitive Greenland's ice sheet may be to even relatively low levels of warming.

SOURCE: BASED ON BIERMAN ET AL (2024); PAXMAN ET AL (2024) contribution from the Greenland ice sheet, the WAIS, and portions of the EAIS.[49,55–57] Such extensive sea level rise would be catastrophic for today's coastal communities — yet we are currently on track for even higher temperature peaks than those that drove these past sea level rises.

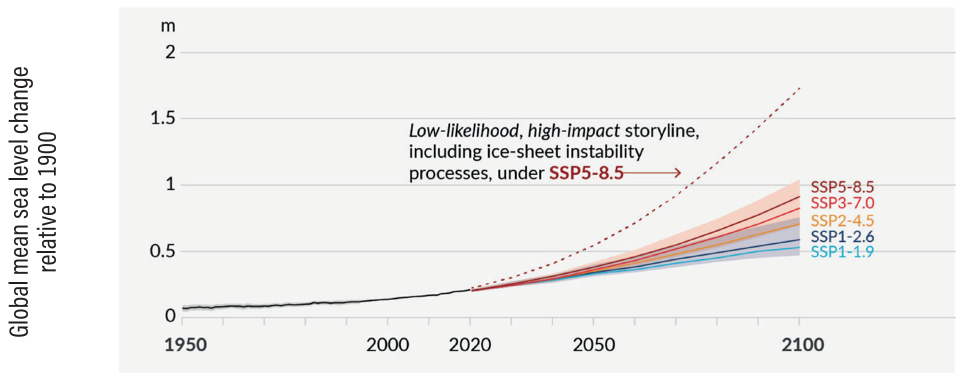
Greenland responds in a more linear manner (more predictably) to increasing atmospheric temperatures. The Greenland Ice Sheet is over 3000 m thick in places and above 3000 m altitude in its interior. If the height of this ice sheet is lowered through surface melting and ice flow into the oceans, it eventually becomes exposed to above-freezing temperatures for longer time periods throughout the year, leading to the eventual unstoppable loss of most of the ice sheet.[58–62] The first recorded rain at the highest point of Greenland, Summit Station, occurred in August 2021 and lasted several days. Rainfall on the Greenland Ice Sheet has increased by 33% since 1991, and the frequency of extreme deluges is increasing.[63] These deluges drain quickly into the ice sheet through vast networks of micro-cracks that may run hundreds of meters deep, carrying warm surface water to the interior of the ice sheet where it heats the ice internally, melting the ice sheet from within.[64] Evidence from ancient soil recovered from beneath the modern-day northwest Greenland shows that the ice sheet 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.[65] Similar analysis has recently shown that even the central summit of Greenland was ice free within the last 1 million years,[17] 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.

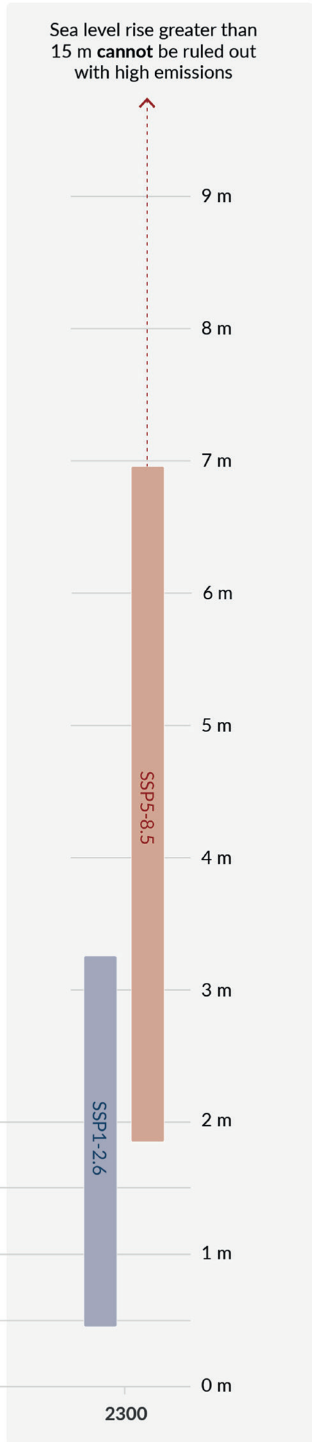
This is similar to earlier evidence of Arctic warming recorded by lake sediments, highlighting Arctic system vulnerability.[66,67]

The WAIS (and large parts of the EAIS) is a very different story: much of it does not really sit over land, but rather over island archipelagoes separated by extremely

Decisions made by policy-makers today will determine the rate of future sea-level rise, driving associated risks to security and development for centuries.

FIGURE 2-5. **Projections of future sea-level rise under different emissions**



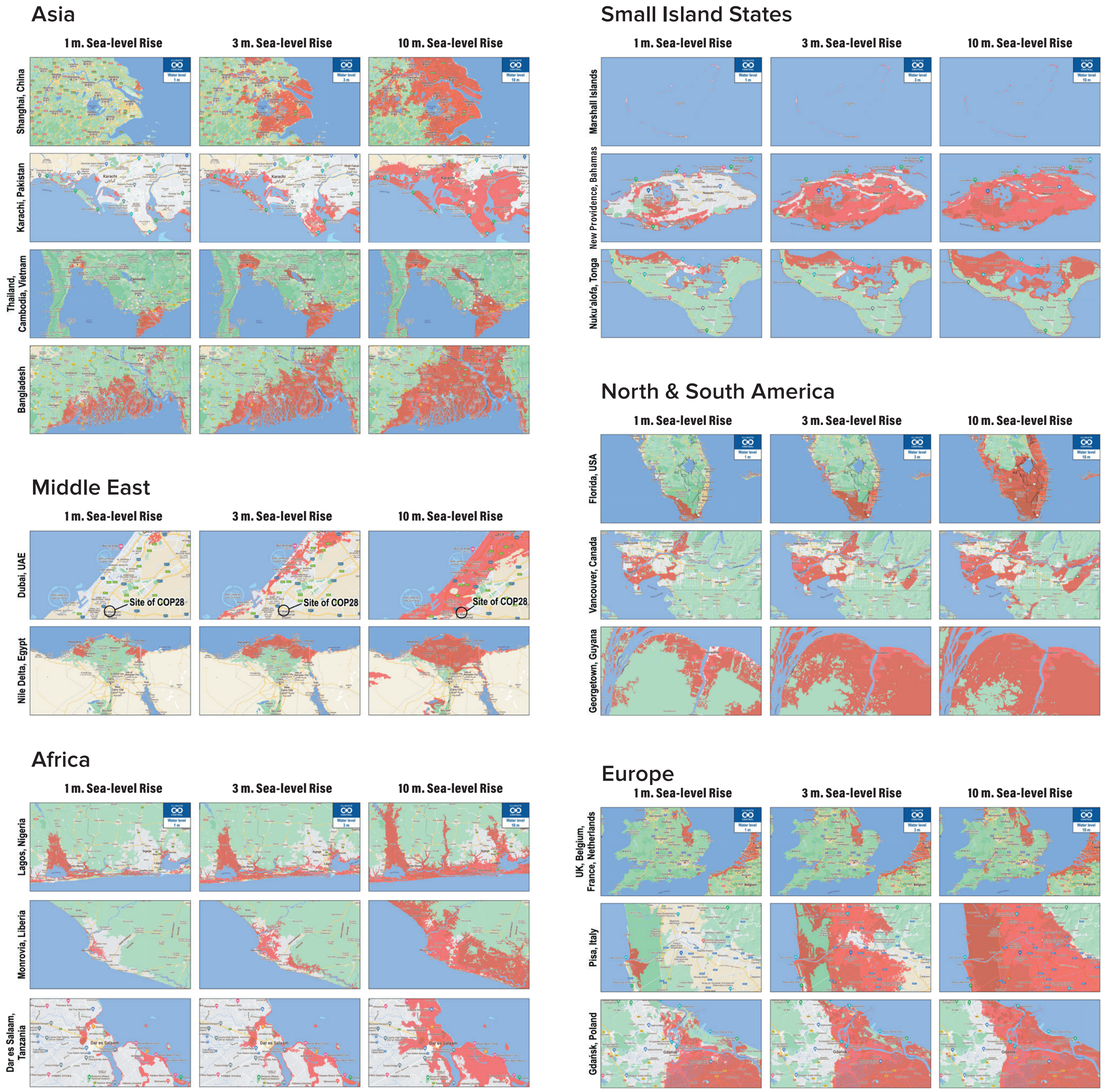


With high emissions, up to 15 meters rapid increase in SLR by 2300 – due to ice loss feedbacks in Greenland and Antarctica – cannot be ruled out.

SOURCE: IPCC AR6.

FIGURE 2-6. **Ice Sheets and Sea-level Rise: Our Decisions, Our Children's Future**

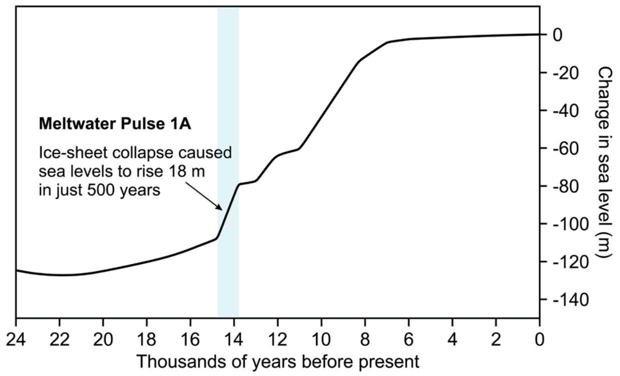
1 m. Sea-level Rise	3 m. Sea-level Rise	NOT SHOWN: 6 m. Sea-level Rise	10 m. Sea-level Rise
Now long-term inevitable (by mid-2100s), but potentially by 2070 with current emissions	Likely inevitable in 1000–2000 yrs; BUT by early 2100's with current emissions	Early 2200s with current emissions	By 2300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



Humanity's continued high emissions have committed Earth to at least 1 meter of sea-level rise, and likely 2–3 meters. However, we can still decide how quickly those rising waters will come. Exceeding 1.5°C takes us into the danger zone where additional loss of parts of the Antarctic and Greenland ice sheets could become inevitable. This would lead to multiple meters of sea-level rise that would be unstoppable for centuries to thousands of years. These maps provide examples of the choice before us, and the devastating impact of sea-level rise should today's high emissions continue, rather than peak and decline in this crucial decade. The choice is ours.

SOURCE: CLIMATE CENTRAL. TO USE THIS TOOL WITH OTHER CITIES/REGIONS, SEE: HTTPS://COASTAL.CLIMATECENTRAL.ORG/MAP/

FIGURE 2-7. **Rapid Sea-level Rise 14,500 Years Ago (Meltwater Pulse 1A)**



Over just ~350 years, sea levels rose by 18 meters (3.5 to 4 meters per century). This massive sea-level rise came mostly from melt of the Laurentide Ice Sheet then covering Canada and the USA, but it shows an ice sheet can collapse quite quickly.

deep (>2.5 km below sea level) and vast basins.[68–70] Much of its ice rests on a bed that slopes downwards toward its center. As warm water melts the marine edges of the WAIS, the ice retreats over these ever-deeper ocean basins. This exposes more and more of the underside of the ice sheet to warming waters, rapidly forcing further melting and eventually causing the ice sheet to become unstable. These processes may cause very rapid ice-sheet loss and resulting sea-level rise over just a few centuries,[8,27,28,71] and the importance of several recently discovered feedback mechanisms has been highlighted since the last IPCC assessment which could accelerate melting further.[3,4,9–11]

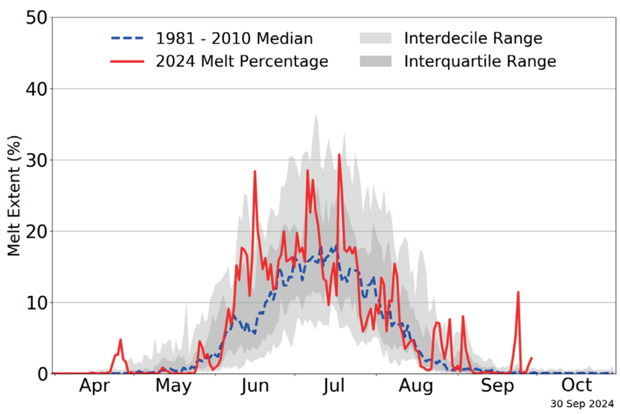
Indeed, Thwaites Glacier (often referred to as the ‘Doomsday Glacier’) has experienced pulses of rapid retreat in the past in which the glacier stepped back at rates of over 2.1 km per year — twice the fastest rate observed between 2011 and 2019.[48] Comparably fast rates are expected in the near future when the glacier migrates off stabilizing high points on the seafloor on which it currently sits.[3,48] Similar conditions exist on parts of East Antarctica and have become far better documented on the continent through coordinated scientific efforts over previous decades.[72–74] Recent work also suggests that although the East Antarctic Ice Sheet was once considered relatively stable, large parts of this vast ice sheet resemble vulnerable West Antarctic sectors, and could contribute substantially to sea level rise if temperatures rise above 1.8°C.[21,75]

Ice sheets have other global impacts in addition to sea-level rise. They influence both atmospheric and ocean circulation at high latitudes and globally, which transfer heat around the planet. Changes in the height and extent of Earth’s ice sheets, together with the incursion of new cold and fresh water into ocean currents from ice sheet melt, cause changes in weather patterns near the poles and at lower latitudes.[16] Additionally, these circulation systems affect nutrient supplies in marine ecosystems. Recent studies suggest that increasing meltwater discharge from Antarctica could reduce the strength of the Antarctic overturning circulation by more than 40% by 2050, potentially leading to collapse.[76] The resulting subsurface warming would lead to an amplifying feedback in West Antarctica, leading to further ice shelf melting and sea-level rise in a region that is already vulnerable to irreversible retreat.[76,77]

The main questions for scientists and policy makers are (1) how fast can sea-levels rise (rate)?; (2) how high will sea levels reach?; and (3) at what point do these future higher sea levels become locked in? In general, scientists agree that every tenth of a degree matters;[18,71] and that 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 5 cm a year from Antarctica by 2150 should today’s emissions continue, and cause temperatures to exceed 3-4°C above pre-industrial by 2100.[28]

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 once temperatures stabilize or even decrease with so-called net-zero emissions and/or carbon dioxide removal (CDR). Ice core and sea level records clearly show that it takes tens of thousands of years to grow an ice sheet, but two orders of magnitude

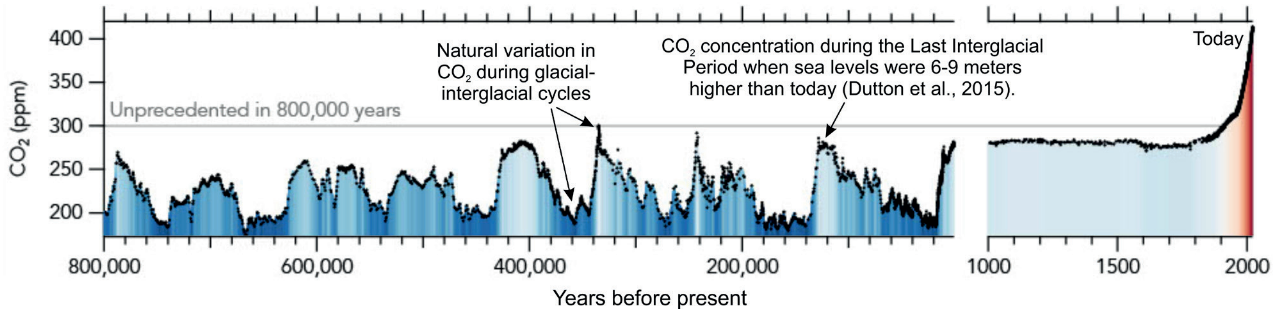
FIGURE 2-8. **Greenland Surface Melt Extent in 2024**



Graph shows the percentage of the Greenland ice sheet surface that experienced surface melting in 2024.

