State of the Cryosphere 2022

Growing Losses, Global Impacts

We cannot negotiate with the melting point of ice.

NOVEMBER 2022

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Cover Photo: Looking across bedrock to the terminus of Vanderford Glacier, Wilkes Land, East Antarctica (credit: Richard S. Jones, Monash University, Australia)

DEDICATION

This Report is dedicated to the memory of legendary Arctic sea ice researcher David G. Barber (1960–2022), University of Manitoba, Canada; whose visionary leadership and research was equaled only by his commitment to communicating Arctic climate science to the world.

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Foreword

2022: Growing Losses, Global Impacts

Far too much human suffering occurred in 2022 due to rapid loss of ice in the cryosphere, Earth's snow and ice regions, from human-caused global warming.

Most occurred in places far from ice and snow: coastal sea-level rise from ice sheet loss; water shortages well downstream from shrinking glaciers and snowpack; floods, avalanches, wildfires and extreme weather events.

All were caused in whole or in part by loss of the cryosphere's stabilizing influence on the global climate system. Our global ice stores are receding at rates unthinkable just a decade ago, whether held in ice sheets, land glaciers, permafrost or sea ice.

This *State of the Cryosphere Report 2022: Growing Losses, Global Impacts* especially raises up the IPCC Sixth Assessment conclusion that complete loss of Arctic sea ice in summer is now inevitable, even with the very lowest emissions pathways that peak temperatures at 1.6°C. This finding is a terminal diagnosis for that ecosystem and its essential role reflecting sunlight as the "Earth's refrigerator," something sea ice scientists have been warning for decades would come with continued high emissions. No one seems to have listened.

But the impending loss of Arctic summer sea ice it is not the only sign of growing cryosphere collapse. This year also saw March rains on East Antarctica, with temperatures 40°C above normal; a spike in Greenland surface melt for the first time ever in September; loss of over 5% of glacier ice in the Alps over a single summer; and the first documented rise in methane release due to global warming from a permafrost monitoring site. It also saw greater shell damage in parts of the Arctic Ocean, a clear sign of acidification; and an apparent crash in snow crab populations likely tied to warming waters.

Research published this year also shows growing convergence between ice sheet models and what paleo-climatologists (those who study Earth history going back millions of years) have warned for decades: that ice loss and irreversible sea-level rise may be occurring faster, and at lower temperatures than previously forecast: even from the massive East Antarctic Ice Sheet, with temperatures above 1.8°C. Nearly all these impacts are irreversible on human timescales. It might take only decades to melt a glacier, but centuries to thousands of years of lower temperatures to grow it back.

The message from the global cryosphere in 2022 is that we are already well into the risk zone for irreversible damage from continued loss of the planet's global ice stores. Nevertheless, the 2022 UNFCCC Synthesis Report on reported pledges (NDCs) showed not the 45% decrease in emissions needed by 2030 to keep 1.5°C within reach, but a 10% *increase* by 2030.

Our planet's melting ice pays no attention to climate pledges and NDCs. It responds only to the level of CO_2 and warming in the atmosphere. In 2022, the year-on-year increase of about 2.5 ppm continued unabated, as it has for the past two decades. Until this CO_2 rise slows, halts and begins to decrease, the ice will continue to respond as it always has: to the only number that really matters.

Pam Pearson
Director, ICCI

CHAPTER 1

Emissions Pathways and Cryosphere

Only Very Low and Low Emissions Can Feasibly Prevent Essentially-Permanent Loss and Damage

Very Low and Low Emissions (Peak 1.6–1.8°C, declining by 2100): At least 50% reductions by 2030, with carbon neutrality (net zero CO_2 emissions) reached by 2050, and net negative emissions (carbon drawdown) afterwards. Cryosphere begins to stabilize in 2040–2080, with slow continued emissions from permafrost for one-two centuries, and glacier loss continuing for several decades, but slowing by 2200. Multi-year Arctic sea ice will begin to re-form once temperatures approach around 1°C. Some loss of ice sheets will continue for several hundred, to thousands of years due to ocean warming, but likely not exceeding 3 meters of global sea-level rise especially with very low emissions with extensive carbon-dioxide removal, aiding a more rapid temperature return towards that of today or preferably, below 1°C.

Fulfillment of All 2022 Pledges/NDCs* (1.9°C in 2100, overshoot >2°C post-2100): Countries meet all current pledges or Nationally Determined Contribution (NDCs), including informal pledges, long-term net-zero targets and those not yet backed up by concrete legislation or other actions, under the most optimistic scenarios. Cryosphere-related losses become significant, with impacts from sea-level rise and loss of many glaciers inevitable, and 6–10 meters of inevitable global sea-level rise over centuries to millennia. Severe, more immediate losses occur in polar and some near-polar fisheries. Loss of nearly all mid-latitude glaciers occurs by 2200.

Implemented Policies as of 2022 (2.7–3.1°C in 2100 and rising): Countries fulfill those climate policies backed up by concrete national measures and legislation, without backsliding caused by other competing considerations such as economic stimulus supporting fossil fuels. Cryosphere-related losses are more rapid and more extreme, with loss of nearly all glaciers outside the poles; inevitable loss of the Greenland and West Antarctic ice sheets and over centuries to millennia, 10–20 meters of global sea-level rise; and marine damage from acidification spreading from polar oceans to some lower latitudes.

Current Growth in CO_2 (2–3ppm per year, temperature 4–5°C in 2100 and rising): Today's emissions continue on their current pathway, resulting in rapid cryosphere collapse; and essentially permanent and extreme loss and damage. Sea-level rise rates of 5 cm/year may occur by 2150, with up to 15 m sea-level rise by 2300. Most of the Arctic and Southern Oceans become extremely corrosive and unable to support current patterns of marine life, with widespread polar extinction events.

The two lowest emissions pathways are the only ones with any possibility of preventing essentially permanent impacts, due to cryosphere processes.

* Based on Climate Action Tracker June 2022 Update, https://climateactiontracker.org/global/temperatures/

Background

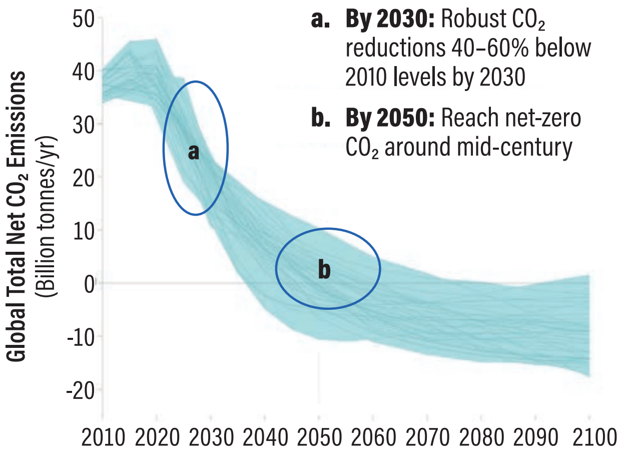
The cryosphere in the distant past has responded to relatively slow changes in temperature and greenhouse gas concentrations. These were paced by small changes in the Earth's orbit around the sun, leading to a slow rise in temperature, usually over tens of thousands of years, with thaw and loss of many 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 occasionally, 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 ever-so-slowly rose.

It cannot be over-emphasized that these shifts in temperature and CO_2 concentration were smaller, and occurred much more slowly than anything human emissions of greenhouse gases are causing today. The CO_2 difference between an Ice Age, and a warmer "interglacial" period such as that humans have experienced for the past 10,000 years or so was a fairly consistent ≈180ppm (Ice Age) and ≈280ppm (warm period), going back about 3 million years: so the entirety of existence of modern humans and our hominid ancestors. Similarly, during this latest warm period and the past 10,000 years of human civilization, the Earth has remained at around 280ppm. CO_2 concentrations were still at around 285ppm in 1850, but with the burning of fossil fuels it breached 300ppm around 1910, 320ppm in the 1960's and then accelerated to 400ppm around 2015. It exceeded a 422ppm daily mean twice in 2022, and continues to grow by 2–3ppm each year, despite existing climate pledges that in accordance with the 2015 Paris Agreement, should have resulted in a peak of CO_2 emissions by 2020.

By continuing to emit CO_2 and other greenhouse gases without pause, the world's nations and industrial sectors have already pushed the planet well beyond anything that has existed since about 3 million years ago. The outcome for global impacts from the cryosphere, such as coastal flooding and loss of entire island and low-lying nations from the Marshall lslands to the Netherlands, depends entirely on how high humanity decides is acceptable for temperatures and CO_2 concentrations to rise.

FIGURE 1-1. **1.5°C Emissions Pathways**



SOURCE: IPCC SR1.5; GRAPHIC ADAPTED FROM JOERI ROGELJ

By continuing to emit CO_2, the world's nations and industrial sectors have already pushed the planet beyond anything since 3 million years ago.

This is not however a pre-determined outcome. In its Special Report on 1.5°C of Warming (SR1.5) from 2018, as well as its Sixth Assessment (2021–22), the IPCC outlined the range of choices facing governments, industry and other stakeholders. The table that follows (next page) lists the range of possible carbon emission pathways as outlined in the latest IPCC report, the Working Group I portion of AR6 released in August 2021; together with as their SR1.5 and previous equivalents, the Representative Concentration Pathways (RCP) scenarios. The RCPs have been extensively used over the past two decades of cryosphere projection studies, so remain highly relevant when discussing the future of cryosphere.

It is important to note that these emissions pathways do not as yet include resulting emissions from permafrost at the different temperature levels, which might add between 10–30ppm, roughly speaking, to 2100 CO_2 concentrations.

The two lowest emissions pathways or scenarios are the only ones with any possibility of preventing the essentially permanent (on human timescales) impacts outlined in this report, due to cryosphere processes that cannot be reversed in anything less than centuries, to tens of thousands of years. A decision to exceed these limits is a *de facto* decision to cause these changes to occur.