CREDIT NSIDC

FIGURE 2-9. **Atmospheric CO_2 Concentrations, Past 800,000 Years**



Even during past "warm" periods, CO_2 never exceeded 300ppm; in 2024, it reached 428ppm and will likely average above 423 for the year.

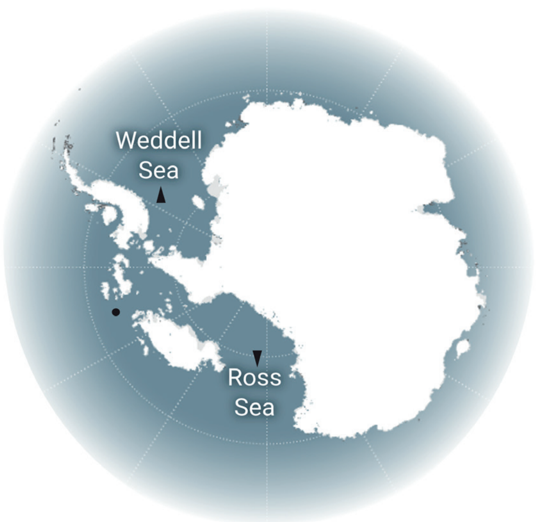
SOURCE: BRITISH ANTARCTIC SURVEY, ICE CORE DATA.

less (100x less) time to shrink one. Sea level lowering from these new highs will not occur until temperatures go well *below* pre-industrial, initiating a slow ice sheet re-growth.[78] Overshooting the lower limit of the Paris Agreement would therefore cause essentially permanent loss and damage to the Earth's ice sheets, with widespread impacts that are not reversible on human timescales.

Regardless of the uncertainties surrounding the rates of future melt, we know that the rate of ice loss in Greenland today is five times what it was 20 years ago,[35] and Antarctica's contribution to sea level rise is six times greater than it was 30 years ago.[31,79–82] 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 1°C above pre-industrial;[83–85] note that we are currently 1.2°C above pre-industrial.[86] A key argument therefore in favor of very low emissions is that staying below the 1.5°C limit will allow us to return more quickly to the 1°C level, drastically slowing global impacts from ice sheet loss and especially WAIS collapse.[87] This would reduce the risk of locking in significant amounts of long-term, irreversible sea-level rise. This will help to provide low-lying nations and communities more time to adapt through sustainable development, although some level of managed retreat from coastlines in the long term is tragically inevitable.

There is no Plan B. The decisions made by policymakers today on future emissions of greenhouse gases will determine the rate of future sea-level rise on a global scale, and drive associated risks to security and development for centuries to millennia to come. If nations care about human migrations and social change, they must be committed to the realities of sea level impact. To maintain the possibility of staying below 1.5°C, CO_2 emissions must be at least halved by 2030, and reduced to zero by mid-century. Otherwise, world leaders are *de facto* making a decision to erase many coastlines, displacing hundreds of millions of people – perhaps much sooner than we think.

FIGURE 2-10. **Antarctica Between 1°C and 2°C in Earth's Past**



How Antarctica looked the last time that temperatures were 1–2°C above pre-industrial levels, - during the last interglacial period (~130,000 years ago).

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Chris Stokes, Durham University

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CHAPTER 3

Mountain Glaciers and Snow

1.5°C Course Correction Essential to Prevent Escalating Loss and Damage for Many Decades

Current NDCs (2.3°C by 2100): Even 2°C will lead to escalating loss and damage throughout this entire century, well beyond limits of adaptation for many mountain and downstream communities. Nearly all tropical and mid-latitude glaciers would cross thresholds causing their eventual complete loss, with critically important High Mountain Asian glaciers losing around 50% of their ice. Catastrophic hazard events seen already today, such as glacial lake outburst floods and landslides, will increase in frequency and scale. Risks are especially high in Asia, where outburst floods can wash away infrastructure and cities within hours with little warning. Severe and potentially permanent changes to the water cycle, due to loss of snowpack and ice run-off during the warm summer growing season, will impact food, energy and water security.

1.5°C Consistent Pathways: This level of mitigation is the only chance to preserve at least some minimum glacier ice (15–35%) in some mid-latitude regions, including Scandinavia, the Alps, and Iceland; and maintaining up to 50% of current ice in the Caucasus, New Zealand and much of the Andes. Losses in High Mountain Asia will be far less at this temperature level, with two-thirds preserved glacier ice. Nearby communities must nevertheless prepare for significant adaptation efforts in coming decades, including continued catastrophic floods, especially with extreme rain-on-snow events. However, for most communities, these changes will not move beyond adaptation limits, and rates of glacier melt would slow by mid-century, and stabilize by 2100. Snowpack would also stabilize, though at higher altitudes than today. Some glaciers might even begin to show signs of very slow re-growth in the 2200s, as one of the first possible visible signs of planetary restoration in net-zero pathways.

Current rise in CO_2 levels continues (3–3.5°C by 2100): Catastrophic and cascading impacts from glacier and snow loss are associated with such levels of rapid warming, with some vulnerable mountain and downstream communities experiencing non-survivable conditions already by mid-century due to loss of seasonal water availability, or destructive floods from which they are unable to recover. Over time, even many of the largest glaciers in High Mountain Asia and Alaska are unlikely to survive. Snowpack will become unreliable, with rain falling at higher elevations and more frequently throughout the year when snow would otherwise be expected. Currently fertile agricultural regions such as the Tarim and Colorado River basins may no longer be able to support significant agricultural activities. Losses in mountain biodiversity stemming from cryosphere warming will be extreme across many high-elevation ecosystems.

Background

Glaciers (together with snowpack) have varying importance to nearby communities and those further downstream as a source of water for drinking and/or irrigation, with some contributing only a few percent over the course of a year, but of greater importance during dry seasons, heat waves and droughts.[15,16,17] Glaciers in some regions, such as the tropical Andes, or the Indus and Tarim basins in High Mountain Asia, contribute a high proportion of seasonal water supplies; in the dry Tarim and Aral Sea basins, close to 100% during the summer months.[18]

While the rapid melting of glaciers temporarily increases water availability, as the glaciers continue shrinking, seasonal availability will begin to decrease (referred to as passing "peak water"). This may make certain economic activities – and even continued human habitation – impossible. Indeed, most glacier-covered regions outside high latitude polar regions and the Himalaya have already passed this period of "peak water".[19,20] Adaptation efforts are therefore needed immediately to

2024 Updates

- Glacial melt globally set a record loss in 2023, according to the World Glacier Monitoring Service (WGMS).[1] Reported observations thus far from 2024 indicated record losses in some regions, with Sweden showing the highest melt levels in 80 years of observations.[2] Currently, 2024 is also on a record loss trajectory in Asia.[3] Extremely low snowfall combined with extremely high summer temperatures seem to have contributed to high 2024 loss in these regions.
- Venezuela joined Slovenia as the second country in the world to lose its final glacier: the Humboldt Glacier ice field became too small to flow under its own pressure in spring 2024, thus becoming stagnant at approximately 0.01km.[4]
- Glaciers in the Andean tropics are now smaller than at any time in 11,700+ years. In 2024, they became the first global glacier region confirmed to be smaller than at any previous time since the end of the last Ice Age.[5]
- 2024 data from 5,500 glaciers across the Andes show the mountains have lost 25% of their ice coverage since the Little Ice Age, and that their tropical glaciers are melting ten times faster than the cumulative global average.[6]
- The melt rate of the Juneau Ice Field quintupled between 2010–2020 compared with the 1980s, potentially locking in continued ice loss and centuries of consequential sea level rise.[7]
- Ten million people are currently at risk of catastrophic flooding hazard events from glacial lake outburst floods, especially in Alaska, High Mountain Asia, and Iceland. In Asia alone, the frequency of these events is expected to triple by century's end without substantial emission reductions.[8]
- Under a high emissions scenario, two-thirds of Mount Everest's famous East Rongbuk Glacier is projected to be lost by 2100. In addition to being an iconic part of the Asian water tower, East Rongbuk has climbing and cultural significance.[9]
- New observations from glacial meltwater in Svalbard, Greenland, Iceland, and Alaska show high levels of methane, in part from permafrost. This confirms that mountain glaciers are a methane source and underscores the importance of including permafrost thaw in NDCs.[10]
- Northern hemisphere winter 2023–2024 saw record low snowfall in the Hindu Kush Himalaya, highlighting concerns for runoff-fed rivers and water security.[3]
- Locked-in melt has committed the loss of at least one-third of glacier mass in the European Alps glaciers by 2050 without further warming. With the current warming trajectory, two-thirds of the glacier mass may be lost by 2050.[11] In western Austria, near-complete glacial loss is projected if the lower 1.5°C Paris limit is not achieved.[12]
- Recent findings on ice retreat in the Eastern Himalaya show climate change directly links to glacier instability that drives cascading hazards.[13]
- A paper from July 2024 finds fluctuations in Peruvian Andes meltwater that are directly linked with changes in global biodiversity. This suggests mountainous aquatic biodiversity will be affected globally as glaciers retreat.[14]

prepare for this future, in tandem with mitigation efforts to preserve glaciers as much as possible as key priorities. In addition, glaciers have deep cultural and spiritual significance for Indigenous Peoples and local communities, as shown in recent studies from the Peruvian Andes[21] and the Swiss Alps.[22]

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.[23] These glaciers have mostly been shrinking since the end of the Little Ice Age, but global warming greatly accelerated their melting. Some of these, especially in parts of the northern Andes, would have provided a reliable seasonal source of water for hundreds or thousands of years without human-induced warming. Their loss – which for some glaciers may occur by mid-century – would impact rural populations in northern Peru especially, as well as in Bolivia and northern Chile, while also impacting major cities such as La Paz.[24]

Severe losses also are occurring today from lower and mid-latitude glaciers and others outside the polar regions: these include glaciers in the European Alps, southern Andes and Patagonia, Iceland, Scandinavia, the North American Rockies and much of Alaska, New Zealand, the Caucasus and 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 by 2100.[25,26] Others, such as those in the Hindu Kush Himalaya (HKH), may experience up to 80% of ice loss.[18] With very low emissions however, up to 40% of glacier ice in the HKH region could be preserved.[18] Projections in a few glacier regions even show slow re-growth beginning between 2100 and 2300, but only with very low emissions and essentially carbon neutrality by 2050.[27]

Credit: John Wendle

The Stanley Glacier in Uganda's Rwenzori Mountains. Even under a very low emissions scenario, the Rwenzoris are expected to be ice-free by mid-century.

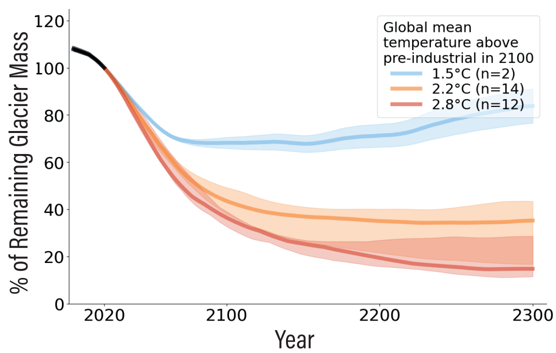
Any other emissions path will eventually result in almost complete loss of all mid-latitude glaciers. With high emissions, and global mean temperature rise exceeding 4°C by 2100, any substantial seasonal snowpack also will become rare outside the polar regions and very high mountains.[23] The need to cut emissions is underscored by recent research that confirms even high-altitude glaciers previously considered to not be prone to hazards have been weakened sufficiently to be capable of producing catastrophic and cascading floods.[28]

In those "high elevation and high latitude" regions, only 35–75% of glacier volume will remain by the end of this century under high emissions scenarios.[29] However, if we follow a very low emissions pathway, the glaciers and snowpack of High Mountain Asia – important for seasonal water resources – will stabilize and eventually begin to return within centuries under net-zero pathways. Glaciers in Central Asia and the southern Andes

Image by Praful Rao of Save the Hills

Flood damage in Rangpo, India caused by the Sikkim flood, when the Teesla III Dam was swept away by a glacier lake outburst flood (GLOF) in October 2023; on August 16, 2024 a GLOF from Thyanbo Glacier washed away Thame Village in Nepal.

FIGURE 3-1. **Glaciers of High Mountain Asia**



High Mountain Asia includes the highest mountains of the world, but even these extremely high altitude glaciers, which provide seasonal water to at least 2 billion people, will lose most of their ice by 3°C.

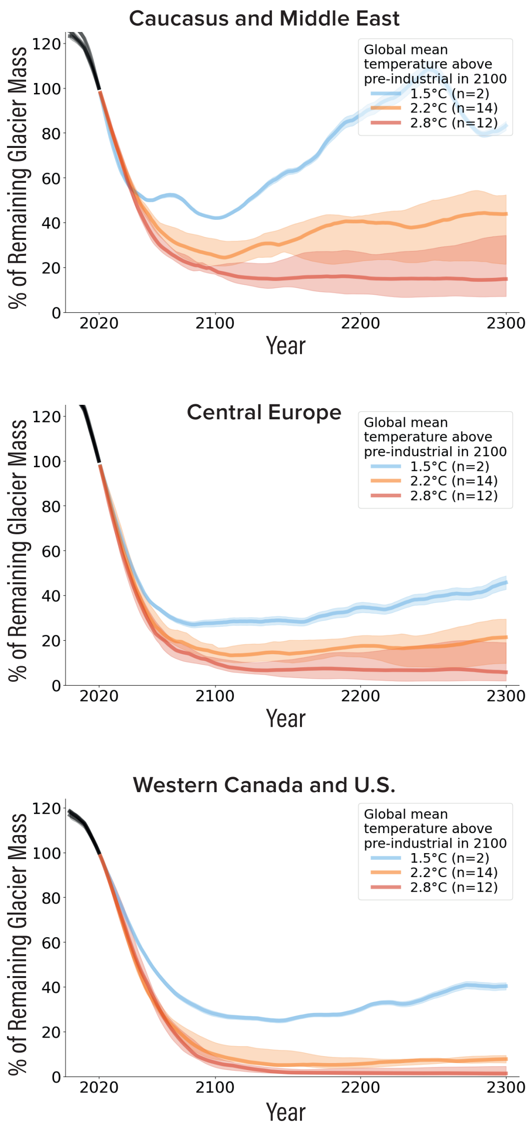
SOURCE: SCHUSTER ET AL. (2024)

also would preserve twice as much ice with rapid emissions reductions consistent with the 1.5°C limit.[26] At higher emissions levels resulting in peak temperatures above 2°C, losses in high elevation and high latitude regions will continue. With very high emissions, like today's year-on-year rise in CO_2 concentrations, this loss would be ever more rapid.[29]

Glaciers generally gain mass via snow deposition in winter and lose mass as meltwater in summer over the course of a year. Global warming means that a given glacier will experience a net loss of ice every year at higher and higher elevations, because the annual gain by snowfall turning to ice decreases, and an increasing loss from melting especially at low elevation significantly outpaces the gain each year. A threshold is crossed when the entire glacier, from bottom to top, is losing ice each year: at that point, the glacier is doomed. The majority of glaciers in the European Alps experienced this during the summers of 2022 and 2023,[30,31] with an overall loss of 10% of the total volume of Swiss glaciers alone over the two summer melt seasons.[31,32]

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

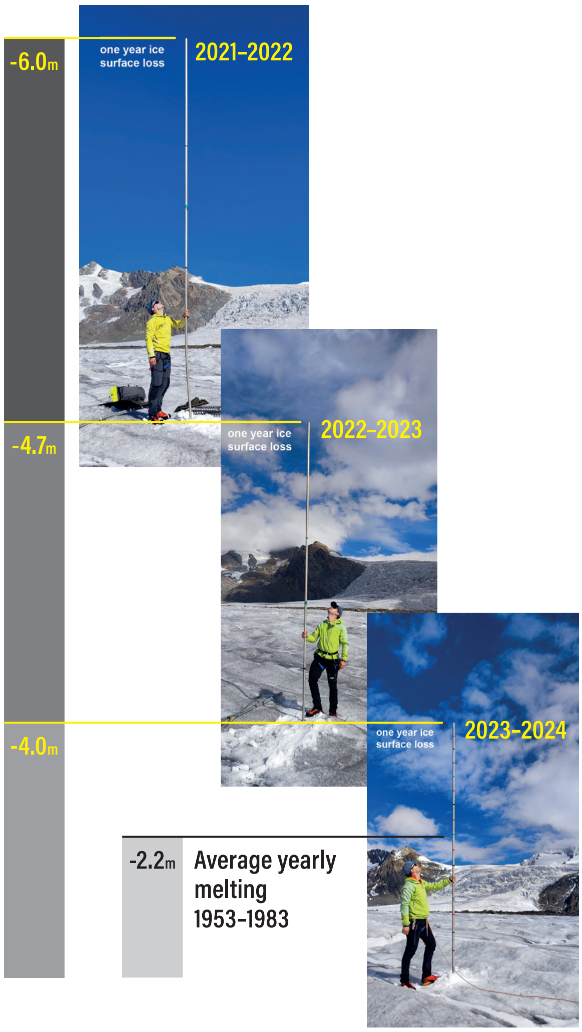
FIGURE 3-2. **Mid-Latitude Glaciers**



At 1.5° C, not only do models show the glaciers in the Caucasus, Alps and western North America preserving more of their ice, but some level of re-growth by 2300.

CREDIT: SCHUSTER ET AL. (2023)

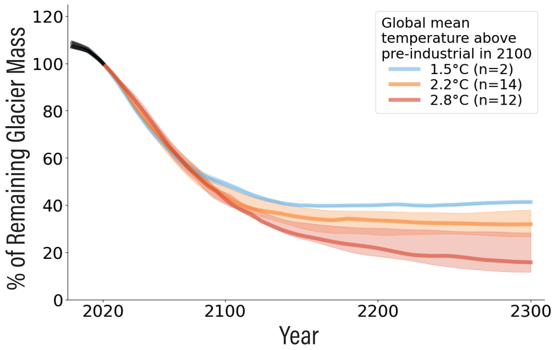
FIGURE 3-3. **Three Record Years of Ice Loss**



Height of glacier ice loss from the Great Aletsch Glacier (Switzerland), Europe's largest glacier, taken at Konkordiaplatz high up on the glacier, at around 2800 meters during record melt years 2022, 2023 and 2024 compared to the average yearly ice loss between 1950–1980.

PHOTO: MATTHIAS HUSS.

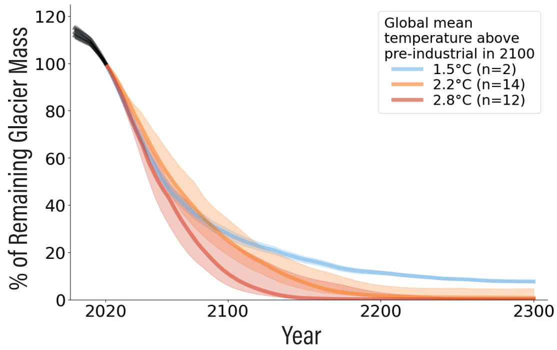
FIGURE 3-4. **Glaciers of Alaska**



Very large glaciers, such as those in Alaska, behave somewhat like ice sheets: slow to melt in the beginning, but then accelerating and continuing for centuries.

SOURCE: SCHUSTER ET AL. (2024)

FIGURE 3-5. **Glaciers of Scandinavia**



Ice loss in Scandinavia is accelerating: Sweden lost more ice in 2024 than ever before in 80 years of observations. Some remnants of ice will be preserved however with low emissions.

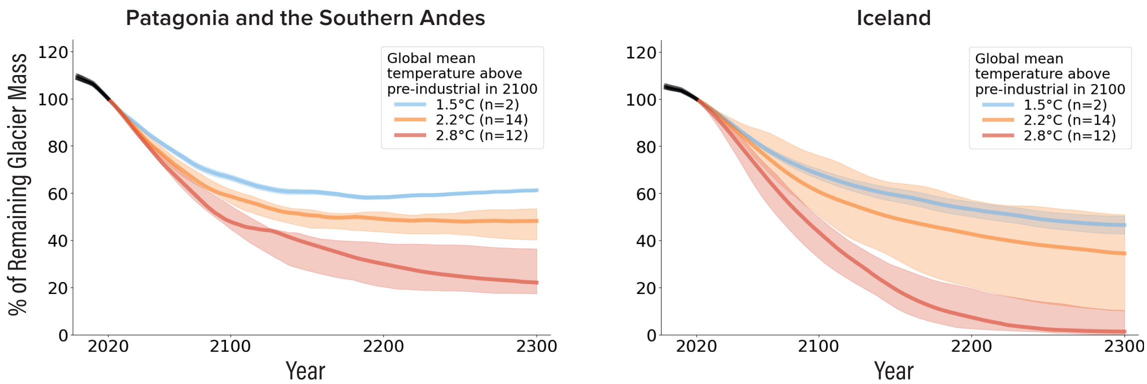
SOURCE: SCHUSTER ET AL. (2024)

those have shrunk by about two-thirds in surface area. Half of the glaciers in World Heritage sites globally will likely disappear by 2100 if emissions continue at their current high levels.[33] From 1901 to 2018, glaciers outside Antarctica contributed nearly 7 cm to global sea-level rise.[34] While such melt has been rapid, glaciers grow back only slowly, especially at temperatures above pre-industrial. A recent study under review seems to indicate that "re-growth" of mountain glaciers, to scales present in the mid-1900's or even today, would take many centuries; and perhaps even millennia in some regions even after temperatures decrease due to lower CO_2 concentrations in the atmosphere.[35,36]

Therefore, on human timescales, the disappearance of today's glaciers is an essentially permanent change to the mountain landscape. Very low emissions are key to ensuring as little ice as possible is lost during this current period of rapid decline. A very low emissions pathway is essential to preserving the ecosystem services glaciers provide, which are already facing losses and extinctions,[18,37,38] and to minimizing the risk of severe hazards such as glacial lake outburst floods that accompany loss of mountain glaciers.[39,40,41,42]

To preserve as much glacier ice, snow and their ecosystem services as possible and minimize catastrophic events, 2025 NDCs must commit to a credible 1.5°C goal.

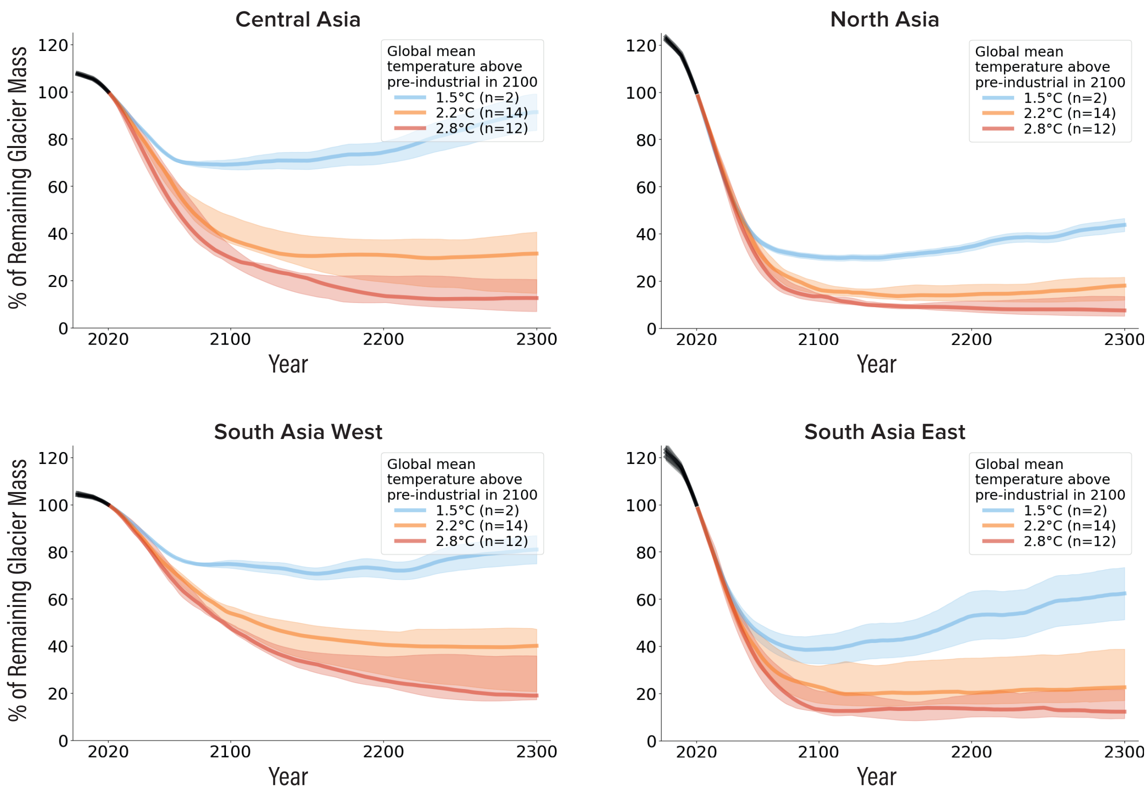
FIGURE 3-6. **High Latitude Glaciers**



Glaciers in Patagonia and Iceland 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 3-7. **Glaciers of Asia**



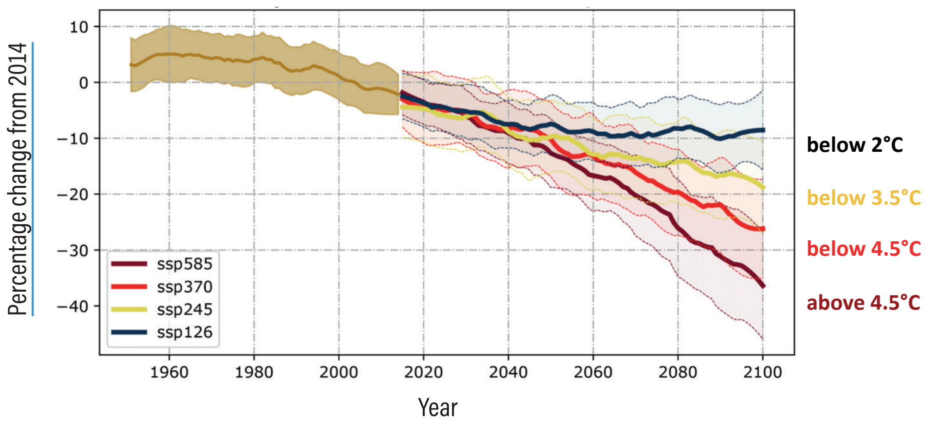
Glaciers in Central, North and South Asia lose nearly all of their ice by 3°C, and only show some recovery by humanity following a 1.5°C consistent pathway.

SOURCE: SCHUSTER ET AL. (2024)

In addition to glaciers, mountains also store water in the form of snow. In fact, seasonal freshwater in many mountain and lowland regions is dependent on annual snowfall, and meltwater from snow is of greater importance than meltwater from glaciers in many areas. However, snowfall has become less consistent in many mountain watersheds, with extremes of "snow drought" alternating with high amounts of snow, or wet snow, that increase the risks of avalanche and flood,[43] such as in California, USA in winter 2023[44] and the Hindu Kush Himalaya in winter 2023–2024.[3] In many mountains, it now appears that snow generally is following the same downward trajectory as glaciers: snowfall is reducing as temperatures rise above freezing at higher and higher altitudes, with precipitation that would have fallen as snow in past decades, increasingly coming down as rain,[34] and often in the form of hazardous extreme rainfall.[34] At lower elevations and latitudes, snow will fall less often or not at all, and the winter season will shorten.[45,46] Seasonal snowpack will not form, resulting in loss of stored water in the snow itself and in underground aquifers. A decreasing extent and duration of snowpack has already been observed in many mountain areas.[47,48] Continued declines in annual snowpack will result in negative economic impacts for many sectors, especially agriculture,[49] hydropower, and tourism,[50] with global ramifications; and threatens the availability of sufficient water supplies for downstream populations.[29,51]

Mountain snow sustains water supplies for ecosystems and people far beyond mountain regions, as meltwater travels great distances across grasslands and deserts to densely populated and cultivated coastal regions. For example, people in cities as diverse as Los Angeles, Delhi, and Marrakech are to some degree dependent on meltwater from snow. In the western U.S., rising temperatures have caused a general decrease in annual snowpack, leading to ever more severe water shortages.[52] In both the Arctic and mountain regions, the well-being of people and many species depend on seasonal snow cover. For reindeer-based Arctic Indigenous cultures, increasing numbers of animals are lost to starvation when more unseasonal rains fall on snow, forming thick layers of ice that makes it impossible for reindeer to access grazing through the ice cover.[53] Decreases in snow cover negatively impact snow-dependent tourism, especially in the United States, Japan, and Europe.[54] Lack of mountain

FIGURE 3-8. **Decline in Northern Hemisphere Snowpack**



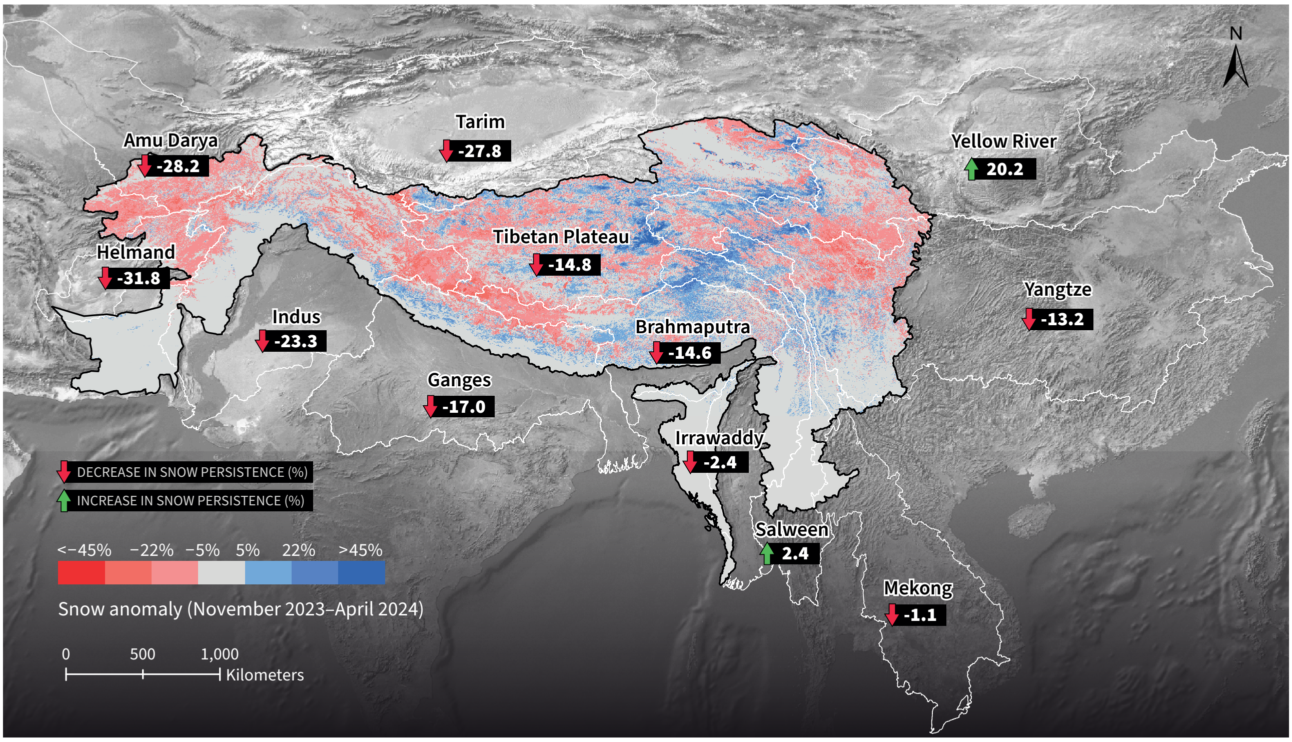
Under a high emissions scenario, snow cover in the Northern Hemisphere will decline by nearly 50% by 2100.