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+

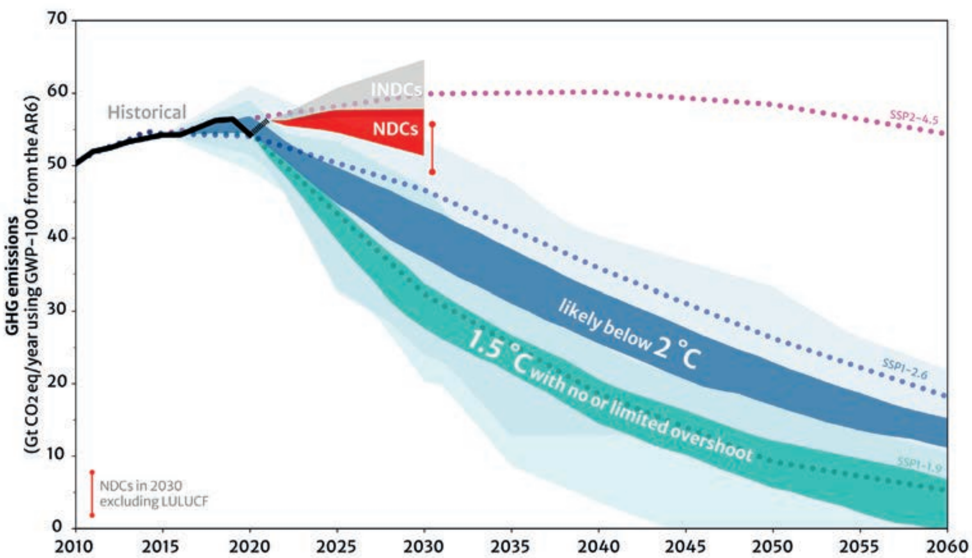
Both of these lowest emissions pathways remain physically, technologically, and economically feasible and even advantageous to both human populations and ecosystems, especially because many of their elements greatly improve human health outcomes. Both involve a steep decline in CO_2 emissions to 50% of 2010 emissions levels within the next eight years, by 2030. Most of this 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 by that date.

Subsequently, in the 20 years between 2030–2050, CO_2 emissions would further decline to near zero. These later steps would address the more difficult (by comparison) reductions needed in the industrial and agricultural sectors, especially from carbon-intense processes such as steel and meat production. After 2050, so-called negative emissions – pulling carbon out of the atmosphere through changes in agricultural practices or mechanical carbon removal technologies, the latter still largely under research and development – will ensure that CO_2 levels begin to decline more rapidly, causing temperatures to follow.

It is important to note again that IPCC and other emissions experts still find that these very low and low emissions pathways remain feasible. They do however require an immediate and "state of emergency" global political response, one sustained over the next three decades. Encouragingly, if governments choose to follow the "very low" emissions pathway, some benefits – such as slight decreases in extreme weather – may begin to be felt around 2040. However, because the past 30 years since adoption of the Framework Convention have seen

With adequate action that follows the science, humanity can still prevent the worst of these cryosphere impacts.

FIGURE 1-2. **October 2022 UNFCCC Synthesis Report**



SOURCE: UNFCCC NDC SYNTHESIS REPORT, OCTOBER 26, 2022

IPCC and other emissions experts still find these very low emissions pathways remain feasible, but they require an immediate and "state of emergency" global political response.

inadequate action, humanity must tragically be prepared for a series of increasingly difficult and deadly climate-related losses and disasters from now-inevitable cryospheric changes over the next 20 years, even with this most beneficial pathway.

Where are emissions today, and what kinds of reductions will take place with current climate pledges?

Country commitments, or "Nationally Determined Contributions" (NDCs), were first made in connection with the Paris Agreement in 2015, and updated at COP26 in November 2021. Countries also agreed at Glasgow to bring updated NDCs to COP27 in Egypt; but as of October 2022, only 24 countries had done so. Some of these NDCs consist of concrete measures backed up by regulation or legislation. Others, including many less formal pledges made in Glasgow are merely goals, such as "carbon neutrality by 2050," without any specifics as to how the respective governments plan to achieve such goals.

This Report primarily relies on the calculations of the Climate Action Tracker (CAT), produced by a consortium of European research institutions* to evaluate where current NDCs, or other climate commitments will take the globe in terms of future temperatures and CO_2 concentrations. The CAT differentiates between "concrete" policies and NDCs (backed up by actual policies, such as legislation or other measures) and "optimistic" pledges and NDCs, including stated goals not yet reported under the Paris Agreement. As updated in June 2022, these will result in approximately 1.9°C, and 2.7°C by 2100, respectively; but in both cases, with temperature rise continuing to some degree post-2100.

In its October 2022 Synthesis Report on submitted NDCs, the UNFCCC found a resulting temperature in 2100 of 2.5°C (Figure 1-2, previous page), with only 24 countries having updated their 2021 NDCs despite agreement at COP26 to do so. More seriously, despite the IPCC finding that emissions should be reduced by 43–45% by 2030 to keep 1.5°C physically within reach, emissions instead will rise 10.6% by that date, even with these "improved" NDCs. Even these figures rely on full NDC implementation by governments. However, several countries with the greatest current legislated policies, such as Sweden, Germany, Denmark and the UK, have formal climate councils tasked with evaluating compliance. Nearly all have determined that even these legislated goals are not being met, which would push temperatures higher.

The updated Climate Action Tracker temperature estimates will be published in early November at COP27; but the estimates associated with concrete steps taken by governments are not expected to change, especially due to a focus on natural gas resources after the Russian invasion of Ukraine in February 2022. While this still may result in renewed emphasis on renewables as a means towards energy independence, government reactions may also lock in continued fossil fuel infrastructure for many years.

More alarming however is the reality that in 2022, the annual year-on-year rise in CO_2 concentrations in the atmosphere has not yet deviated from the extremely damaging "high" emissions pathway, which will result in passing 1.5°C potentially by 2030, 2°C in the 2040s, 3°C in the 2070s and potentially above 4°C in 2100; with continued temperature rise post-2100. Anticipating future reductions, many climate experts have noted that the "very high" emissions pathway RCP8.5 is no longer a "feasible" scenario for future emissions; but it remains the reality that to-date in 2022, no clear decline in human emissions can be seen.

This would result in a very rapid and essentially permanent collapse of many systems in the cryosphere, with extreme loss and damage for many generations; but that we are beginning to see already today, at 1.2°C and 422pmm. This Report outlines the scale of these impacts for the five most important cryosphere dynamics with both regional, and planet-wide impacts: ice sheets and sea-level rise; polar and near-polar ocean impacts, including long-term acidification; glaciers, snow and related water resources; permafrost carbon emissions; and Arctic sea ice.

With adequate action that follows the science, humanity can still prevent the worst of these impacts; but with each passing year of continued high emissions and associated rise in CO_2 in the atmosphere, the window of prevention is closing.

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CHAPTER 2

Ice Sheets and Sea-level Rise

Loss of Some Coastlines Now Inevitable – but Very Low Emissions Can Save Many More

Very Low and Low Emissions (Peak 1.6–1.8°C, declining by 2100): Global sea levels will continue to rise for centuries, reaching around 2–3 meters above today's in the next few hundred years, with about half a meter occurring within the next 50–100 years. This assumes ice sheets respond to warming in a limited and steady manner, not adding substantially to sea-level rise from mountain glacier* loss and ocean thermal expansion.

Fulfillment of All 2022 Pledges/NDCs (1.9°C in 2100, overshoot >2°C post-2100): Primarily because of a relatively slow collapse of portions of the West Antarctic Ice Sheet (WAIS), as well as accelerated Greenland ice loss, plus loss of nearly all glaciers, global sea levels eventually will reach 3–6 meters above today's. Even higher levels cannot be ruled out: the last time temperatures exceeded the 2°C threshold, sea-level rise was 6–9 meters. Sea levels would reach at least 0.75 meters above today's level early in the next century. More troublingly, at this higher temperature, a steady predictable rate of sea-level rise from ice sheets is less certain, and so the rate and amount of sea-level rise by 2100 could be greater.

Implemented Policies as of 2022 (2.7–3.1°C in 2100 and rising): This scenario will push ice sheets in ways not seen since the end of the last Ice Age, 20–10,000 years ago. WAIS collapse is likely to be rapid once temperatures exceed 3°C, with involvement of portions of East Antarctica (such as Wilkes) and greater loss from Greenland. WAIS collapse would be well along by 2300. Sea-level rise will continue at a relatively rapid pace for many centuries and be essentially permanent on human timescales, reaching 15–20 meters or more above today's level. Sea-level rise of more than 1 meter before 2100 becomes highly probable in this scenario.

Current Growth in CO_2 (2–3ppm per year, temperature 4–5°C in 2100 and rising): Loss of large portions of both polar ice sheets and all glaciers will occur. WAIS collapse would be inevitable and potentially rapid, with sea-level rise of 2 meters possible by 2100, and up to 5 meters by 2150. 10 meters sea-level rise from all sources is likely by 2300. Sea-level rise will continue for many centuries even with temperature stabilization and slow decline, with the eventual complete loss of the Greenland ice sheet. Such a rapid rise in atmospheric CO_2 concentrations and temperature has no counterpart in Earth's geologic record, but Antarctica is known to have had essentially ice-free conditions at +6°C above today's level. Restoration of the polar ice sheets would only begin with temperatures well below pre-industrial (i.e., substantial global cooling).

The East Antarctic Ice Sheet could contribute substantially to sea-level rise if temperatures rise above 1.8°C

* Here glaciers refer to all land-based ice other than the Antarctic and Greenland ice sheets

2022 Updates

- We may already be committed to peak warming greater than 1.5°C[20], highlighting the urgency of reducing emissions to avoid the most severe impacts of ice sheet melt that would result from overshoot.
- The Arctic is warming four times faster than the rest of the world since 1979, rather than 2–3 times faster as previously estimated[55].
- Heatwaves in Antarctica continue to break records, putting ice shelves at greater risk of collapse[28].
- The East Antarctic Ice Sheet, once considered relatively stable, could contribute substantially to sea-level rise if Paris Agreement goals are not met[64].
- Sections of the West Antarctic Ice Sheet may collapse even without further emissions, causing more than 4 meters of additional sea-level rise; however, the risk can be diminished by meeting Paris Agreement goals[26].
- Greenland ice loss is committed to around 30cm of sea-level rise already at today's temperature increase of 1.1°C [10].
- Almost all sea-level rise, since 1900 is due to anthropogenic global heating and can only be abated by returning to pre-industrial temperature[32].
- **Overall: improved understanding of physical ice sheet processes shows that ice sheet melt from both Greenland and Antarctica may result in greater and/or more rapid sea-level rise than previously estimated.**

Once ice sheet melt accelerates due to higher temperatures, it cannot be stopped or reversed for many thousands of years, even once temperatures stabilize.

Background

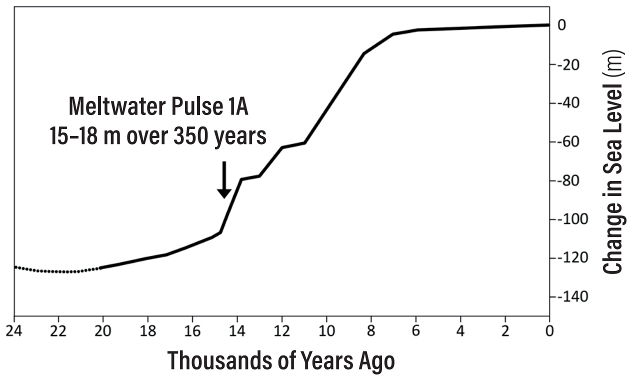
For the Earth's polar ice sheets on Greenland and Antarctica, which together hold enough ice to raise sea level by 65 meters, risks of non-reversible melting increase as temperature and rates of warming rise. The Earth's climate record makes clear that warming above even 1°C over pre-industrial levels has resulted in very different coastlines in Earth's past, due to extensive melting of the West Antarctic Ice Sheet (WAIS), Greenland[4,35] and by 1.5°C, possibly parts of East Antarctica[64]. While some of these changes occurred very slowly in the past, over thousands of years, there have also been periods where extremely rapid sea-level rise (around 4 meters per century) has occurred, due to rapid ice sheet collapse. Termed "melt-water pulses," the last took place around 14,000 years ago, when global sea levels rose between 12–18 meters in just 350 years.

The observed human-induced global temperature increase over the past few decades is much faster than anything documented in Earth's past. CO_2 increases in the last 50 years are 200 times greater 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 been observed over the past few decades, and could potentially be more rapid than at any other time in the past 130,000 years.[63] Better understanding of ice sheet behavior, especially interactions between the ice and the warming oceans that surround them, informs us that ice sheet collapse and rapid sea-level rise cannot be ruled out[16,15,5,62] especially if peak warming were to exceed 3°C. This is especially the case for the West Antarctic Ice Sheet (WAIS): some studies show the threshold for WAIS collapse may already have passed at around 0.8°C above pre-industrial[41] although the WAIS could hold stable for some centuries unless further warming occurs. Even if ice sheet loss is inevitable once triggered, this can be slowed to take place over longer timescales if temperatures remain close to 1.5°, 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 the ice sheets increases as both the peak in global temperatures and the rate of warming rise. The massive Greenland and Antarctic ice sheets consist of compressed snow that fell, in the oldest sections, over a million years ago. In equilibrium, calving of icebergs and outflow of melt water into the ocean are balanced by mass gain via snowfall. Observations now confirm that this equilibrium has been lost on Greenland, the WAIS, and the Antarctic Peninsula; and potentially portions of the ten-times-larger East Antarctic Ice Sheet.

All changes in the total mass of 'land ice' bound within the Earth's ice sheets have direct consequences for global

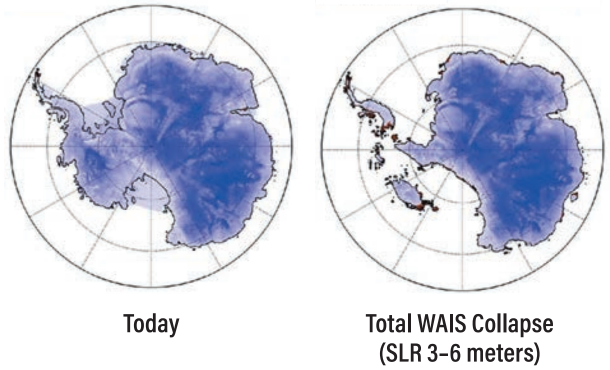
FIGURE 2-1. **Rapid Sea-Level Rise 14,000 Years Ago**



Around 14,000 years ago, sea levels rose 3–5 meters per century, probably due to collapse of the Laurentian ice sheet over Canada.

HEIDI SEVESTRE, ADAPTED FROM ROBERT A. RODE FROM PUBLISHED DATA

FIGURE 2-2. **West Antarctic Ice Sheet Collapse**



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 occasional meltwater pulses (noted above) probably as a result of catastrophic collapse of the Laurentide Ice Sheet over Canada.

Antarctic ice shelves also play an important role in ice-loss processes, as they hold back, or "buttress," the ice sheets upstream. Loss of this buttressing effect through ice shelf thinning and break-up can accelerate the rate of ice flow from the land into the sea[56]. 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[31]. Antarctic ice shelf thinning has also accelerated over recent decades, driven by intrusion of warmer ocean currents[53]. Reduced ice-shelf buttressing driven by such warm ocean currents accounts for a significant portion of Antarctic mass loss[33] and could drive increasingly significant sea-level rise in the future[6,31,56].

Ice sheets in Greenland and (parts of) Antarctica have certain thresholds where irreversible melt becomes inevitable and, in the case of the WAIS, potentially rapid[48,60]. In Earth's past, several of these thresholds have occurred somewhere between 1 and 2 degrees of warming: 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). (It should be noted that changes around past thresholds were driven by slow increases in atmospheric greenhouse gases but were paced by slow changes in Earth's orbit – unlike today's rapid, human-caused rates of change.) Parts of East Antarctica, especially the massive Wilkes and Aurora Basins (~4 meters of potential SLR), may also have a threshold around or just beyond 2°C[64,3].

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[49,19,18,29]. 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.

FIGURE 2-3. **Vulnerable Portions of East Antarctica**

Yellow circles mark vulnerable portions of East Antarctica

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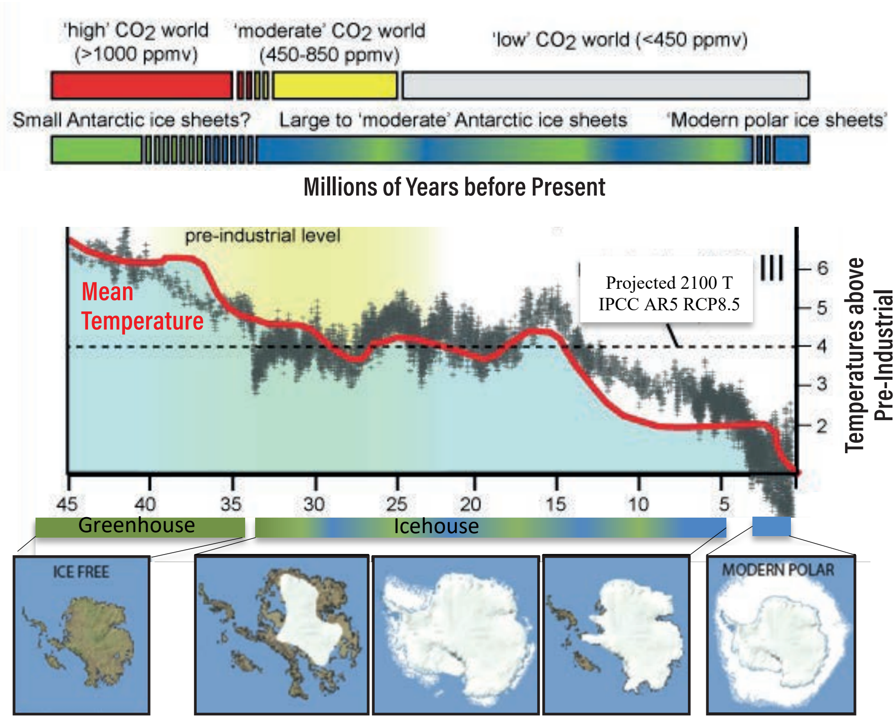
FIGURE 2-4. **Antarctica with Past CO_2 Concentrations and Temperature**



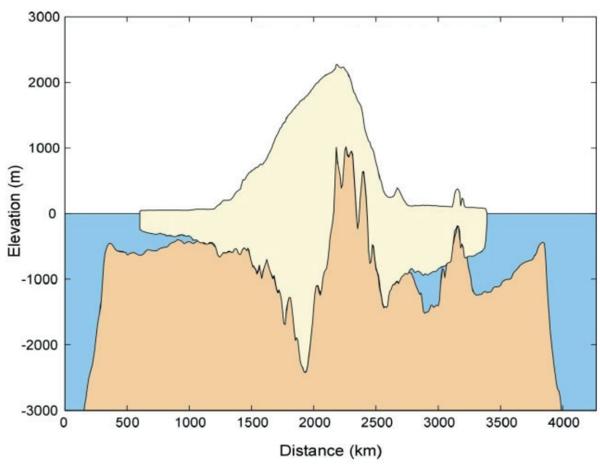
ADAPTED FROM CARLOTA ESCUTIA

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 eventual unstoppable loss of most of the ice sheet[2,25,43,11,9]. The first recorded rain at the highest point of Greenland, Summit Station, occurred in August 2021 and lasted several days.

The WAIS is a very different story: much of it does not really sit over land, but rather over island archipelagoes separated by extremely deep (>2.5 km below sea level) and vast basins[23,1]. Much of its ice rests on a bed that slopes downwards toward its center (Figure 2-5). 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. Similar conditions exist on parts of East Antarctica and have become far better documented on the continent through coordinated scientific efforts over the past five years, though much remains to be

We are currently on track for even higher temperature peaks than those that drove past sea level rises.

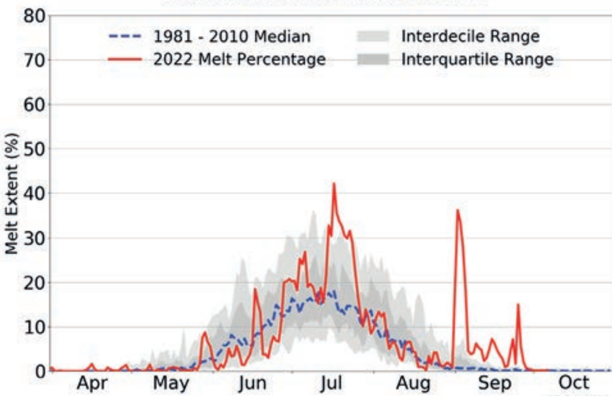
FIGURE 2-5. **Cross-section through West Antarctica**



Much of West Antarctica is below sea-level, allowing water to flow in and potentially, rapidly destabilize the ice sheets above.

SOURCE: ILLUSTRATION BY JONATHAN BAMBER

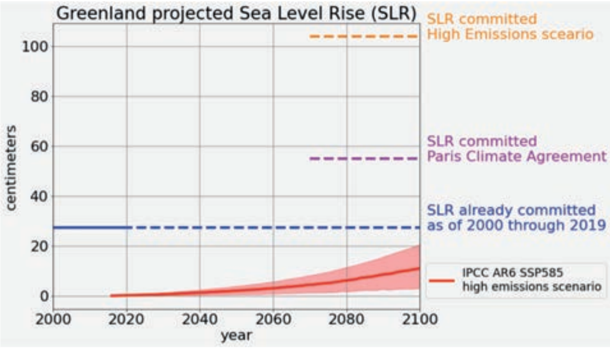
FIGURE 2-6. **Greenland Surface Melt Extent 2022**



In 2022, Greenland experienced a spike in surface melting in early September for the first time in the satellite record, with over one-third of the ice sheet experiencing melt and conditions above freezing at Summit Station.