CREDIT: MUDRYK ET AL. 2020

snow cover also increases the risk of wildfires, as well as natural hazards that can materialize as disasters such as mudslides in the wake of such wildfires. In some areas, the impacts of glacier melt and snowmelt on freshwater availability have already contributed to increasing tensions and/or conflicts related to water resources.[35]

A strengthening of climate pledges will have especially significant benefits for those communities in the Andes and Central Asia that are most dependent on glacier runoff as a seasonal source of water for drinking, hydropower and irrigation. Stronger pledges also will significantly benefit economies dependent on meltwater

FIGURE 3-9. **Loss of Snowpack in Vital Asia River Basins**



Snow cover anomaly between November 2023 and April 2024 compared with average (2003–2023).

CREDIT: ICIMOD

Photo: Vastram / Alamy Stock Photo

View of Shahdag Mountain, Azerbaijan. Glaciers in Azerbaijan have melted 18% in the past 7 years, but as much as half the loss could be stopped under very low emissions.

from glaciers and seasonal snowpack for power generation,[55] agriculture and revenue from snow tourism, such as in the European Alps and North American West. Low emissions also allow local communities more time to adapt, even in those equatorial and mid-latitude regions where smaller glaciers are doomed to disappear completely even at 1.5°C.

Every fraction of a degree of global temperature rise substantially impacts the loss of the mountain cryosphere.[26,56] New research highlights ongoing overconfidence in sufficiently drawing down temperatures with any overshoot of the Paris Agreement, reinforcing the need for drastic emissions cuts.[57] Due to warming to-date, mountain and downstream populations must be prepared for current steep losses to continue through at least mid-century. However, a sharp strengthening of climate action towards the 1.5°C limit will determine the future after that point. To preserve as much glacier ice, snow and the ecosystem services they provide, as possible and to minimize catastrophic events in the second half of this century, 2025 NDCs must commit to a credible 1.5°C goal.[58] This requires course correction to a minimum of 40% reduction in human-induced GHG emissions by 2030, and stronger commitments and implementation of actions in the near-term 2030-2040 timeframe. These low emissions pathways, minimizing overshoot, mark the difference between rapid and disruptive loss of regionally important glaciers and snowpack, and significant steps towards their preservation.

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CHAPTER 4

Permafrost

Exceeding 1.5°C Makes Mitigation Far More Difficult, Adding to Loss and Damage Locally and Globally

Current NDCs (2.3°C by 2100): Permafrost emissions at this temperature level will increase burdens of mitigation, adaptation, and loss and damage not just locally due to infrastructure damage, but across the planet by decreasing the remaining carbon budget. Once thawed, permafrost begins emitting carbon dioxide (CO_2) and methane (CH_4). These emissions are irreversibly set in motion and will not cease for one to two centuries, meaning that future generations must offset them (draw down carbon) at scales the size of major greenhouse gas emitting nations. If current NDCs are not greatly improved, annual total permafrost emissions (as both CO_2 and CH_4)* may total the size of the entire European Union's emissions (calculated from 2019 as ≈200Gt total by 2100) and about twice that by 2300. Since the Arctic is warming 2–4 times faster than the rest of the planet, northern high-latitude permafrost regions will reach 4–8°C on average, with more extreme heat events that can lead to "abrupt thaw" processes where coastlines or hillsides collapse or lakes form, exposing much deeper and greater amounts of permafrost to thaw, which means emissions might be greater than projected.

1.5°C Consistent Pathways: Remaining below 1.5°C still will produce significant permafrost thaw and related emissions, but keeps them on a much smaller scale since temperatures in the Arctic will "only" average 3–4°C higher than today. This means the additional mitigation needed to offset permafrost emissions will be far less, thereby minimizing loss and damage, as well as decreasing adaptation requirements. Infrastructure damage in the "Country of Permafrost" – Russia, Canada and Alaska, as well as the Tibetan Plateau and other mountain regions – will also be much less if global average temperature remains below 1.5°C compared to impacts that will occur if current NDCs (2.2°C) are not strongly improved. Annual permafrost emissions will still need to be offset by future generations but should be 30% less (about 120–150 Gt by 2100) than what will occur with current NDCs.

Current Rise in CO_2 Levels Continues (3–3.5°C by 2100): If today's rapid warming and permafrost thaw continue, mitigation to maintain net zero emissions from both the "Country of Permafrost" and human activities will become virtually impossible, with permafrost quickly eating up much of the remaining carbon budget to remain within 1.5°C. At such high temperatures, much of Arctic permafrost and nearly all mountain permafrost will thaw, producing annual carbon emissions by the end of this century that are on par with China's annual emissions today, greatly accelerating global heating. Loss and damage from increased emissions globally, as well as pan-Arctic infrastructure damage and catastrophic events such as hillside collapse, will increase, with more economic burden on permafrost communities, moving many well beyond adaptation limits.

* Permafrost emission in CO_2 equivalents (CO_2eq) include both CO_2 and methane emissions from permafrost but are referred to as "carbon emissions" through most of this text for ease of reference.

2024 Updates

- The first comprehensive greenhouse gas budget accounting for carbon dioxide, methane, and nitrous oxide during the period 2000–2020 shows that the Arctic-boreal permafrost region is now a net source of warming. This region's ability to sequester carbon is increasingly offset by emissions from fires, permafrost thaw, inland waters, and wetlands. Since the net warming primarily comes from methane, it lingers and influences global temperatures on decadal timescales after its release into the atmosphere.[1]
- Arctic permafrost releases high levels of carbon dioxide and methane in the fall and early winter as summer thaw grows progressively deeper, overwhelming the Arctic's ability to naturally balance itself through carbon sequestration from plant growth. In other words: permafrost in northern circumpolar regions has become a source of atmospheric carbon, which will increase over time if temperatures continue to rise.[2]
- The Arctic contains numerous feedback mechanisms that worsen permafrost thaw and ice loss. For tundra ecosystems, new research on the impacts of future warming reveals that an average temperature increase of 1.4°C in the air and 0.4°C in the soil would boost respiration by 30%, nearly four times greater than previously estimated. These changes accelerate the transition of Arctic tundra from carbon sinks into carbon sources and amplify the effects of climate change.[3]
- On a global scale, permafrost responds to every increment of warming, rather than destabilizing at certain temperature thresholds or tipping points. This means that there is no "safety margin" for acceptable permafrost thaw. Rising temperatures intensify local impacts and global feedbacks.[4]
- Permafrost thaw is also tightly connected to hydrology. Emerging changes to the Arctic water cycle driven by rising temperatures and permafrost thaw could greatly alter high-latitude landscapes and ecosystems this century. Under a high emissions scenario, the Arctic will experience up to 25% more above-ground runoff and 30% more below-ground runoff by 2100, with the southern Arctic becoming progressively drier. This altered water cycle could influence Arctic sea ice, biodiversity patterns, and even the global climate by impacting ocean freshwater storage and major Atlantic currents.[5]
- Rising water temperatures, destabilization of riverbanks due to ground thaw, and increased water levels also increase the rate of Arctic riverbank erosion in permafrost regions, as heat transfers from the flowing rivers into surrounding frozen soils and sediments. Riverbanks with greater ice content are more resilient than those with less ice; however, this protective buffer disappears as temperatures rise. These factors pose a major risk to buildings, roads, and power lines when rivers erode into their floodplains.[6]
- Coastal permafrost erosion decreases the Arctic Ocean's capacity to absorb carbon dioxide, which could lead to a 14% reduction in uptake by 2100 under a worst-case scenario. Another way to frame it: coastal erosion could contribute to an annual increase in atmospheric carbon dioxide equivalent to 10% of all European car emissions in 2021. The findings have worrying implications for the Arctic Ocean's vital ability to act as a carbon sink. This erosion has the potential to increase atmospheric carbon dioxide by 1.1–2.2 million tons per year for every degree Celsius of global warming.[7]
- In alpine regions, small mountain glaciers release high levels of methane gas in their meltwater runoff, unleashing previously frozen methane stores as the ice retreats. Similar studies have documented such methane release from glaciers across Greenland, Svalbard, and Iceland; adding to this knowledge base, new observations in Alaska make clear that retreating small mountain glaciers also contribute to global methane emissions.[8]

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Permafrost emissions at current NDCs will increase burdens of mitigation, adaptation, and loss and damage due to infrastructure damage, and across the planet by decreasing the carbon budget.

Background

Permafrost is ground that remains frozen through at least two years. The permafrost region covers 22% of the Northern Hemisphere land area and holds vast amounts of ancient organic carbon.[11] Observations confirm that permafrost is rapidly warming and releasing part of that thawed carbon into the atmosphere as both carbon dioxide (CO_2) and methane. Permafrost thaw is projected to add as much greenhouse gas forcing as a large country, depending on just how much the planet warms. Today, at 1.2°C of warming above pre-industrial, annual permafrost emissions are about the same as Japan's, currently a top-20 emitter of greenhouse gas emissions.[12]

Permafrost stretches across Arctic tundra and boreal forest, especially in Siberia, and also occurs in high mountain regions globally. Of greatest concern to climate is near-surface permafrost (i.e. the first few meters below the surface), but permafrost sometimes extends to depths of over a thousand meters.[13,14,15]

Permafrost is a frozen mixture of soil, rock, ice and organic material, holding about three times as much carbon as currently exists in the Earth's atmosphere. In addition to the Arctic, it includes permafrost spread across the Tibetan Plateau and near-coastal Arctic subsea regions.[11,16,17] Cold temperatures in stable permafrost

FIGURE 4-1. **Permafrost Emissions at 1.1°C**

Committed annual permafrost emissions to 2100 will be about the scale of Japan's annual emissions today, about 0.5Gt/year, even with no further rise in temperature.

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

have protected this organic matter from decomposing for many thousands of years.

Permafrost also occurs in shallow near-coastal seabeds especially off Eastern Siberia, in areas not covered by sea water at the end of the last Ice Age, but flooded as temperatures rose. This subsea permafrost is rapidly thawing, as it has been "prewarmed" by overlying seawater throughout the past 10–15,000 years, with elevated methane concentrations measured in shallow coastal waters.[18] Subsea permafrost's current and future contributions to carbon emissions remain uncertain but could be significant. Estimates of total amounts, which are highly uncertain, range from 170-740 Gt carbon, with 14–110 Gt carbon potentially released under high emissions by 2100 and up to 45-590 Gt by 2300 as the Arctic Ocean continues to warm on a multi-century level once atmospheric temperatures pass 4°C.[18]

The Arctic and high mountain regions are now warming at 2-4 times the global average,[19] making these ancient permafrost stores of carbon highly vulnerable to thaw; followed by subsequent release of that stored carbon through the action of soil microbes over many years after that initial thaw.[20]

Most of this released carbon comes as CO_2. However, permafrost also exists under lakes, wetlands and peatlands. When it thaws under such wet conditions, some of that carbon enters the atmosphere as methane. While not lasting as long in the atmosphere as CO_2, methane warms the climate far more potently during its lifetime: about 30 times more than carbon dioxide over a 100-year period, and nearly 100 times more over 20 years, leading to faster and more intense warming globally.[21] There is some evidence that methane emissions from permafrost wetlands and peatlands have begun to increase.[1]

Some projections show that methane released from sub-Arctic North American wetlands could triple by the end of the century if temperatures exceed 3-4°C, but these emissions could be nearly halved by following a low emissions pathway.[22] If global mean temperature rises even above 2°C however, more than 75% of permafrost peatland regions in northern Europe and western Siberia will become too warm and wet to maintain permafrost by

2024 UPDATES (CONTINUED)

- Unfrozen "talik" layers in dryland permafrost release large methane emissions, nearly three times higher than northern wetland emissions. Taliks emit higher levels of methane during the winter rather than summer, and could create a positive feedback loop that greatly increases temperature and permafrost thaw in Arctic regions.[9]
- Continued high emissions will trigger rapid and irreversible acceleration of subsea permafrost thaw along Arctic coastlines by 2080, with all coastal permafrost thinner than 100 meters disappearing by 2300. In this worst-case scenario, the loss of year-round Arctic sea ice and ensuing Arctic amplification would push subsea permafrost across a critical threshold into runaway loss. Only low emissions, with carbon dioxide production cut to net zero around 2075 or sooner, will allow large areas of the Arctic seafloor currently underlain by permafrost to remain frozen for the next thousand years.[10]

the 2060s. Yet even with low emissions, models do not project a return to conditions suitable to maintain peatland permafrost in Norway, Sweden, Finland, and parts of Russia – suggesting that these permafrost peatlands are close or have already passed a tipping point.[23]

Models project that the land area covered by surface permafrost (in the first few meters of soils) will decline across large regions as temperatures rise.[17] Estimates show that here has already been about a 7% decrease in near-surface permafrost extent over the past five decades,[24] and at the global average temperature increase of 1.2°C, we are already committed to losing about 25% of surface permafrost. Scientists anticipate that 40% of near-surface permafrost area will be lost by 2100, even if we hold temperatures close to 1.5°C globally. Over 70% of pre-industrial surface permafrost will thaw by 2100 should temperatures exceed 4°C.[25]

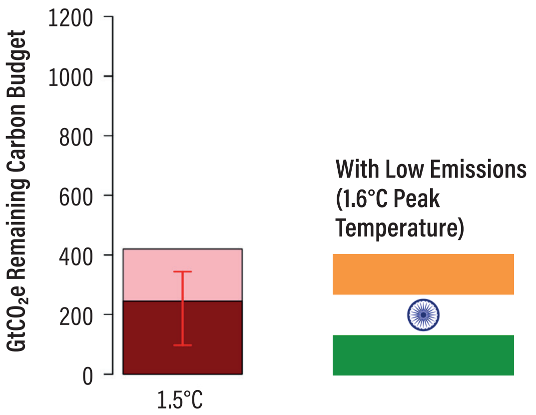
In addition to the impacts of permafrost thaw on global climate, the direct physical effects of permafrost thaw – such as ground slumping, lake drainage, increased erosion and flooding – have severely impacted Arctic and mountain people, lands, and economies for decades. Thawing permafrost is causing the loss of Arctic lands, threatening cultural and subsistence resources, and damaging infrastructure, like roads, pipelines and houses, as the ground sinks unevenly beneath them.[26] According to AMAP's latest *Climate Update*, more than 66% of Arctic settlements are located on permafrost. In Alaska, for example, permafrost thaw will increase cumulative maintenance costs of public infrastructure by an estimated US$5.5 billion by 2100.[27] Some Alaskan permafrost is now in a thawed state year-round. With high emissions, three-quarters of Alaska's permafrost zone may reach this permanently unfrozen state within the next decade, with the thawed layer reaching depths of 10 m or more by 2100.[28]

Coastal and riverine permafrost erosion has already required some communities in Alaska to relocate homes and entire communities. Russia (with 60% of its total land area on permafrost) faces the most extensive risk, with recent studies estimating infrastructure loss and damage of tens of billions of dollars by 2050 if current warming continues.[29]

The Tibetan Plateau has warmed two times faster than the global average over the past several decades, increasing the vulnerability of its permafrost to thawing, sinking, and collapse. Limiting warming below 1.5°C instead of 2°C could reduce the costs of infrastructure damage from permafrost thaw in the Tibetan Plateau by $1.32 billion before the end of the century.[30] Under even "moderate" emissions, nearly two-thirds of the permafrost area in the Tibetan Plateau will become a "high-hazard" zone by 2100.[31]

Permafrost thaw occurs gradually over its entire region but is also vulnerable to abrupt thaw events that can result in collapse and erosion, which can further accelerate thaw by exposing additional permafrost to warmer air temperatures and rain.[32] Such rapid collapse can result in the formation of new lakes or wetlands, where additional and deeper thaw may occur. In northwestern Alaska, lake drainage rates are now ten times higher than their historical average in the 1980s, with 100–250 lakes rapidly lost each year.[33]

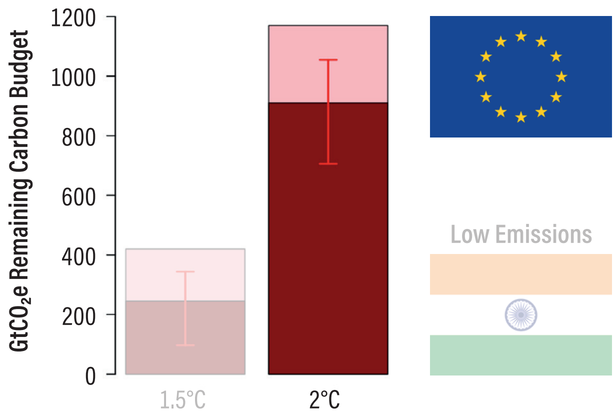
FIGURE 4-2. **Permafrost Emissions Decreas Our Carbon Budget at 1.5°C...**



Committed annual permafrost emissions to 2100 on scale of India's annual emissions today, about 2.5Gt/year, total ≈150–200GtCO$_2$e

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

FIGURE 4-3. **...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$_2$e

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

Credit: U.S. National Park Service

Noatak National Preserve, Alaska, 2004, when an exceptionally warm summer in 2004 triggered this 300 meter shear that exposed even more permafrost to abrupt thaw.

More incidents of extreme summer rainfall may also rapidly increase the depth of permafrost thaw by more than 30%. Under a high emissions scenario, precipitation in the Arctic is projected to increase by 60% by 2100 and increasingly shift from snow to rain due to rising air temperatures.[34] Climate warming also decreases the duration of winter snow cover while increasing the amount of snowfall. Deeper snow only lasting short periods can rapidly thaw permafrost; over several decades, it can lead to a four-fold increase in the amount of thawed permafrost and related carbon emissions.[35]

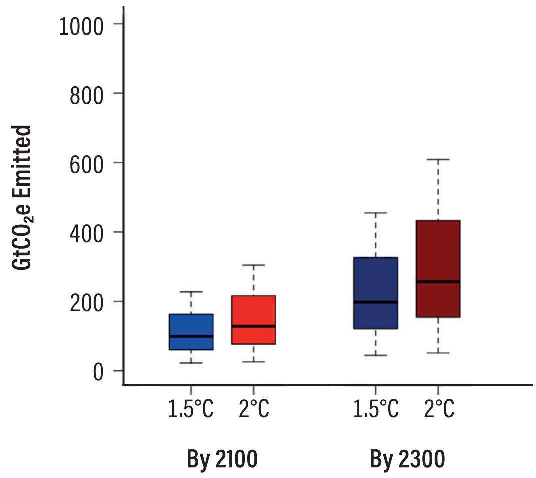
Increasing wildfires in the Arctic due to warmer and drier conditions also cause deeper and more rapid post-fire permafrost thawing.[36] At high latitudes, where much of the permafrost domain is located, most emissions from wildfire originate from combustion of soil rather than the combustion of above-ground biomass. Like emissions from other abrupt thaw events, these fire-related emissions – either from direct combustion, or from the effects of fire on permafrost – are typically excluded from global-scale models.[37,38]

Coastal permafrost is especially vulnerable to abrupt thaw, with the additional erosion from wind and waves by warmer and more storm-prone Arctic seas. As coastal permafrost thaws, it can contribute to increased erosion of thousands of kilometers along the coasts of Alaska, Canada and Russia, and across the Arctic.[39,40,41,42] Rising global temperatures have even accelerated permafrost thaw in Greenland, increasing the vulnerability of its coastal communities to unpredictable landslides and collapse.[43]

Near-coastal subsea permafrost is sometimes confused with deep seabed methane clathrates (methane deposits). These represent an additional potential source of methane emissions, with the most vulnerable part at around 300–400 m depth along the upper continental slope off Eastern Siberia. Such clathrates may have contributed to rapid warming events in Earth's deep past, around 85 million years ago or more, though this remains controversial. Some of the extensive methane releases observed both on the East Siberian Shelf Seas and in sinkholes on the Yamal peninsula are hypothesized to come from collapsing methane hydrates.

Feedback loops may therefore abound that increase permafrost emissions more than currently estimated. Warming in the Arctic already is occurring 2–4 times faster than the rest of the planet, with loss of snowpack, glaciers and sea ice.[19] The darker exposed bare ground and seawater absorb far more heat, further accelerating Arctic warming and additional thaw and loss of permafrost. A

FIGURE 4-4. **Emissions Continue for Centuries – 1.5°C versus 2°C**



ADAPATED FROM GASSER, ET AL. (2018)

2°C higher annual temperature globally translates into 4–8°C higher annual temperatures in the Arctic, including longer and more intense fire seasons and increasing heat waves where temperatures exceed 20°C sometimes for weeks on end, leading to much greater permafrost loss in a continuing feedback loop.

Current global climate models do not yet include these abrupt thaw processes, which release frozen carbon previously considered immune from thawing for many more centuries.[26,41,44] The number of these rapid thaw events has increased as the Arctic warms and might increase permafrost carbon emissions by as much as 40% as the planet warms to 1.5°C or more.[42]

During a warm period roughly three million years ago, more than 90% of the permafrost then existing (which was nearly as large as today's permafrost extent) disappeared under climate conditions similar to those projected under high emissions. Near-surface permafrost remained only in a few pockets of the eastern Siberian uplands, Canadian high Arctic archipelago and northernmost Greenland.[45]

Once triggered, emissions from permafrost thaw processes are most often permanent on human timescales, because re-building of new permafrost soils takes centuries to thousands of years.[46] While new vegetation growing on thawed permafrost soils might take up some portion of these emissions, the sheer scale of permafrost emissions at warmer temperatures would likely dwarf such uptake.

The global impacts of permafrost thaw therefore have cascading effects on health, infrastructure, ecosystems and a wide range of socioeconomic variables.[47,48] The greatest global risk, however, arises from the additional carbon released, which will decrease the carbon budget available to countries to prevent temperatures from rising above 1.5°C, 2°C or more.[49,50]

The scale of permafrost emissions in the future nevertheless remains within human control, by holding temperatures as close to 1.5°C as possible. While there are large ranges for future emissions from the "Country of Permafrost," they are almost certainly on the same scale as large industrial countries[20,51] and will rise with each tenth of a degree:

- If we limit warming to 1.5°C, annual emissions through 2100 will be about as large as those annually from India today, 2.5 Gt/year, totaling around 150 Gt CO_2-eq by 2100.
- Should we instead reach 2°C, permafrost emissions will about equal those of OECD Europe, 3-4 Gt/year, for about 200 Gt CO_2-eq by 2100.
- Higher temperatures, exceeding 3-4°C by 2100, will likely result in up to 400 Gt CO_2-eq additional carbon release from permafrost, adding the equivalent of another United States or China (currently 5-10 Gt/year) annually to the global carbon budget through 2100.[25,37,41,51,52,53]

Calculations of the remaining planetary carbon budget must take into account these indirect human-caused emissions from permafrost thaw to accurately determine when and how emissions reach "carbon neutrality"; and not just through 2100, but well into the future.[50,51,54] The actions of decision makers today to delay actions to decrease CO_2 emissions will thereby commit future generations to offset permafrost carbon

Buildings in Nunapitchuk, Alaska, are sinking due to thawing permafrost, a frozen layer of soil that has underpinned the Arctic tundra and boreal forests for millennia. This thawing ground produces massive sinkholes, forms and drains new lakes, and collapses shorelines already at today's temperatures.

CREDIT: SUE NATALI / WOODWELL CLIMATE RESEARCH CENTER.

emissions through negative emissions (carbon dioxide removal), even after all human emissions cease and temperatures stabilize.[47]

There are no local, on-the-ground solutions for keeping permafrost frozen on a regional scale, with its carbon locked in the soil. The only means available to minimize these growing risks is to keep as much permafrost as possible in its current frozen state, holding global temperature increases to 1.5°C. This will greatly decrease the amount of additional carbon entering the atmosphere from permafrost thaw for the next one-two centuries, and thereby minimize the long-term burden of negative emissions laid on future generations.

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Sea Ice

Cascading Global Feedbacks above 1.5°C Would Increase Adaptation Needs, Loss and Damage Worldwide

Current NDCs (2.3°C by 2100): Global feedbacks from sea ice loss at both poles would increase adaptation and loss-and-damage burdens around the planet. Every year, the Arctic Ocean would be practically sea ice-free for up to four months (July-October). The less reflective open water would absorb more heat from polar 24-hour sunlight conditions. This warmer Arctic will increase coastal permafrost thaw, adding more carbon to the atmosphere and increasing coastal erosion; speed Greenland Ice Sheet melt and resulting sea-level rise; and have unpredictable and potentially extreme impacts on mid-latitude weather patterns. Around Antarctica, near-complete loss of sea ice every summer seems plausible at 2.3°C given current trends at today's 1.2°C. Loss of buttressing sea ice would speed ice shelf collapse, thereby increasing melt from the Antarctic Ice Sheet and resulting sea-level rise. Warmer waters also mean that any recovery of sea ice may take many decades, especially around Antarctica, even with a subsequent return to lower atmospheric temperatures, because the ocean will hold that heat far longer. While some economic analysts see Arctic sea ice loss as a positive due to greater regional economic potential, the extreme levels of loss and damage and increased adaptation needs would almost certainly greatly eclipse any temporary economic gains, even by Arctic nations themselves.

1.5°C Consistent Pathways: Studies consistently indicate that Arctic sea ice will still melt almost completely some summers even at 1.5°C, but not each year and only for a brief period (days to a few weeks) when it does. Reducing the frequency of ice-free conditions will greatly decrease impacts and feedbacks both in the Arctic and throughout the planet, decreasing adaptation burdens, though still with some impacts tipping into loss and damage, especially for Arctic Indigenous and coastal communities. Projections of sea ice loss in the Southern Ocean around Antarctica are considerably less certain, but record-low conditions in 2023–24 indicate that its threshold for complete sea ice loss in summer might be even lower than for the Arctic. "Very low" emissions (SSP1-1.6, which peaks at 1.6°C) may lead to some recovery of sea ice at both poles by 2100, when temperatures begin to decline below 1.4°C.

Current rise in CO_2 levels continues (3–3.5°C by 2100): If CO_2 concentrations continue to grow in the atmosphere at today's pace, which has not decreased despite current pledges, global temperatures will reach at least 3°C by the end of this century. At such high temperatures, the Arctic Ocean will be ice-free for nearly 180 days each year, leading to enhanced Arctic warming, increased permafrost degradation, increased Greenland Ice Sheet melt and weather extremes. Though less certain, Antarctic sea ice declines may rival that in the Arctic. Ultimate loss and damage locally and globally will be extreme, well beyond limits of adaptation.

Background

ARCTIC SEA ICE

Arctic sea ice serves as a "global refrigerator" and is an important regulator of the Earth's temperature. This large area of ice-covered 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 polar summer "day," cooling the planet. In contrast to reflective sea ice and snow, the darker open ocean water absorbs heat, amplifying Arctic and overall global warming. Sea ice has served this cooling role in the climate system almost continuously for at least the past 125,000 years, but a study this year found that its cooling effect has decreased by around 20% since 1980 due to loss of summer ice cover.[6]

The area of Arctic sea ice that survives the summer, however, has declined by at least 40% since 1979, when reliable satellite measurements first became available.[9,10] Estimates based on eyewitness accounts from ships and polar explorers place the decline since 1900 at around 60%,[11] most of which has occurred since 1980. In addition, the Arctic Ocean has become dominated by a thinner, faster moving covering of seasonal ice which typically does not survive the summer.[12] This is in contrast to the coverage of thick, rough "multiyear ice" which stands to go extinct entirely with the advent of ice-free summers.[12–15] The total volume of Arctic sea ice since the 1970s has therefore declined by nearly three-quarters: a much faster and greater decline than its area.

This rapid loss of summer sea ice is a significant cause of "Arctic amplification," which refers to the greater rise in temperature observed in the high latitudes of the Northern Hemisphere compared to the rest of the globe.[12,16,17] It also carries wide-ranging weather, ecological, and economic consequences. These include the loss of traditional livelihoods for Arctic Indigenous

2024 Updates

- Only the lowest emissions scenarios, consistent with 1.5°C, offer a possibility of maintaining some remnants of year-round Arctic sea ice. Up to three months of sea ice-free conditions would result with global temperatures at 2°C, extending to four months with ≥2.5°C warming, six months with ≥3.5°C, and eight months with very high emissions (4–5°C and above). Briefly exceeding the lower Paris Agreement 1.5°C temperature threshold would still lead to occasional summer sea ice-free periods every several decades, but these periods could fully disappear with minimal overshoot and sufficient negative emissions that lower CO_2 in the atmosphere. Ice-free conditions can "remain an exception rather than the new normal" if temperatures stay at or return below 1.5°C with only temporary overshoot.[1]
- For the third summer in a row, Antarctic sea ice coverage dropped below two million square kilometers in February 2024, a threshold which had not been breached since satellite records started in the 1980s. These increasingly intense and long-lasting extreme events are growing evidence that Antarctic sea ice may have undergone a "regime shift", entering a fundamentally new state.[2] Antarctic sea ice extreme lows persist rather than recover between seasons, with low sea ice cover observed in all sectors around Antarctica.[3]
- Antarctica's record-breaking low extent in 2023 would have only occurred once every 2,000 years without anthropogenic climate change; and the fact that it happened at all indicates that human emissions are likely influencing recent Antarctic sea ice behavior. Given current emissions and warming, it is likely that Antarctic sea ice will struggle to recover the ice lost from these recent extreme events over at least the next two decades. 1.5°C emissions trajectories on the other hand may eventually slow extreme sea ice loss by 2100, which could help stabilize adjoining ice shelves, and thus losses from the ice sheet itself.[4]
- Antarctica's coastline is fringed with sea ice that protects ice shelves and large glaciers around the continent, but loss of sea ice could remove this protective barrier, resulting in increasing exposure to large ocean waves. In the Antarctic Peninsula, sea ice protecting the Larsen B coastline for over a decade broke away in January 2022 due to a combination of unusually high temperatures, record-breaking low levels of sea ice in the open ocean, and intense ocean swells. Glaciers in this region responded by thinning and retreating, breaking off icebergs at remarkable rates.[5]

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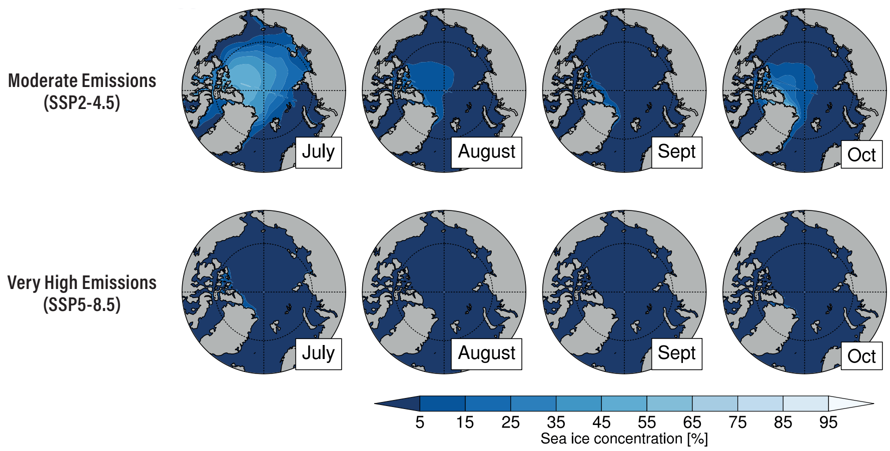
FIGURE 5-1. **Arctic Sea Ice Loss Nearly Year-Round at Moderate and Very High Temperatures**



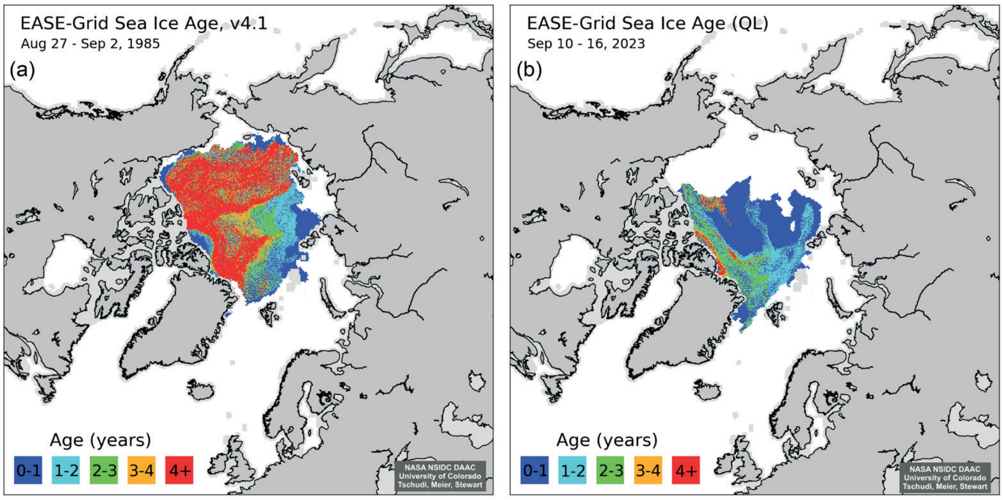
With so-called moderate emissions (temperatures peaking at 2.7°C), the Arctic would be ice-free for much of the summer and fall. With today's emissions continuing however, the Arctic Ocean would reach an ice-free state year-round, with highly unpredictable global feedbacks and consequences, but including accelerated permafrost thaw carbon emissions and Greenland melt.