NSIDC / THOMAS MOTE, UNIVERSITY OF GEORGIA

FIGURE 2-7. **Committed Sea-Level Rise from Greenland at Today's and Future Emissions**



A 2022 study of Greenland, based on observed melt conditions over the past 20 years, calculates that nearly 30 cm sea-level rise from Greenland is now inevitable at today's temperatures.

COURTESY JASON BOX, 2022

learned[8]. Recent work also suggests that although the East Antarctic Ice Sheet was once considered relatively stable, the ice sheet could contribute substantially to sea-level rise if temperatures rise above 1.8°C [64].

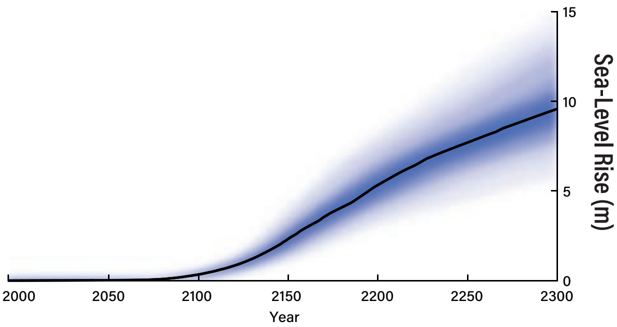
Ice sheets have other global impacts in addition to sea-level rise. They influence both atmospheric and ocean circulation at high latitudes and globally, which transfer heat around the planet. Changes in the height and extent of Earth's ice sheets, together with the incursion of new cold and fresh water into ocean currents from ice sheet melt, cause changes in weather patterns near the poles and at lower latitudes. Additionally, these circulation systems affect nutrient supplies in marine ecosystems.

The main questions for scientists and policy makers are (1) what is the future rate of sea level change? (2) how high will sea level go? and (3) at what point do future higher sea levels become locked in? In general, scientists agree 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 temperature rise to exceed 4° by 2100 [17].

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 less (100x less) time to shrink it. Sea level lowering from these new highs will not occur until temperatures go well *below* pre-industrial, initiating a slow ice sheet re-growth. Sea-level rise caused by overshoot of Paris Agreement goals is therefore an essentially permanent impact, one not reversible on human time scales.

Regardless of the uncertainties surrounding the rate of future melt, we know that Greenland ice loss today is three times what it was 20 years ago; and ice loss from Antarctica has doubled over the same period [57,58,61,50]. 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 [54,52];

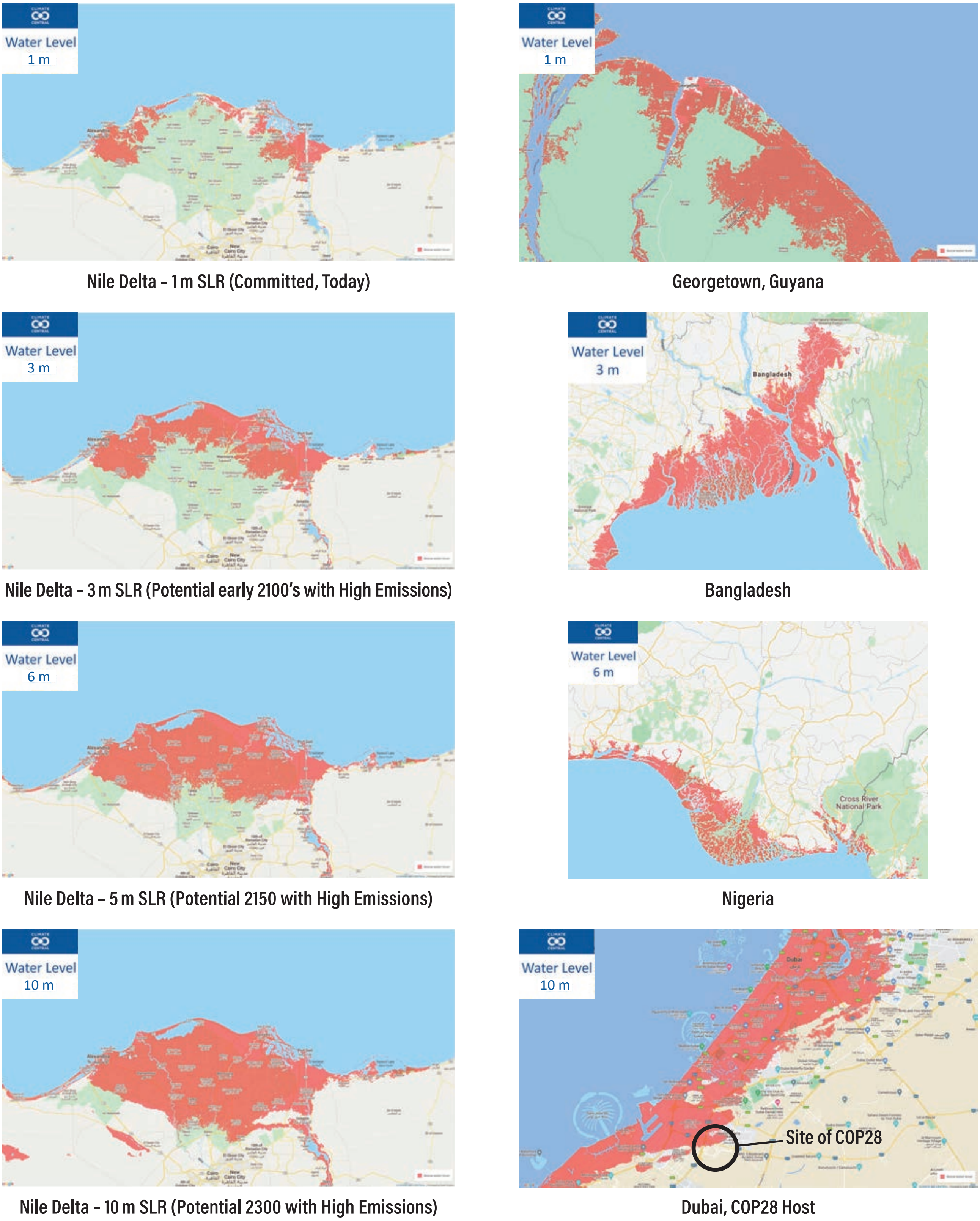
FIGURE 2-8. **Projected Sea-level Rise from Antarctica with High Emissions**



New models taking into account ice sheet collapse properties project potentially rapid sea-level rise from Antarctica under very high emissions; and that once 3 degrees is passed, even rapid carbon dioxide removal cannot halt ice loss.

ADAPTED FROM DECONTO ET AL., 2021

FIGURE 2-9. **Sea-level Rise with Ice Sheet Loss**



Sea-level rise in the Nile Delta region (maps left column) might wipe out the region by 2300 if current growth in CO_2 in the atmosphere continues. Right column, sea-level rise in Georgetown, Guyana (1 meter); Bangladesh (3m); Lagos, Nigeria (6m) and COP28 host Dubai, UAE (10m).

CLIMATE CENTRAL

noting that we are currently 1.2°C above pre-industrial. A key argument therefore in favor of very low emissions, is that staying close to 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 WAIS collapse especially [68]. This will help provide low-lying nations and communities more time to adapt through sustainable development, though some level of managed retreat from coastlines in the long term is tragically inevitable.

The rate of future sea-level rise, and associated risks to security and development, now largely depends on human decisions on future emissions of greenhouse gases. 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 much human settlement along coastlines within the next few centuries, and to displace hundreds of millions of people.

The rate of future sea-level rise, and associated risks to security and development, now largely depends on human decisions on future emissions of greenhouse gases.

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CHAPTER 3

Mountain Glaciers and Snow

Future Loss and Damage Can Be Slowed and Avoided Only with Sharp Emissions Reductions Today

Very Low and Low Emissions (Peak 1.6–1.8°C, declining by 2100): Glaciers and snowpack already have declined rapidly for several decades. That rapid decline inevitably will continue, especially outside the polar regions. With very low emissions, glacier losses will begin to slow slightly already around 2040, though many glaciers are not expected to stabilize until around 2200. Some glacier regions in the mid-latitudes, such as the Alps, may begin to show very slow re-growth (a few percent per decade) by 2100; others require temperatures closer to pre-industrial for recovery. With very low emissions, even low-latitude glaciers may begin to recover, though disappearance of nearly all near-equatorial glaciers by 2050 is plausible even with low emissions. They may not recover until temperatures fall below pre-industrial, or the next Ice Age.

Fulfillment of All 2022 Pledges/NDCs (1.9°C in 2100, overshoot >2°C post-2100): Under this scenario, by 2300, the only surviving glaciers of any substantial size will be limited to the polar regions and highest mountains, such as the Himalayas. Even in these regions, glaciers may shrink to 30–50% of their current size. Snowfall will become scarcer, falling instead as rain that may at times be extreme in this warmer climate, leading to increased erosion, flooding and landslides. In regions such as the western Americas and Himalayas, the loss of glaciers and diminishing snowpack will radically affect seasonal water supplies in some river systems, for example the Colorado, Indus, and Tarim Rivers.

Implemented Policies as of 2022 (2.7–3.1°C in 2100 and rising): Rapid losses will continue in nearly all glacier regions for the next two centuries; by 2300, virtually no glaciers will remain anywhere on the globe outside the polar regions, Patagonia and Himalayas, where only 20–35% of ice will remain. Snowfall will become more rare outside the polar regions and the highest altitudes. With such very high levels of snowfall and glacier loss, glacier re-growth (even with temperatures returning to those of today) to scales present in the middle of the 1900's will likely take many centuries or in some cases even millennia, though snowpack would return as soon as temperatures decline.

Current Growth in CO_2 (2–3ppm per year, temperature 4–5°C in 2100 and rising): Very few mountain glaciers will remain anywhere on the globe by 2200, with mid-latitude glaciers 90% gone already by 2100. Snowfall by 2100 will be extremely limited outside the polar regions and highest altitudes.

On human timescales, the disappearance of glaciers is an essentially permanent change to the mountain landscape.