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

2024 UPDATES (CONTINUED)

- The cooling effect of sea ice by reflecting sunlight has been uncertain due to the potential presence of also-reflective cloud cover even as sea ice declines. High-performance computational techniques together with satellite observations from the 1980s until now confirm that this cooling effect has indeed decreased with sea ice loss not only in the Arctic, but also with the much more recent loss of Antarctic sea ice. Arctic sea ice cooling has decreased by 17–22% between the period of 1980–1988 versus 2016–2023 due to loss of sea ice reflectivity. Cooling from Antarctic sea ice decreased by 9–14% in this same period, despite the fact that Antarctic sea ice extent only began to decline around 2016, after decades of relative stability. This decline in sea ice extent and reflectivity may be part of the reason for more rapid polar warming (3–4 times greater in the Arctic, and twice as much the global mean in Antarctica), contributing to feedbacks much stronger than currently predicted by global climate models.[6]
- The Hudson Bay polar bear population, comprising three of the world's 19 remaining groups (about 4000 individuals), will go locally extinct in the next few decades if today's emissions continue to cause sea ice loss. This is due to loss not only of sea ice extent, but also ice thickness which must be sufficient to hold the weight of bears as they hunt. Once temperatures pass 2°C, the three Hudson population groups would have insufficient strong, thick ice for enough of the year to survive. Presaging this possible future without urgent fossil fuel reductions, unusually high temperatures and strong winds caused an early Hudson Bay ice break-up in spring 2024, with record-low ice extent for May since satellite records began in 1979.[7]
- Declining sea ice extent and longer open water conditions expose Arctic Alaskan coastlines to more intense hazards, including storm surges, floods, and erosion. Should current emissions continue, by 2070 the reduction in sea ice in the Chukchi and Beaufort Seas will allow huge waves to reach Alaskan coastlines throughout December-February, and potentially into the spring as well. Winter storms will simultaneously become fiercer, further increasing risk for those living in these regions. This "potentially disastrous" future for Arctic communities can however be avoided through 1.5°C-consistent emissions reductions that minimize sea ice loss.[8]

FIGURE 5-2. **Loss of Thick Multi-year Arctic Sea Ice**



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

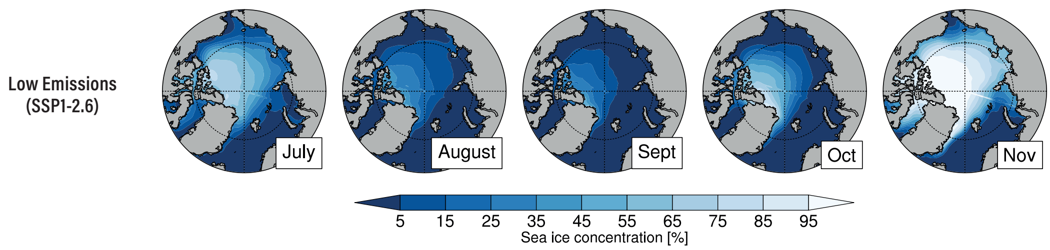
SOURCE: NSIDC

people dependent on stable sea ice platforms for hunting, fishing and travel. Less summer sea ice may also influence mid-latitude weather systems, as exemplified by the persistent and abnormal cold, warm, wet, and dry conditions in recent years that can be related to large north-south undulations in the jet stream.[18–23]

Continued sea ice loss will cause significant harm to Arctic Ocean ecosystems. Many marine organisms there evolved with an ice "ceiling" for much of the year, and populations of these keystone species are expected to crash, except in small pockets with persistent ice during the first ice-free summer event.[12,24] At the other end of the food chain, large predators such as walrus and polar bears that evolved with a "floor" of sea ice will struggle to survive.[7] Even with low emissions, ice-free summer conditions are projected to occur at least once before 2050.[10,14,15,25,26] This will have a lasting effect on the entire Arctic food chain, and perhaps beyond.

Summer Arctic sea ice extent has often been considered a bellwether of climate change, with great attention paid to the September minimum extent each year. In reality, however, sea ice thickness and extent have declined in all months since the 1980s; and the consensus of sea ice scientists is that the ice cover has already fundamentally changed, crossing a threshold to a new state.[12,13,27,28] Amplified Arctic warming has reduced how effectively sea ice can recover in winter.[29] As a result, thinner and younger ice has replaced much of the multi-year ice that used to circulate around the North Pole before being discharged into the North Atlantic Ocean.[12,30,31]

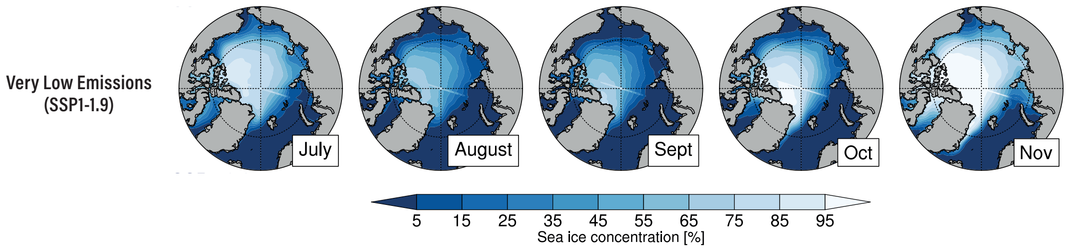
FIGURE 5-3. **Almost No Arctic Summer Sea Ice After 1.8°C**



Even with what most policymakers consider "low" emissions (SSP2-2.6), with global temperatures peaking around 1.8°C, the Arctic will be ice-free most summers, with regional and global consequences, including ecosystem disturbance and potentially, even more extreme weather patterns than today. This emphasizes why even "minimal" overshoot, and remaining close to 1.5°C is so critical.

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

FIGURE 5-4. **More Arctic Sea Ice Year-round with 1.5°C-Consistent Emissions**



Very low emissions (SSP1-1.9) preserve some remnant of sea ice in the Arctic most years.

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

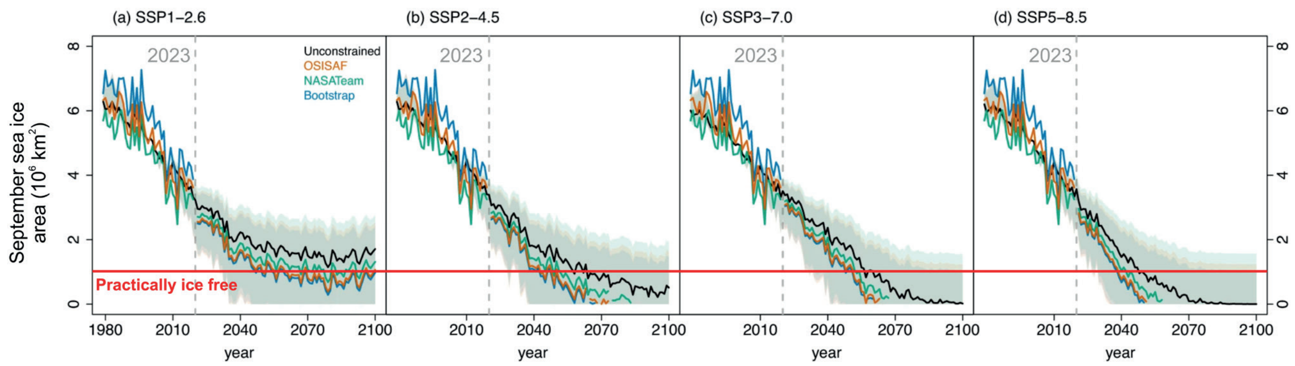
This thinner, weaker ice is more prone to being pushed towards the Atlantic by winds where warmer waters result in faster rates of melting; consequently, sea ice now spends one-third less time in the Arctic Ocean compared to two decades ago.[13]

This former "ecosystem of ice" is today nearly gone. Instead, more than three-quarters of Arctic sea ice now consists of first-year ice that largely melts each summer; the "older" ice now exists for only 1-3 years on average.[12] Warming also has slowed the re-growth of Arctic sea ice in fall and winter following the melt season. Continued Arctic warming has particularly reduced the number of days in which sea ice is produced in the Kara and Laptev seas — regions often called the „ice factories of the Arctic" due to their essential role in forming winter sea ice.[29] The frequency of atmospheric rivers – narrow corridors of warmer, moist air – has increased over the central Arctic, causing slower refreezing of the fragile ice attempting to recover after the summer melt season.[32]

Despite this fundamental change already observed at today's heightened temperatures, the first ice-free summer will be an event that the Arctic likely has not experienced since at least the spike in warming that occurred at the end of the last ice age 8,000 years ago, and possibly not since the warm Eemian period 125,000 years ago.[33] Today's temperatures now almost equal those of the Eemian, when much of Greenland may have been ice-free in part due to feedbacks from this seasonally open and warmer Arctic Ocean, with sea levels 5-10 meters (16-32 feet) higher than today.[34,35] This is the current trajectory of the Earth's climate; CO_2 levels from human emissions today are higher than at any point in at least the last 3 million years.

Like many impacts of climate change, Arctic sea ice loss over the past three decades has not occurred gradually, but rather in abrupt loss events when combinations of wind and warmer temperatures drove lower ice extents that then set a new baseline.[9,36–39] It is likely that a near-complete loss of summer sea ice (defined as dipping

FIGURE 5-5. **Only "Very Low" Emissions Preserve Arctic Summer Ice**



Updated projections of September Arctic sea ice area for different emissions scenarios using state-of-the-art modeling. Only very low emissions (SSP1) results in sea ice recovery above ice-free conditions.

SOURCE: KIM ET AL. (2023)

below 15% of the Arctic Ocean's area, or 1 million km^2 of ice cover) will occur with one of these sudden events, but perhaps not occur again for several years. Eventually total-loss summers will become more frequent, and if global temperatures continue to rise past a threshold of about 1.7°C, they will become the norm for some portion of each summer, with ice-free conditions ultimately extending into spring and autumn.[14,25,40,41]

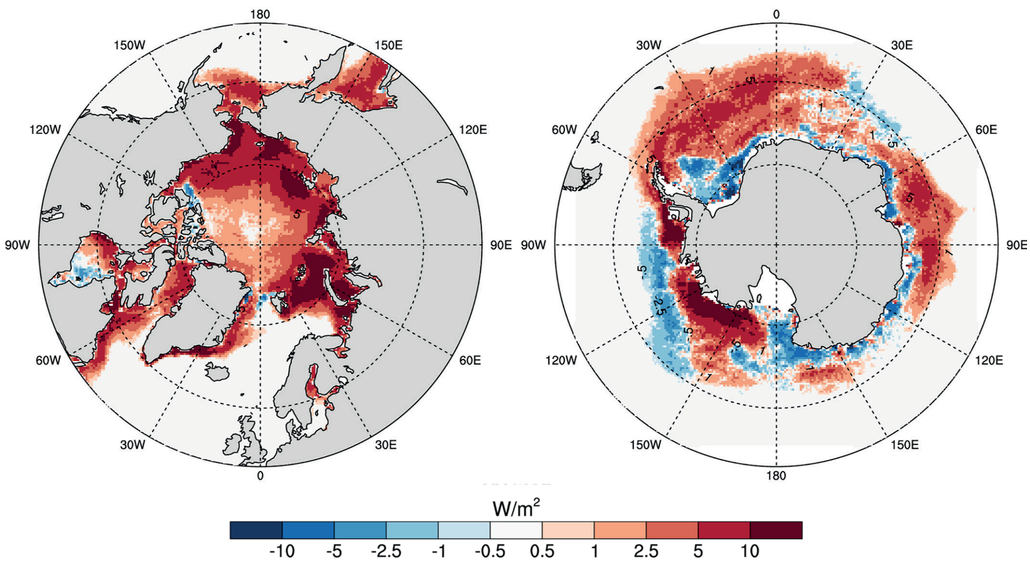
The occurrence of the first sea ice-free Arctic summer is therefore difficult to predict, but scientists now believe it is inevitable, and likely to occur at least once before 2050 even under a "very low" emissions scenario.[10,12,15,41] However, under both very low and low emissions scenarios, summer sea ice extent would likely stabilize, with occasional ice-free years, but remain generally above the threshold for ice-free conditions. Greater amounts of sea ice may then form, slowly increasing as global atmospheric temperatures decline below 1.5°C, but with multi-year ice nevertheless taking many decades to re-form due to a warmer Arctic Ocean.[36]

In contrast, continuing on the current emissions trajectory may lead to the Arctic becoming ice free in the summer as soon as the 2030s.[25] Even moderate emissions will lead to ice-free conditions most summers once global mean temperature rise reaches about 1.7°C. The length of this ice-free state would increase in lock-step with emissions and temperature,[26,40–42] eventually stretching from July–October at 2°C.[1,26,43] The effects of amplifying feedbacks will be widespread, ranging from accelerated loss of ice and associated sea-level rise from Greenland; to losses of ice-dependent species; to greater permafrost thaw, leading to even larger carbon emissions and infrastructure damage.[12,40]

The global impact of complete Arctic summer sea ice loss will therefore include accelerated global warming and its cascading impacts. Given the greater absorption of solar heat into open water, it will lead to higher autumn and winter temperatures in the Arctic that are expected to affect weather patterns around the Northern Hemisphere.[18,20–23,44–47] Unusual weather patterns likely will involve persistent conditions (drought, heatwaves, cold spells, or stormy periods), such as the extreme current multi-year drought in the U.S. Southwest; extreme heatwaves in northwestern North America in June 2021 and much of Europe in 2022 and 2023;[22] the summer 2018 drought in Scandinavia that contributed to extensive wildfires and agricultural losses, and the severe freeze in the central U.S. during February 2021.[19,48] Accelerating permafrost thaw and melting of land ice on Greenland and Arctic glaciers would lead to greater emissions of greenhouse gases and faster sea-level rise.

Finally, while some Arctic and other governments declare that an ice-free summer Arctic will bring near-term economic opportunity, it is important to balance such statements with the global impacts elsewhere. The 2°C of global warming above pre-industrial levels that will

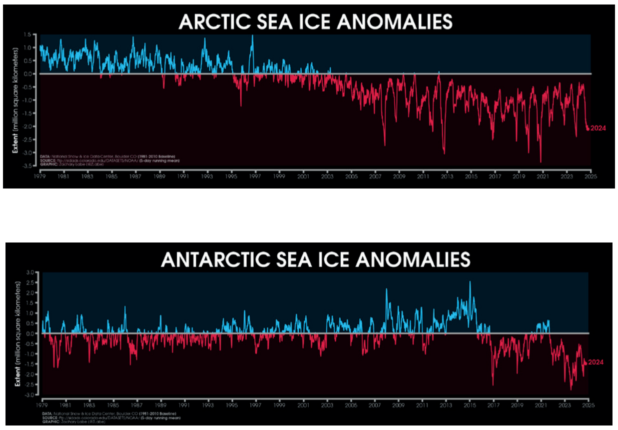
FIGURE 5-6. **Loss of Sea Ice Albedo (Reflectivity) from Warming To-date**



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

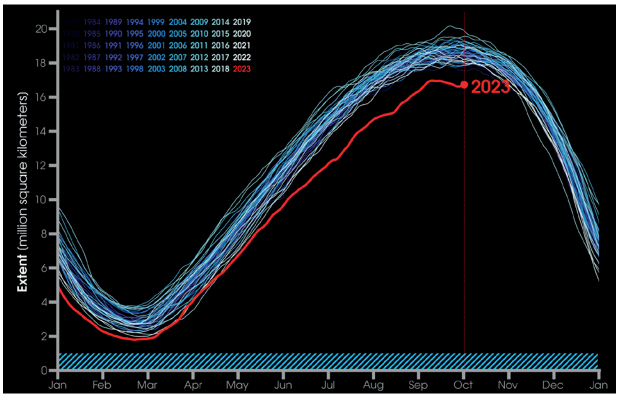
FIGURE 5-7. **Sea Ice Changes**



Sea ice extent anomalies (changes) from the 1981–2010 mean.

SOURCE: ZACH LABE. HTTPS://ZACKLABE.COM/ARCTIC-SEA-ICE-EXTENTCONCENTRATION/
HTTPS://ZACKLABE.COM/ANTARCTIC-SEA-ICE-EXTENTCONCENTRATION/

FIGURE 5-8. **Antarctic Sea Ice Since 1979**



A record low Antarctic summer sea ice extent was reached in February 2023; and then the 2023 "maximum" in September was a record-blowing 1 million km^2 below the previous record. In 2024, sea ice has not recovered but remains barely above 2023 levels.

SOURCE DATA: NSIDC/UNIVERSITY OF COLORADO BOULDER. GRAPHIC: Z. LABE.

cause summer ice-free conditions and allow exploitation of Arctic resources will also amplify the 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.[18,19,23,40,49] Such profound adverse impacts almost certainly will eclipse any temporary economic benefits brought by an ice-free summer Arctic.

The Arctic Ocean has never been ice-free in modern human existence. With the determination by the IPCC[50] that at least one ice-free summer is now inevitable due to human CO_2 emissions, the first cryosphere 'threshold' of collapse has essentially been breached. This collapse will worsen rapidly unless emissions are curtailed to keep temperatures close to 1.5°C.

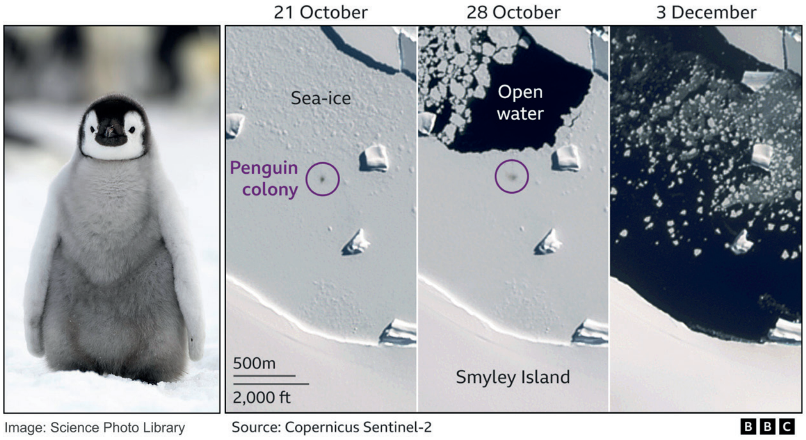
ANTARCTIC SEA ICE

Although the extent of sea ice around Antarctica had been stable or even increased slightly over the last several decades, recent observations document a very sharp decline beginning in 2016, equal to or exceeding those in the Arctic but occurring over the space of only a few years, rather than decades.[51] This sharp decline was highlighted in the summers of 2022 and 2023, when Antarctic sea ice extent fell below 2 million square kilometers for the first time,[52] reaching a record-breaking minimum extent of 1.79 million km^2 on February 21, 2023. This trend of unusually low sea ice extent has continued into the Southern Hemisphere winter of 2023 when sea ice is normally expected to recover; by July 2023, 2.77 million km^2 of ice were 'missing' compared to average conditions between 1981-2010 — a reduction equivalent to losing an area of ice the size of Argentina. The final maximum, reached on September 10, 2023, was fully 1 million km^2 below the previous record and over 1.5 million km^2 below the 1981-2010 average.[53] Low extent continued into 2024. The 2024 minimum in February was only slightly above the 2022 level, making 2022-2024 the three lowest minimums in the satellite record. While there were periods of rapid growth during the austral autumn, ice growth slowed considerably after June with short periods of nearly no increase in extent. This led to 2024 having the second lowest maximum extent, above only 2023.

The recent behavior of Antarctic sea ice is unprecedented since records began. It signals that Antarctic sea ice may have shifted into a new regime of decline because of ocean warming caused by anthropogenic fossil fuel emissions.[2,54]

These 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. The continued loss of Antarctic sea ice will expose ice shelves to greater ocean swell which may trigger their rapid disintegration.[5,55] Ice shelves that weaken or even collapse can 'open the floodgates' to significant sea-level rise, due to their role in restraining the flow of land-based ice into the ocean.[56] Sea ice losses around some regions of Antarctica are also predicted to modify ocean circulation patterns to bring warmer water masses closer to the main ice sheet, accelerating the melting of Antarctic glaciers.[57]

FIGURE 5-9. **Collapse of Penguin Colonies**



Apparent loss of the Smyley Island emperor penguin colony in 2022 due to early Antarctic sea ice breakup; such events are expected to occur more frequently as temperatures increase, placing several penguin species at risk of extinction.

CREDIT: J. AMOS.

Antarctic sea ice also plays an essential role in producing Antarctic Bottom Water — the densest water mass on the planet — which drives the entire global ocean "conveyor belt," transporting carbon and heat deep into the ocean, where it is stored for centuries to millennia. 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.[58] 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 Emperor penguins, which rely on stable sea ice platforms between April and December to successfully 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.[59]

For decades, Antarctic sea ice seemed almost immune to global warming, showing an overall change of 1-2% while Arctic sea ice declined precipitously by 40-60% during the same period. This apparent immunity to global warming may no longer hold. Given the long-term impacts on Antarctic 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-known Arctic cousin.

Extreme levels of loss and damage and increased adaptation needs would almost certainly greatly eclipse any temporary economic gains from sea ice loss.

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CHAPTER 6

Polar Ocean Acidification, Warming and Freshening

No Negotiating with The Chemistry of Ocean Acidification: Course Correction Urgent

Current NDCs (Peak CO_2 500ppm and 2.3°C by 2100): Current NDCs, delaying sufficient mitigation of emissions, will lead to CO_2 levels in the atmosphere near 500ppm, well above the critical 450ppm level identified decades ago by polar marine scientists. Such extreme environmental pressures will affect marine shell-building animals and valuable species in the food chain, such as krill, cod, salmon, lobsters, and king crab. Loss and damage to these polar ecosystems will lead to loss and damage to both commercial and subsistence polar fisheries that rely on them. These corrosive ocean conditions set by peak atmospheric CO_2 levels are essentially irreversible, lasting tens of thousands of years. Additional losses will come from marine heat waves, with warmer waters and lack of protective sea ice for several months each summer. There is no known way for vulnerable polar marine species to adapt to such changes in time. Disturbances of ocean currents due to incursion of freshwater from both ice sheets appear increasingly likely without urgent improvement of current NDCs.

1.5°C Consistent Pathways (Peak CO_2 430ppm): Immediate mitigation measures, resulting in temperatures close to the 1.5°C Paris limit, reliably maintain atmospheric CO_2 well below 450ppm; the most ambitious measures see CO_2 levels peak at 430ppm. This will limit corrosive stressing conditions to mostly seasonal damage in smaller sections of the Arctic and Southern Oceans, where shell damage and altered vital processes are already being observed today. We are already close to this 430ppm threshold: CO_2 levels in 2024 twice reached 428ppm at Mauna Loa Observatory. Losses will still occur: destructive compound events of marine heatwaves and extreme acidification have already caused population crashes at today's 1.2°C; and there is growing evidence of some slowing of major ocean currents. Worse can be expected by 1.5°C. However, very low emissions pathways would see temperatures dropping below 1.4°C by 2100, as CO_2 levels in the atmosphere trend downwards.

Current rise in CO_2 levels continues (CO_2 650ppm and 3–3.5°C by 2100): If CO_2 continues to accumulate in the atmosphere at today's pace, CO_2 levels will reach at least 600ppm by the end of this century, with global mean temperature exceeding 3°C and continuing to increase thereafter. Damaging levels of acidification will occur throughout the Arctic and Southern Oceans. At these CO_2 levels, some near-polar seas, especially the Barents, North and Baltic Seas, also would see critical acidification levels rivaling that of the poles. Corrosive conditions will persist for tens of thousands of years (30,000–70,000 years to return to today's pH levels). This will almost certainly result in mass extinctions of polar species, especially when combined with ocean warming and the longevity of heat held within the ocean. Extreme warming from high CO_2 levels will also have severe consequences for today's system of global ocean circulation, with highly unpredictable disturbance of Atlantic and Antarctic circulation systems. Loss and damage to ecosystems and human communities will be extreme, and irreversible.

2024 Updates

- CO_2 levels reached 428ppm several times in 2024,[1] and this year's average concentration is expected to near 424ppm.[2] Monthly global mean surface temperatures for the year until July 2024 have consistently averaged greater than 1.5°C above pre-industrial,[3] accelerated by an El Niño event which peaked in December 2023.[4]
- The present-day Atlantic Meridional Overturning Circulation (AMOC) may be enroute to collapse, with possible far-reaching and dramatic climate impacts, including a rapid cooling of Northern Europe of greater than 3°C per decade, for which no realistic adaptation measures exist. The timing of such a collapse is uncertain, but previous work suggests an AMOC collapse could be underway between 2025 and 2090.[5,6]
- While the potential for collapse of the AMOC lacks consensus, there is widespread agreement on its future slowing: CMIP6 simulations predict a decline of 28 to 67% in its strength by 2090–2100, resulting in a 30% reduction in heat transport across the Atlantic.[7] Models currently underestimate AMOC variability, with increasing variability resulting in a higher likelihood of collapse.[8] Possible AMOC-stabilisation mechanisms such as compensation by faster melting of the West Antarctic Ice Sheet than the Greenland Ice Sheet[9] and Southern Ocean wind-driven upwelling[10] require further investigation. Once at the point of collapse, it is likely the AMOC would not recover for thousands of years.[11]
- The Antarctic Circumpolar Current (ACC) is predicted to decline in strength by up to 20% by 2050, driven by ice sheet melt and subsequent freshwater input to the Southern Ocean.[12] A weaker ACC can affect global ocean circulation.
- On the global ocean scale, without climate change the mean carbon uptake from 2000–2019 would have been 13% higher and the trend from 1958–2019 would have been 27% higher. Ocean warming is reducing ocean capacity for absorbing CO_2, and this effect is enhanced by changes in winds, especially in regions of the subpolar Southern Ocean and both polar oceans, highlighting their critical role in holding more stable atmospheric CO_2 levels.[13]
- The capacity of the Southern Ocean to absorb CO_2 has been historically underestimated, most notably since 2010 by 29 %, due to sea ice cover. A total reduction of sea ice in the Southern Ocean could result in a 0.14 PgC per year reduction in the carbon sink of this region.[14] Under high emissions, the dominant region of CO_2 absorption may shift further to the Antarctic regions, primarily driven by sea-ice melt, increased ocean stratification and subsequently a weaker carbon gradient with depth in the ocean.[15]
- Ocean acidification of Southern Ocean waters is significantly underway, with a decrease in upper ocean pH of up to 0.02 per decade since the 1990s.[16] pH changes are widespread, and the scale of change varies regionally due to ocean circulation patterns.[16] Acidification is affecting waters within Antarctic Marine Protected Areas, with predicted pH declines of up to 0.36 for the top 200 m by 2100, and severe acidification mixed throughout the water column.[17]
- Sediment-dwelling invertebrate behavior has been found to change due to warming and acidification, with consequences for nutrient cycling throughout ecosystems. Species behavior change may therefore act as an early warning signal for impending ecological transitions.[18]
- In the Arctic Ocean, coastal erosion reduces the ocean's uptake of CO_2. The combined effects of degradation of terrestrial organic matter and melting sea ice will accelerate acidification of the Arctic Ocean.[19]
- Globally, oceans have shown a 62-year warming rate of 0.43 ± 0.08 W m–^{2}, which is accelerating significantly at 0.15 ± 0.04 W m–^{2} per decade, with high latitude oceans identified as warming hotspots, in agreement with observations and model-based studies.[20]
- The Southern Ocean has warmed, intensified by stratospheric ozone depletion and continually increasing atmospheric CO_2. Increased heat from the atmosphere, freshwater input from melting ice sheets, ice shelves and reductions in sea ice are all expected to increase. These effects, combined with the westerly poleward intensification of the Southern Ocean, can enhance northerly heat transport into sub-Antarctic waters.[21]

continued on next page

Background

Increasing CO_2 concentration leads not only to climate change, but also to increasing rates of acidification of the world's oceans. Oceans provide a vital service to the global climate system: by absorbing CO_2, they limit global warming, despite sharp increases in human carbon emissions. However, such ocean carbon absorption comes with a price: when dissolved into seawater, CO_2 forms carbonic acid, fundamentally changing the chemistry of the ocean. This phenomenon is known as ocean acidification. Rates of acidification today are faster than at any point in the past 300 million years.[29]

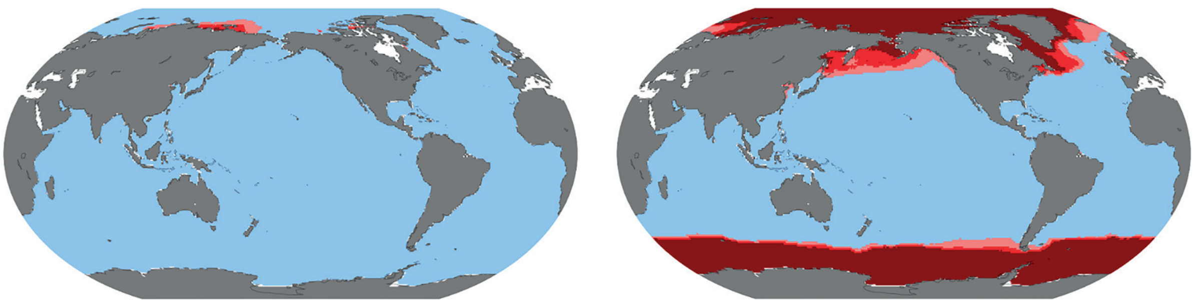
The Arctic and Southern Oceans have absorbed the lion's share of this dissolved CO_2, mostly because colder and fresher waters can hold more carbon, which gets transferred to deep waters allowing more CO_2 to be taken up at the surface. Polar waters have absorbed more than 50% of the carbon taken up by the world's oceans thus far.[30] This makes them an important carbon sink, helping to hold down global heating. However, this "sink" comes at a cost for polar marine environments, because it also results in higher rates of acidification than anywhere else on Earth.