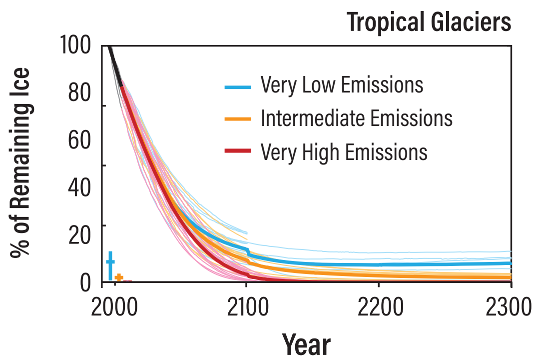
2022 Updates

- Summer heatwaves in the European Alps and Svalbard led to unprecedented melt and retreat of many glaciers in these regions, with extreme temperatures in the Alps potentially having led to glacier collapse and loss of life.
- South Asian agriculture is increasingly dependent on freshwater from sources such as glacier melt and snowmelt, both of which are becoming increasingly erratic water sources.[25]
- Glaciers are important buffers of droughts even in basins with little glacier cover, but 2022 research confirms this buffer effect will decrease as glaciers disappear.[40]
- New research documents the clear link between glacier retreat and the growth of glacial lakes, increasing the risk of glacial lake outburst floods in the Himalaya.[8,11]
- Scientists have identified continuous glacier retreat in the Pyrenees, which is expected to become ice-free in the coming decades.[42]
- New research highlights that any positive climate implications of greening in the Alps (e.g., new opportunities for carbon sequestration) will likely be outweighed by negative impacts such as climate feedbacks and reduced water availability.[34]
- Increasing water temperatures of up to 3.5°C will occur by 2100 in Alpine high-elevation catchments, as well as downstream with high emissions, potentially impacting these ecosystems and water resources.[47]

Background

Many glaciers of the northern Andes, East Africa and Indonesia, especially those close to the Equator, are disappearing too rapidly to be saved even with very low future emissions.[28] These glaciers have mostly been shrinking since the end of the last Ice Age, but global warming has greatly accelerated their melting. Some of these, especially in the northern Andes, would have provided a reliable seasonal source of water for many hundreds 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.

FIGURE 3-1. **Low Latitudes**



Few tropical glaciers will survive even today's 1°C, aside from remnants at altitudes above 6000 m.

FIGURES BASED ON MARZEION ET AL. (2012)

Severe losses also are occurring today from "mid-latitude" glaciers: these include the Alps, southern Andes and Patagonia, Iceland, Scandinavia, the North American Rockies and much of Alaska, and New Zealand. These losses will continue at a steep rate over the next several decades just due to current warming, with smaller glaciers disappearing completely and others decreasing to only 10–20% of their previous size. With very low emissions however, these losses will slow and eventually stabilize, with at least some glacier remnants surviving. Projections in a few glacier regions even show slow re-growth beginning between 2100 and 2300, but only with very low emissions entailing 50% reductions by 2030, and essentially carbon neutrality by 2050.[31]

Any other emissions pathway will eventually result in essentially complete loss of all land glaciers on Earth outside High Mountain Asia and high-latitude polar regions, which include northern Canada and southern Patagonia. With high emissions, and global mean temperature rise

Glacier losses will continue at a steep rate over the next several decades just due to current warming.

exceeding 4°C by 2100, any substantial seasonal snowpack will become a rarity outside the polar regions and very high mountains.

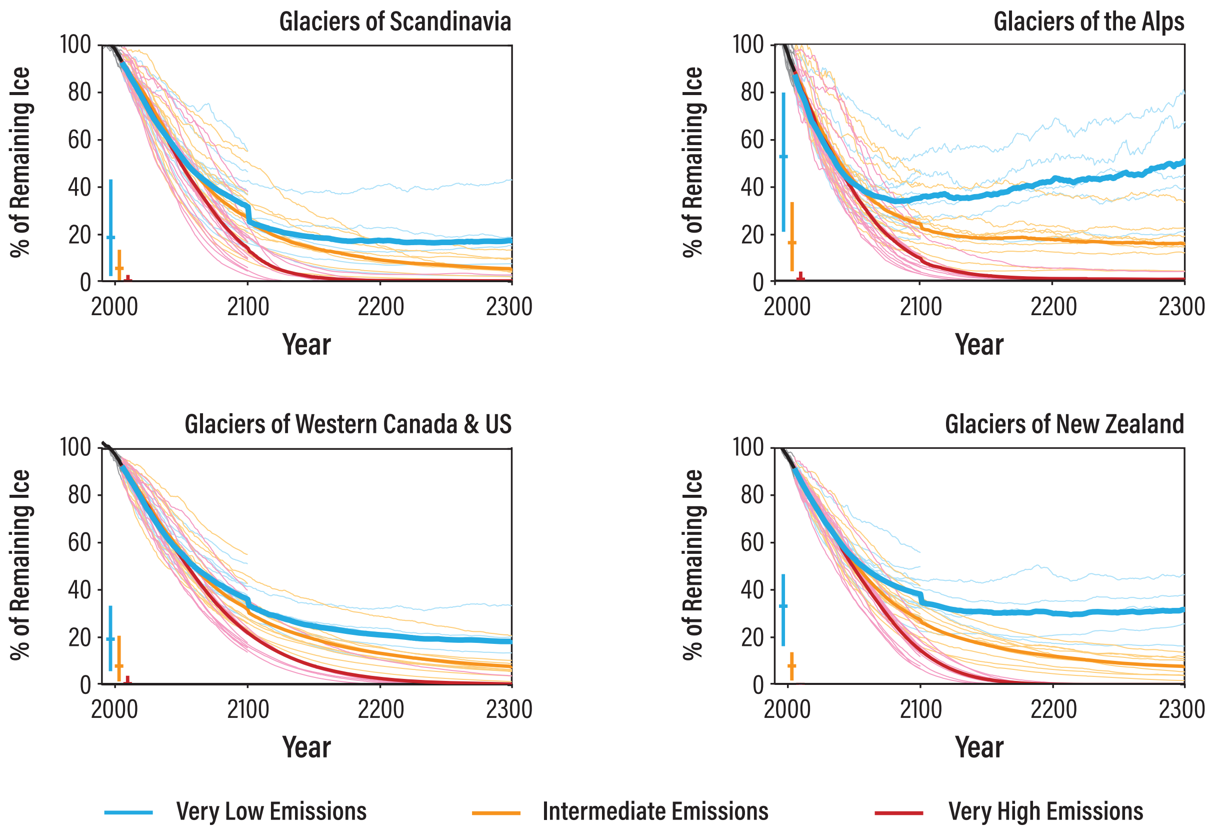
In those “high altitude and high latitude” regions, only 35–75% of glacier volume will remain by the end of this century under high emissions scenarios.[28] If we follow a very low emissions pathway, the glaciers and snowpack of High Mountain Asia – so important for seasonal water resources – will stabilize and begin to return. At all higher emissions levels resulting in peak temperatures above 2°C, losses in this region will continue. With very high emissions similar to today’s year-on-year rise in CO_2 concentrations, this loss would be ever more rapid.[28]

Glaciers gain mass via snow deposition in winter and at higher altitudes, and lose mass as meltwater in summer and at lower altitudes 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 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 to eventually disappear entirely. This is what the majority of glaciers in the European Alps experienced during the summer of 2022, with major ice bodies losing more than 5% of their total volume in one single melt season.

Glaciers can melt and even disappear completely over the space of just decades or a century. When Glacier National Park in the U.S. was created in 1910, it had around 150 glaciers; today, fewer than 30 remain, and those have shrunk by about two-thirds. From 1901 to 2018, glaciers outside Antarctica contributed nearly 7 cm to global sea-level rise.[10] While such melt has been rapid, large glaciers grow back only slowly, especially at temperatures above pre-industrial. Limited modeling seems to indicate that “re-growth” of mountain glaciers, to scales present in the mid-1900’s or even today, would be a matter of many centuries; and perhaps even millennia in some regions (see glacier graphs figures).

Therefore, on human timescales, the disappearance of glaciers is an essentially permanent change to

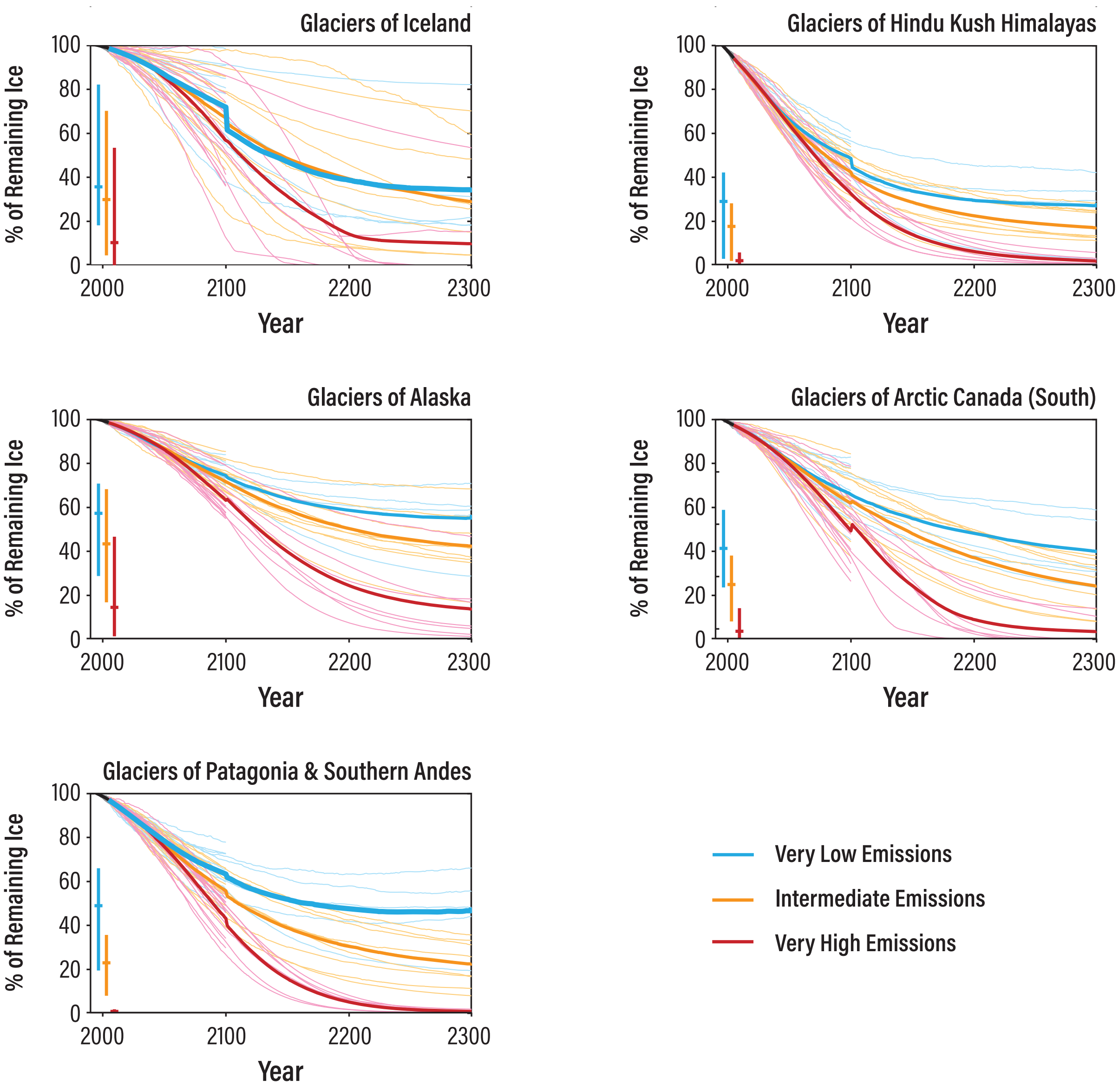
FIGURE 3-2. **Mid-Latitude Glaciers**



Glaciers at the mid-latitudes are especially sensitive to the gradient between 1.5° and 2°C, with many disappearing by 2300 at 2°C, but preserving some percentage of ice mass at 1.5°C.

FIGURES BASED ON MARZEION ET AL. (2012)

FIGURE 3-3. **Polar and High Mountain Asia Glaciers**



The water towers of the Himalayas preserve far more ice at 2°C compared to 1.5°C, as do the glaciers on the margins of Greenland and Antarctica that contribute greatly to global sea-level rise from glacier melt.

FIGURES BASED ON MARZEION ET AL. (2012)

the mountain landscape. Very low emissions are key to ensuring as little ice as possible is lost during this current period of rapid decline, preserving the ecosystem services glaciers provide.

Glaciers and snowpack have varying importance to nearby communities as a source of water for drinking 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.[40] Glaciers in some regions, such as the Andes, or the Indus and Tarim basins in the Hindu Kush Himalaya region, contribute a high

If we follow a very low emissions pathway, the glaciers and snowpack of High Mountain Asia – so important for seasonal water resources – will stabilize and begin to return.

USGS / Morton Elrod, University of Montana

L McKeon, USGS

Glacier National Park: Jackson Glacier in 1912 (above) and 2009 (below)

percentage of seasonal water supplies; in the dry Tarim and Aral Sea basins, close to 100% during the summer months. While the increased melting of glaciers temporarily increases water supply, eventually the decrease in water flow as the glaciers pass "peak melt" and continue shrinking, 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," or peak melting.[15,18] Extensive adaptation therefore needs to begin immediately to prepare for this future, even as mitigation to preserve as much of these glaciers as possible is also prioritized.

In addition to glaciers, mountains also hold water in the form of snow. In fact, far more seasonal freshwater is generally stored in snowpack than in glaciers. Snowfall has however become less reliable 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 in some regions.[15] In many mountains, it now appears that snow generally is following the same downward trajectory as the 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.[15] At lower elevations and latitudes, snow will fall less often or not at all, and the winter season will shorten.[36] Seasonal snowpack will not form, resulting in loss of stored water in the snow itself and in underground aquifers. This can result in negative economic impacts for sectors such as agriculture and hydropower, and threatens the availability of sufficient water supplies for downstream populations.[27]

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 the water from snow. In the western U.S., rising temperatures have caused a general decrease in annual snowpack, leading to ever more severe water shortages.[9] In both the Arctic and mountain regions, the well-being of people and many species depend on seasonal snow cover. For reindeer-based Arctic Indigenous cultures, increasing numbers of animals are lost to starvation when more unseasonal rains falls on snow, forming thick layers of ice that makes it impossible for the reindeer to scrape snowpack away to graze. Decreases in snow cover negatively impact snow tourism, especially in the United States, Japan, and central

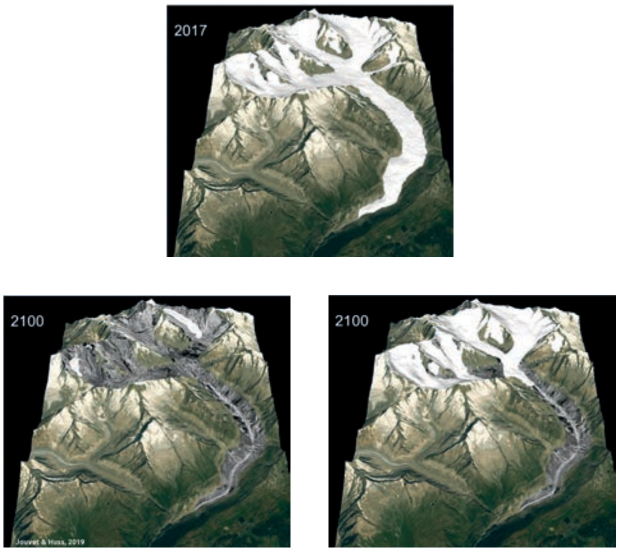
Grace Wangui / Shutterstock

The remote Rwenzori glaciers of Uganda and the Democratic Republic of Congo are among the sources of the Nile. After many years of extreme loss, 2022 observations seem to suggest some stabilization – for now.

ZUMA Press, Inc. / Alamy Stock Photo

Agriculture in the Tarim Basin of China is extremely dependent on glacier and snowpack run-off in the summer growing season.

FIGURE 3-4. **Great Aletsch Glacier**



The Great Aletsch Glacier, Switzerland, in 2017 (top), in 2100 with high emissions (lower left), and in 2100 with low emissions (lower right).

COURTESY OF MATTHIAS HUSS

Low emissions pathways, minimizing overshoot, could make the difference between disruptive loss and preservation.

Europe.[15,35] Lack of mountain snow cover also increases the risk of wildfires, as well as catastrophic events such as mudslides in the wake of such wildfires. In some areas, the impacts of glacier melt and snowmelt on freshwater availability have already contributed to increasing tensions and/or conflicts related to water resources.[1]

A strengthening of climate pledges will have especially significant benefits for those communities in the Andes and Central Asia that are most dependent on glacier runoff as a seasonal source of water for drinking and irrigation; and on economies dependent on meltwater from glaciers and seasonal snowpack for power generation, agriculture and revenue from snow tourism, such as the 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.

Umar Shah / Shutterstock

Meltwater, combined with precipitation falling as rain rather than snow, contributed to extreme flooding this summer in both Pakistan and Bangladesh. Above: Khyber Pakhtunkhwa (KPK), Pakistan, 2022.

To preserve as much glacier ice and ecosystem services as possible, a sharp strengthening of climate action is needed towards the 1.5°C limit. This requires a general 50% reduction in human emissions by 2030, and stronger commitments in the near-term 2030–2040 timeframe. These low emissions pathways, minimizing overshoot, could make the difference between rapid and disruptive loss of regionally important snow and glacier systems, and significant steps towards their preservation.

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

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Permafrost

Higher Human Emissions Today Mean Higher Permafrost Emissions for Centuries

Very Low and Low Emissions (Peak 1.6–1.8°C, declining by 2100): Permafrost thaw is already adding carbon dioxide and methane emissions equal to those of Japan today, at 1.1°C of warming. Even with low emissions, thawed permafrost thaw will add carbon dioxide and methane to the atmosphere at a rate on par with human emissions from India today, totaling around 150–200 Gt CO_2* by 2100. Once permafrost thaw has occurred, its emissions can continue for centuries; so permafrost carbon release would continue well after 2100, even as atmospheric temperatures begin to decline sometime between 2060–2080. Future generations will need to deploy and continue carbon dioxide removal strategies to balance these long-term emissions until they cease, simply to hold temperatures steady. Surface permafrost** will largely disappear below the Arctic Circle, and from nearly all mountain regions globally, with extensive infrastructure damage. Even in this low emissions scenario, such local impacts will force a number of Arctic communities to relocate entirely.

Fulfillment of All 2022 Pledges/NDCs (1.9°C in 2100, overshoot >2°C post-2100): Permafrost thaw will add carbon dioxide and methane to the atmosphere at a rate on par with human emissions from the European Union today, totaling around 220–300 Gt CO_2 by 2100. These permafrost emissions will continue for centuries after peak temperature is reached between 2120–2140. Future generations will need to deploy and continue carbon dioxide removal strategies equal to these long-term permafrost emissions until they cease, simply to hold temperatures steady. Near-surface permafrost will disappear in extensive regions below as well as above the Arctic Circle, and most existing infrastructure built on vulnerable permafrost will require replacement.

Implemented Policies as of 2022 (2.7–3.1°C in 2100 and rising): Permafrost thaw will add carbon dioxide and methane to the atmosphere at a rate on par with human emissions from the United States today, totaling around 350–400 Gt CO_2 by 2100. These emissions will continue for centuries, even after peak temperature is reached between 2150–70. Future generations will need to deploy and continue carbon dioxide removal strategies equal to these long-term emissions until they cease well past 2300, simply to hold temperatures steady. Over 70% of original pre-industrial surface permafrost globally will disappear. Extensive erosion, due to permafrost thaw, ice-free conditions in northern seas, and more violent storms will require extensive replacement or relocation of coastal and riverside Arctic infrastructure in Russia, Canada and Alaska.

Current Growth in CO_2 (2–3ppm per year, temperature 4–5°C in 2100 and rising): Permafrost thaw will add carbon dioxide and methane to the atmosphere at a rate on par with human emissions from the U.S. or China today (5–10Gt/year), totaling around 400–500 Gt CO_2 by 2100. These emissions will continue for some centuries after peak temperature is reached, which may not occur until well after 2200. Future generations will need to deploy and continue carbon dioxide removal strategies equal to these long-term emissions until they cease well past 2400, simply to hold temperatures steady. Surface permafrost will largely disappear globally with massive impacts on infrastructure and population in the permafrost region.

* Actually CO_2 equivalents (CO_2-e) over a 100 year period. This allows the climate impacts of both CO_2 and methane to be considered together. In this chapter, we use "CO_2" to refer to CO_2-e for simplicity.