Ocean acidification makes it more difficult for shell-building animals to reproduce, as well as to build and maintain their skeletal structures. In all seawater-dwelling organisms, ocean acidification also increases the energy costs of maintaining pH in the cells and tissues.[31] In this way, ocean acidification harms key organisms such as marine gastropods and pteropods, sea urchins, clams and crabs.[32,34] Some polar organisms are adapted to stable pH conditions that have existed for several million years. When pre-exposed to stable conditions, organisms are sensitive to even small changes

2024 UPDATES (CONTINUED)

- One modelling study highlights the potential of the Southern Ocean to continue warming after net CO_2 emissions reach zero, due to modifications in circulation as a result of initial warming.[22]
- In the northern hemisphere, Arctic marine heatwaves are expected to increase in duration and frequency, due to increased surface heat, acting as a heat transport pathway from the atmosphere to the subsurface ocean and lower latitudes, which is intensified by freshening.[23]
- During the twentieth century and early twenty-first century, Arctic sea ice loss has mainly been linked to heat transferred from the atmosphere; however, over time, ocean warming progressively becomes the most important contributor.[24] The earliest ice-free conditions in the Arctic could occur in the 2020–2030s and under all emission trajectories are likely to occur by 2050.[25] With loss of sea ice in the Arctic, eddy activity is expected to surge, with a tripling in activity predicted in a 4 °C warmer world, altering the transport of heat, carbon, oxygen and nutrients with significant impacts on regional climate and ecosystems.[26]
- The rapid decline in Antarctic sea ice extent since 2016 is associated with warming of the Southern Ocean, with record minima in 2023 for both summer and winter sea ice extent, and this low trend holding in 2024.[27,28]

FIGURE 6-1. **Acidification with Low Emissions (left) and Very High Emissions (right)**



Difference between acidification levels in a 1.5° world (RCP2.6) (left map), and a 3–4° world (RCP8.5) (right 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.

IMAGE SOURCE: IPCC SROCC (2019).

FIGURE 6-2. **Shell Damage from Acidification**

Pteropods are an important part of the polar ocean food chain, with damage from acidification already observed in the wild. Top: Healthy pteropod. Bottom: pteropod shell damage from corrosive waters.

SOURCES: TOP: N.BEDNARSEK; BOTTOM: NIEMI ET AL. (2020)

in seawater chemistry, and will be strongly and quickly impacted by the more rapid and greater ocean acidification of polar waters.[34,35] Attempts by organisms to adapt behaviorally have implications for the wider food web.[18] Such impacts have already been observed[36,37,38] and will only get worse as ocean acidification intensifies. These harmful impacts at the lower end of the marine food chain will cascade towards higher ends of the food chain, such as whales and humans.

There is currently no practical way for humans to reverse ocean acidification. The only way to slow and eventually halt the acidification process is through rapid CO_2 emissions reductions and future carbon dioxide removal (CDR). If emissions continue to rise, these more acidic conditions will persist for tens of thousands of years. This is because processes that buffer (decrease) the acidity in the ocean occur very slowly, over nearly geologic time scales. Although CO_2 only lasts for 800–1000 years in the atmosphere, ocean processes are much slower. It will take some 30–70,000 years to bring acidification and its impacts back to pre-industrial levels, following the weathering of rocks on land into the ocean.[29] This very long lifetime of acidification in the oceans is a crucial reason why mitigation efforts focused on "solar-radiation management," as opposed to decreasing atmospheric CO_2, represent a special threat to the health of the world's oceans, especially those at the poles.

Global temperatures peaking at 1.5°C will occur at atmospheric CO_2 levels of around 450 ppm, which scientists of the Inter-academy Panel (a consortium of national Academies of Sciences) identified in 2008 as an important threshold for serious global ocean acidification.[39] This represents an additional 30% increase in acidification globally, with higher levels again projected in polar waters. However, current pledges will result in CO_2 levels above 500 ppm, and a global temperature increase of around 2.3°C. By that point, acidity will have more than doubled in polar oceans.

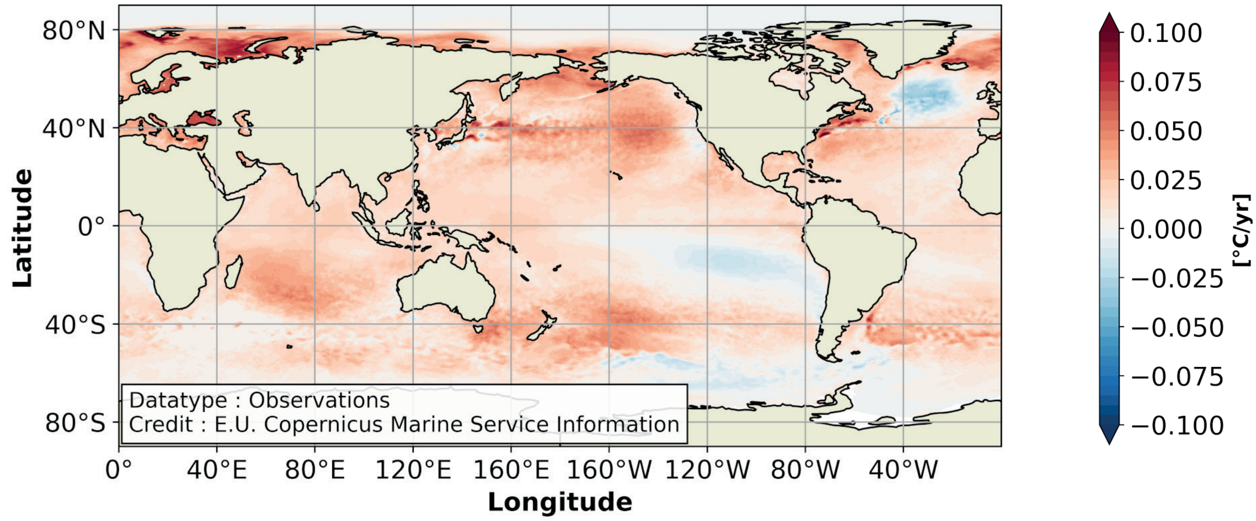
Atmospheric CO_2 levels above 500 ppm are projected to cause widespread areas of corrosive waters in both polar oceans. The Arctic Ocean appears to be most sensitive: already today, it has large regions of persistent corrosive waters. These corrosive areas in the Arctic Ocean began expanding in the 1990s. Indeed, shell damage and reduced shell building has been observed for over a decade now in some regions of the polar oceans where acidification thresholds have been exceeded already, due to local conditions.[40] In the Southern Ocean, a reduction in pH of 0.02 units per decade since the 1990s has resulted in the ability of some vulnerable organisms to build shells declining by around 4% between 1998 and 2014.[16,38] Pteropods – tiny marine snails known as "sea butterflies" – are particularly susceptible to these expanding corrosive waters, with shell damage documented in portions of the Gulf of Alaska, Bering and Beaufort seas; as well as regions in the Southern Ocean.[36] Pteropods are hugely important in the polar food web, serving as an important source of food for young salmon, Arctic cod, char and other economically important species.

Over the past several million years, global ocean acidity has been relatively stable. Today's rate of change is unprecedented in at least the past 300 million years, when severe changes in ocean conditions, including high rates of acidification, resulted in the mass extinction of many organisms.[41] While polar and global oceans have undergone changes in Earth's past, these occurred significantly more slowly. The speed of today's acidification is therefore a key part of its threat: it is occurring far too quickly to allow many species of today to adapt, evolve and survive.

This rapid acidification is occurring at a time when polar species face extreme stress from other climate change impacts as well.

The compounding effects of multiple stressors is especially the case in the Arctic, where in addition to rising acidification, warming has been unusually rapid.

FIGURE 6-3. **Sea Surface Temperature Trends (1993–2021)**



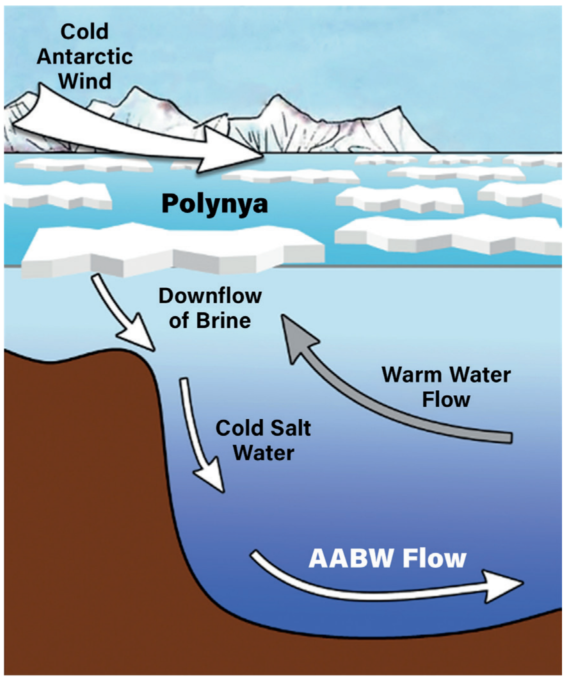
Near-polar waters, such as the Barents Sea have warmed extensively over the past two decades. The one exception is the colder "blue blob" south of Greenland, due in part to cold freshwater pouring from the Greenland Ice Sheet. Note that white coloring at higher polar latitudes is not due to lack of warming, but incomplete data for this period.

CREDIT: E.U. COPERNICUS MARINE SERVICE INFORMATION

Summer surface water temperatures have increased by around 2°C since 1982, primarily due to sea ice loss (causing more heat to be absorbed from the sun's rays) and the inflow of warmer waters from lower latitudes. At today's global warming of 1.2°C above pre-industrial, Arctic sea ice cover and thickness has decreased throughout the year. Current warming also has caused the near-total disappearance of the thick multi-year ice that previously covered much of the Arctic Ocean year-round.[42] Many meters thick and persisting for 7-10 years, this older and thicker ice can be thought of as the "coral reefs" of polar oceans, providing habitat and a food source for many polar species, including ice-associated algae. With all multi-year ice projected to disappear, even with very low emissions that will still result in 1.5-1.7°C of global warming, so too may disappear the species that rely on this thicker ice.

The Southern Ocean around Antarctica also has warmed more than other ocean regions, in particular along the western Antarctic Peninsula, although this warming is now being observed around the continent. Antarctic sea ice reached record lows in austral summer 2023 when virtually all sea ice disappeared along the western Antarctic Peninsula. Antarctic sea ice extent has tracked at very low levels again throughout 2024, for the third consecutive year. These trends of warming, sea ice loss and freshening caused by ice melt are combining with ongoing ocean acidification to place unprecedented stress on Antarctic marine ecosystems. Chilean scientists have

FIGURE 6-4. **How Antarctic Bottom Water (AABW) Forms**



AABW formation can be said to drive the entire ocean circulation system, and is threatened by the combination of warming and freshening of Antarctic waters. It originates in the "polynyas" (stretches of open water surrounded by ice) as Antarctic sea ice forms each winter.

SOURCE: MOROZOV ET AL (2021)

found an increase in marine heatwaves each decade since 1981 in regions north of the Antarctic Peninsula; and in the Amundsen-Bellingshausen, Ross and Davis Seas.[43] The observed Southern Ocean warming seems increasingly important in the overall global ocean heat increase.

The warming of polar waters has resulted in more frequent extreme heat events, with temperatures that go beyond levels that polar species evolved to survive, essentially trapping polar endemic species with nowhere else to migrate. Warming waters also cause the poleward movement of other species, increasing competition for food resources.[40,6] In some instances, especially where extreme ocean heatwaves occur, polar species have apparently even experienced lethal temperatures. Large die-offs of seabirds and gray whales in regions of the Bering Sea have occurred several times over the past decade, and seem to be associated with these marine heatwaves. Ice-associated algae and animals are also being lost as sea ice declines due to warming. Ocean pollution adds another layer of stress to polar species.[44] The projected effects of climate-induced stressors on polar marine ecosystems present risks for commercial and subsistence fisheries, with implications for regional economies, cultures and the global supply of fish and shellfish.[36,45]

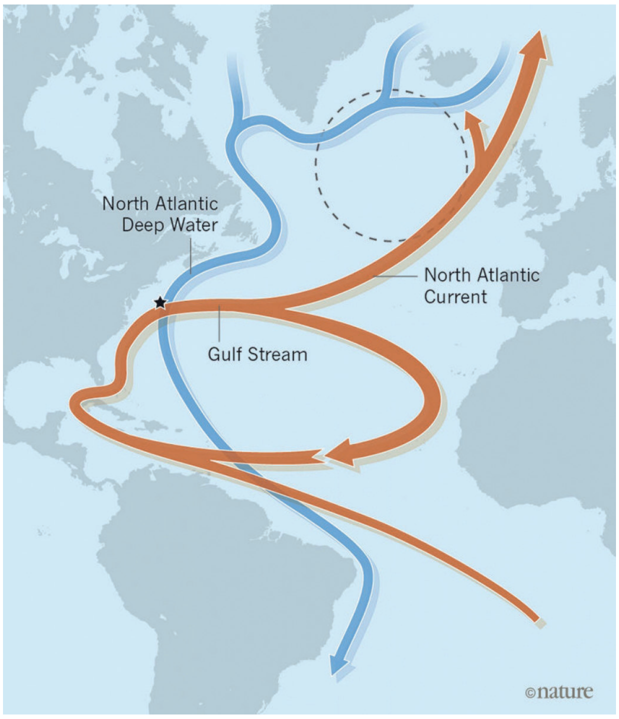
Increased run-off from glaciers, ice sheets, and – in the case of the Arctic Ocean – rivers, is affecting global ocean circulation as more freshwater pours into polar ocean surface waters. Colder, fresher water sits like a lid on top of the deeper, warmer and saltier water below, reducing vertical transport of water upwards. This can stall ocean currents, especially the AMOC – the system of ocean currents carrying warm water from the tropics to the North Atlantic. The AMOC acts as a motor for currents in the North Atlantic, and thereby drives global ocean currents, redistributing nutrients worldwide.

There is growing consensus and concern among scientists that the AMOC is slowing and that the rate of slowdown could be happening more quickly than anticipated. AMOC collapse would result in rapid and catastrophic climate change globally, particularly impacting northern Europe. In October 2024, 40 climate scientists signed a letter to the Nordic Council of Ministers urging greater urgency in emissions reductions to minimize the risks of AMOC collapse.[46]

The phenomenon of a freshwater "lid" isolating the surface and deep ocean prevents nutrients from reaching the surface where most species live,[47,48] carbon sequestration in deeper waters, and heat transport. Freshening itself can have negative physiological impacts, or impair species movements.[49,50]

The Antarctic Circumpolar Current (ACC), the world's strongest ocean current, is predicted to slow down by up to 20% by 2050 due to freshening from Antarctic ice melt, with widespread impacts on ocean circulation and climate.[12] Another major driver of global ocean circulation, carbon sequestration, and nutrient distribution is the Antarctic Bottom Water (AABW) formed during annual sea ice formation along the margins of Antarctica.[51] The IPCC has assessed that AABW formation will decline in a warming world due to increased freshwater input from the melting Antarctic Ice Sheet and a decline in sea ice. The Weddell Sea Bottom Water contributes nearly half of the AABW, and its volume has reduced by 30% since 1992. This reduction is probably associated with a decline in sea ice formation. Further reduction in AABW formation, and thus nutrient, heat, and carbon circulation, will likely depend on future carbon emissions.[52]

FIGURE 6-5. **Global Ocean Currents**



The massive movement of ocean currents, including transfer of heat and nutrients, comes largely from conditions in both polar oceans.

SOURCE: MAROTZKE (2012)

There is growing consensus and concern among scientists that the AMOC is slowing and that slowdown could be happening more quickly than anticipated.

Polar waters contain some of the world's richest fisheries and most diverse marine ecosystems. At 2°C or higher, the combination of sea ice loss for several months of the year, no multi-year sea ice at all, ocean warming, acidification and freshening will alter polar marine ecosystems beyond recognition, as well as the fisheries and aquaculture that depend on them. The impacts above 2°C are essentially irreversible, and will occur with all but the very lowest emissions pathways. A world kept close to 1.5°C or lower can limit the severe and irreversible effects on polar ocean ecosystems and fisheries, though some losses unfortunately are now inevitable.

A future in which polar ocean impacts can still be kept under control requires a 50% reduction in CO_2 emissions by 2030, motivated by high ambition and commitment toward global decarbonization; with essentially zero emissions by 2050, and negative emissions (removing carbon from the atmosphere) thereafter.

Both polar oceans already appear to be nearing critical acidification, warming and freshening thresholds. There is high likelihood that these changes are a harbinger of much worse to come; until, and unless, human-caused CO_2 levels begin to fall sharply.

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