** Defined as the upper three meters of soil

2022 Updates

- Nearly three dozen of the world's leading permafrost researchers and policy experts published a consensus paper which identified several key messages: 1) It is not too late to prevent future permafrost loss by reducing fossil fuel emissions, but continued high emissions will accelerate permafrost thaw and related CO2 and methane emissions; 2) Urgent action is required to reduce intergenerational consequences; 3) Permafrost carries deep ecological and cultural significance for Arctic communities; and 4) There are no "miracle cures" to protect the global climate system from generations of unstoppable permafrost emissions without urgent and deep emissions cuts consistent with the 1.5°C goal of the Paris Agreement.[1]
- The first observational evidence for increasing methane emissions from thawing permafrost was documented for the early summer months at a site in the Lena River Delta, where emissions have been measured since 2004, likely due to earlier arrival (by 11 days) of warmer temperatures during this same period.[54]
- More incidents of extreme summer rainfall may increase the depth of permafrost thaw by more than 30% in the northeastern Siberian tundra. 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.[28]
- Rising summer temperatures have recently triggered widespread permafrost thaw across high-latitude regions of Alaska, with some permafrost now in a thawed state throughout the year. As temperatures increase, the thickness of these permanently thawed regions will progressively increase. Under a high-emissions scenario, three-quarters of Alaska's discontinuous permafrost zone may reach this unfrozen state within the next decade, with the thawed depth increasing to 10 m or more by 2100.[10]
- Rising global temperatures have even accelerated permafrost thaw in Greenland, increasing the vulnerability of coastal mountain regions to unpredictable landslides and collapse.[46] As temperatures reach new record highs, the increasing frequency and scale of landslides across Greenland pose an increasing risk to local communities.
- If global mean temperature rises above 2°C, more than 75% of permafrost peatland regions in northern European and western Siberia will become too warm and wet to maintain permafrost by the 2060s. Strong action to reduce emissions and keep global temperatures well below 2°C may allow suitably cold and dry conditions in western Siberia to preserve at least parts of these regions. Even with low emissions however, 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.[11]
- Permafrost degradation underneath lakes and in their surroundings in Alaska can destabilize the ground, triggering rapid drainage and emptying the lake within several days to weeks due to thawing, erosion, or overflow. 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.[24]
- The presence of infrastructure built on permafrost ground usually increases the amount of heat entering the soil compared to undisturbed tundra, accelerating thaw and increasing the risk of collapse.[41] According to AMAP's latest *Climate Update*, more than 66% of Arctic settlements are located on permafrost and, in Alaska, permafrost thaw will increase cumulative maintenance costs of public infrastructure by an estimated US $5.5 billion by 2100. Reducing emissions will help curb temperature rise and limit damage.[2]

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.

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.[45] 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 1.1°C of warming above pre-industrial, annual permafrost emissions are about the same as Japan's, currently about the seventh largest global contributor of human emissions.[44]

FIGURE 4-1. **Permafrost Emissions Today 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)

Permafrost stretches across Arctic tundra and taiga 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.[17,25,34] 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 with Tibetan Plateau and near-coastal subsea permafrost included.[15,43,45] Cold temperatures in stable permafrost 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 to today's. 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 these shallow coastal waters.[35]

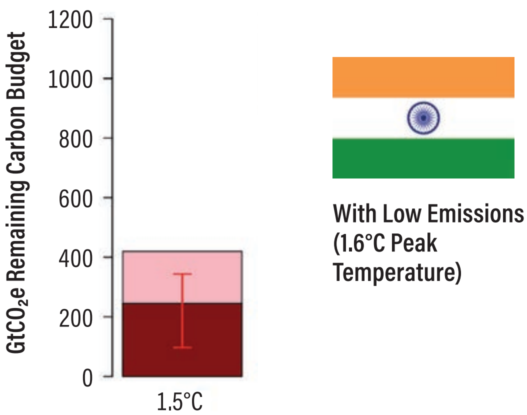
The Arctic however is now warming at 2–4 times the global average,[33] making these ancient permafrost stores of carbon highly vulnerable to thaw; followed by subsequent release of that stored carbon as both CO_2 and methane through the action of soil microbes over many years after that initial thaw.

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.[43] Model estimations show that there has already been about a 7% decrease in near-surface permafrost extent over the past five decades,[26] 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.[4]

As temperatures have risen, permafrost has not only declined in area, but thawed to greater depth and is beginning to release its stored carbon, potentially at levels equal to that of Japan today (0.3–0.6 Pg carbon).[44] Most of this released carbon comes as CO_2. However, if permafrost thaws under wet conditions, such as under wetlands, lakes or coastal waters; 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.[12]

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

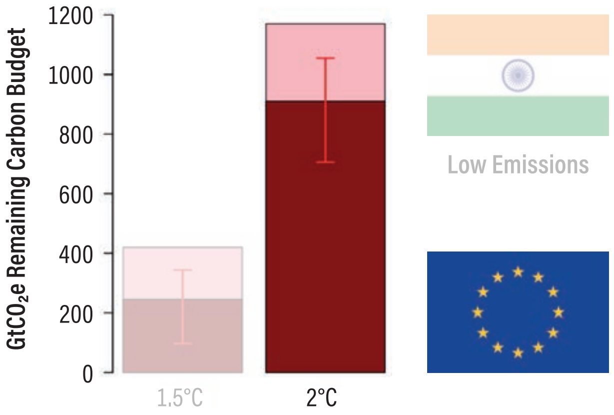
FIGURE 4-2. **Permafrost Decreases Our Carbon Budget**



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

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

FIGURE 4-3. **Permafrost Emissions at 2°C in 2100**

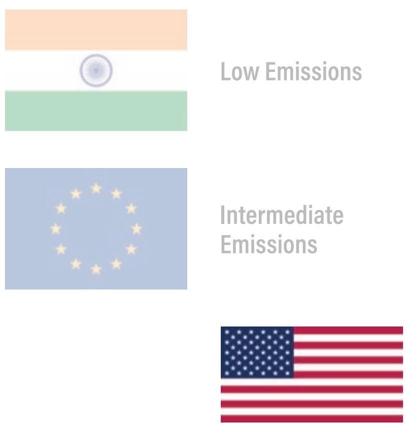


Committed annual permafrost emissions to 2100 on scale of the EU's annual emissions today, about 3–4Gt/year, total ≈220–300GtCO$_2$e

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

air temperatures and rain.[42] Such rapid collapse can also result in the formation of new lakes or wetlands, where additional and deeper thaw may occur. Coastal permafrost is especially vulnerable to these factors, 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.[19,40,48,49]

FIGURE 4-4. **Permafrost Emissions at 3°C in 2100**



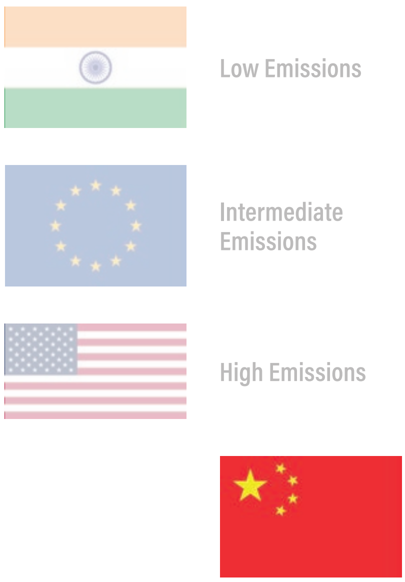
Committed annual permafrost emissions to 2100 on scale of the United States' annual emissions today, about 5Gt/year, total ≈350–400GtCO$_2$e

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

Current global climate models have not included such abrupt thaw processes, which expose deeper frozen carbon previously considered immune from thawing for many more centuries.[40,48] 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.[49] Increasing wildfires in the Arctic due to warmer and drier conditions also cause deeper and more rapid post-fire permafrost thawing.[29] At high latitudes, where much of the permafrost domain is located, most emissions from wildfire originate from below-ground combustion – 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.[31,47]

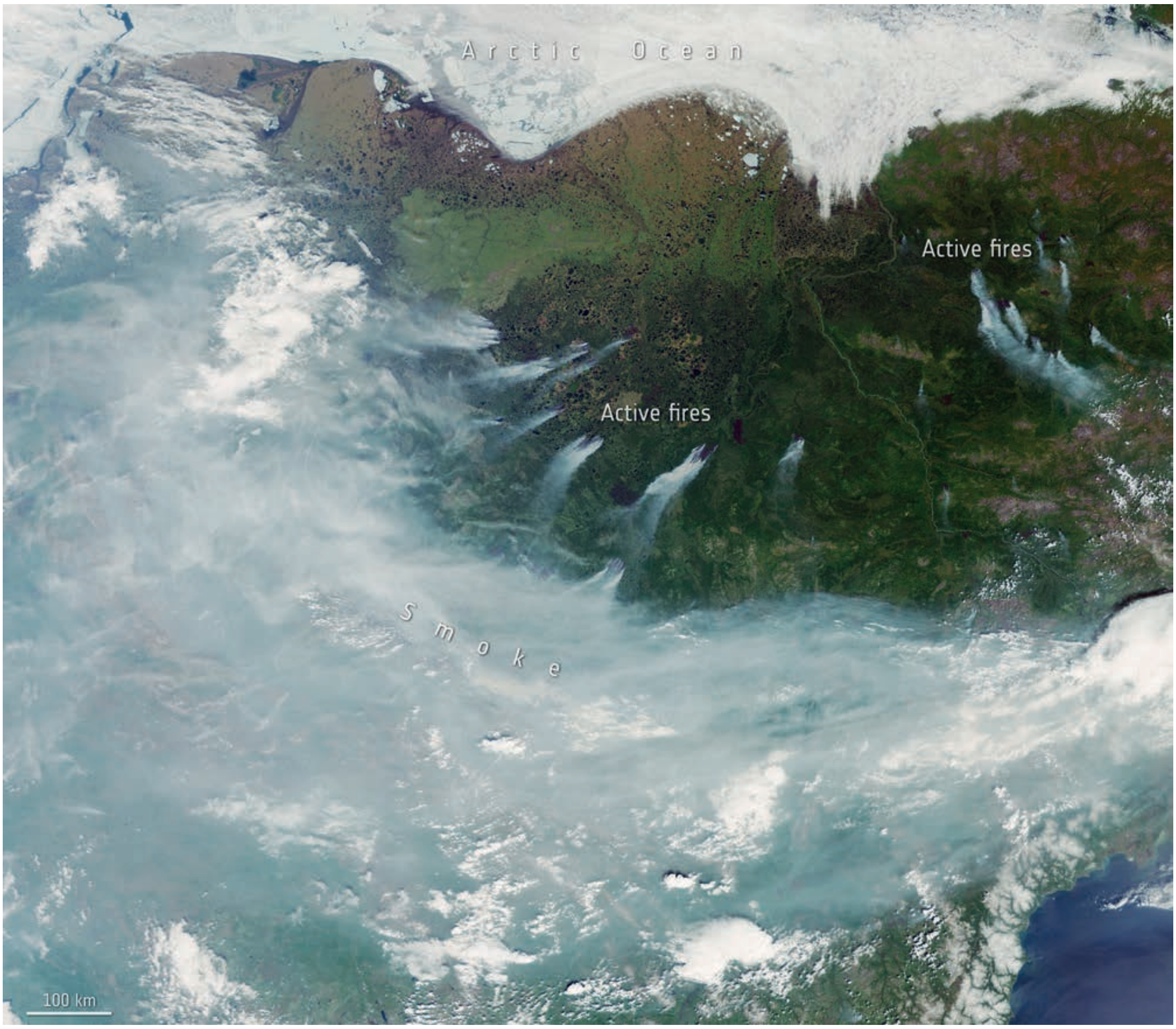
Once triggered, emissions from permafrost thaw processes are most often permanent on human timescales, because re-building of new permafrost soils takes centuries to thousands of years.[8] While new vegetation growing on thawed permafrost soils might take up some portion of these emissions, the sheer scale of permafrost emissions at warmer temperatures would dwarf such uptake. New research actually shows that Arctic greening stimulated by

FIGURE 4-5. **Permafrost Emissions at 4–5°C in 2100**



Committed annual permafrost emissions to 2100 on scale of China's annual emissions today, about 10 Gt/year, but unlike China's planned reduction to net zero by 2060, those from permafrost will continue at the same pace, ultimately totaling 400–500 GtCO$_2$e by 2100

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



Source: ESA

Satellite image of fires in Sakha, Chukotka and the Magadan Oblast, June 2020

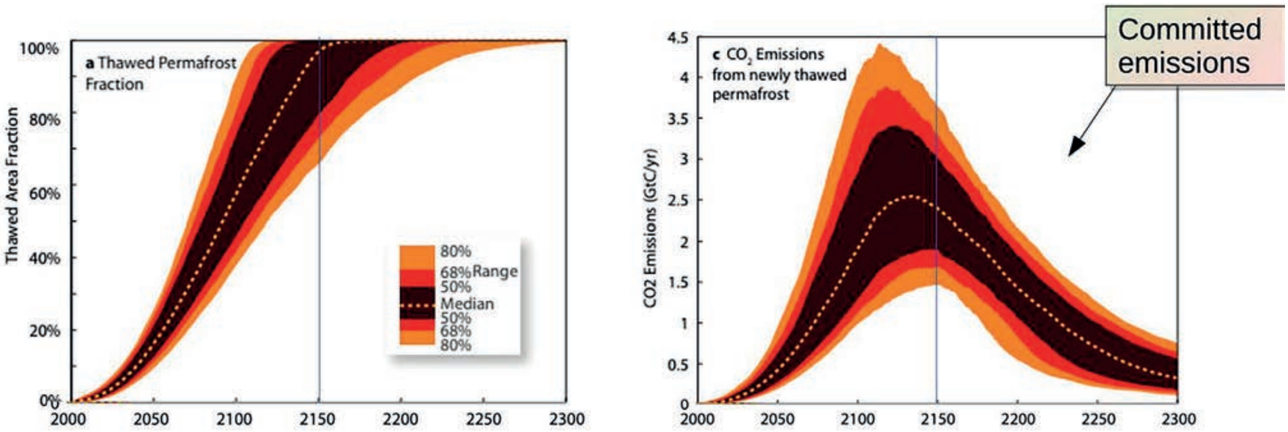
higher temperatures and rising CO_2 may cause even larger losses of permafrost carbon, because the roots of these new plants stimulate emissions from microbes in the soil.

Subsea permafrost beneath the shallow coastal waters of the Arctic Ocean may also release greenhouse gases. These are permafrost soils that were flooded as sea levels rose at the end of the last ice age; their current and future contribution to carbon emissions remains 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 vulnerable to release by 2300 as the Arctic Ocean continues to warm on a multi-century level once atmospheric temperatures pass 4°C.[35]

This 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 300–400m 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 is hypothesized to come from collapsing methane hydrates.

Permafrost emissions today and in the future are on the same scale as large industrial countries[44] but can be minimized if the planet remains at lower temperatures. If we limit warming to 1.5°C, emissions through 2100 will be about as large as those of India today, 2.5Gt/year, totaling around 150–200 Gt CO_2 by 2100. Should we instead reach 2°C, permafrost emissions will about equal those of the entire European Union today on an annual basis, 3–4 Gt/year, for about 220–300 Gt CO_2-eq by 2100. Even higher temperatures, exceeding 3–4°C by 2100, will however likely result in up to 400–500 Gt CO_2-eq additional carbon release

FIGURE 4-6. **Permafrost thaw (left) is followed by centuries of emissions (right)**



SARAH CHADBURN, ADAPTED FROM SCHNEIDER VON DIEMLING ET AL. (2015)

from permafrost, adding the equivalent of adding another United States or China (currently 5–10 Gt/year) annually to the global carbon budget through 2100.[4,13,14,21,31,48]

Calculations of the remaining planetary carbon budget must take these indirect human-caused emissions from permafrost thaw into account to accurately determine when and how emissions reach "carbon neutrality"; and not just through 2100, but well into the future.[1,7,13] This is because the thawing of permafrost is a slow process and because once thawed, permafrost soils continue to emit carbon for at least 100 years, and possibly several centuries. The actions of decision makers today to delay actions to decrease CO2 emissions will thereby commit future generations to offset permafrost carbon emissions through negative emissions (carbon dioxide removal), even after all human emissions cease and temperatures stabilize.[8]

In addition to the impacts of permafrost thaw on global climate, the direct physical effects of permafrost thaw (i.e., ground slumping, lake drainage, increased erosion and flooding) have been having severe impacts on Arctic 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.[41] Coastal and riverine permafrost erosion has already required some communities in

FIGURE 4-7. **Emissions Continue for Centuries after Initial Thaw: at 1.5°C**

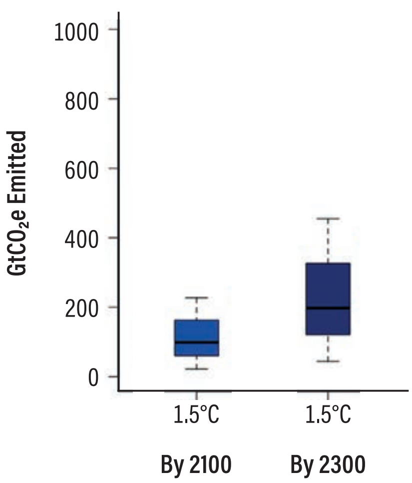


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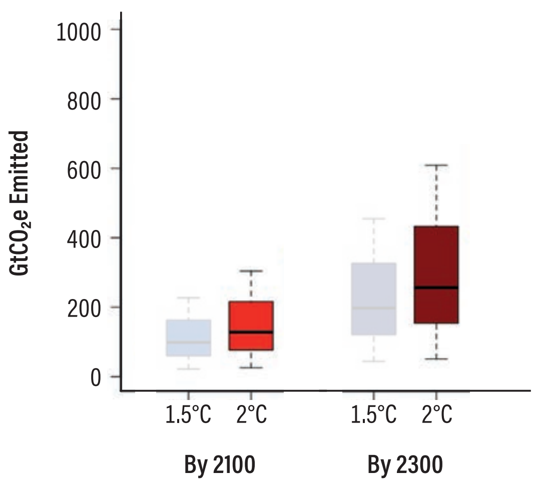
FIGURE 4-8. **Multi-generational Permafrost Emissions at 2°C**



ADAPATED FROM GASSER, ET AL. (2018)

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.[53]

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°, 2°C or more.[7,13] Warming in the Arctic already is occurring three to four times faster than the rest of the planet, due in part to the loss of snowpack, glaciers and sea ice.[33] The darker exposed bare ground and seawater absorb far more heat, further accelerating Arctic warming and additional thaw and loss of permafrost. A 2°C higher annual temperature globally translates into 4–6°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.

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.

Actions of decision makers today to delay actions to decrease CO_2 emissions will commit future generations to negative emissions.

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The people of Shishmaref voted to move their entire village because of erosion caused by climate change.

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Arctic Sea Ice

Crossing This Threshold Is Now Inevitable

Very Low and Low Emissions (Peak 1.6–1.8°C, declining by 2100): Even very low emissions can no longer prevent complete loss of multi-year Arctic sea ice due to at least one ice-free summer, likely before 2050. The crossing of this first global cryosphere threshold is now inevitable. However, if temperatures stabilize just above 1.5°C and then decline in line with these low and very low emissions pathways; Arctic summer sea ice most years could stabilize just above total loss conditions (defined as less than 1 million km^2). The number of ice-free summers will then slowly decline, helping stabilize global climate and feedbacks such as sea-level rise from melting of the Greenland ice sheet and Arctic glaciers, and permafrost emissions.

Fulfillment of All 2022 Pledges/NDCs (1.9°C in 2100, overshoot >2°C post-2100): Summer sea ice will disappear most Septembers starting at ~1.7°C global warming, and the autumn freeze-up process will begin later. By the 2.2°C peak, ice-free conditions will occur as early as June and persist well into November. This will greatly accelerate sea-level rise from melting of the Greenland ice sheet and Arctic glaciers, as well as carbon emissions from thawing permafrost. Today's Arctic ecosystem will be lost, with Arctic species replaced by those invading from the south as the Arctic Ocean becomes more like its southern counterparts.

Implemented Policies as of 2022 (2.7–3.1°C in 2100 and rising): The 1.7°C summer loss threshold will be reached already by ~2040. Ice-free conditions during summer, as well as much of spring and fall, will further accelerate Greenland melt and related sea-level rise and permafrost emissions. Ecosystem disruption will become more pervasive, reaching also into near-Arctic waters such as the Barents, Bering, and North seas, in concert with lower salinity due to extensive meltwater and worsening ocean acidification. These changes will disrupt plankton and algae growth in summer, with cascading effects up the marine food web. With greater ocean warming from the 3.1°C peak, recovery of Arctic sea ice will take centuries.

Current Growth in CO_2 (2–3ppm per year, temperature 4–5°C in 2100 and rising): The conditions of ecosystem collapse noted above will be apparent by 2030, spreading throughout the Arctic Ocean far more rapidly than with lower emissions. Depending on peak global mean temperatures, recovery of Arctic sea ice to even today's conditions (if temperatures return to around 1°C) would likely take over 1000 years as the Arctic Ocean will hold this heat for so long.

With the determination by the IPCC 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.

2022 Updates

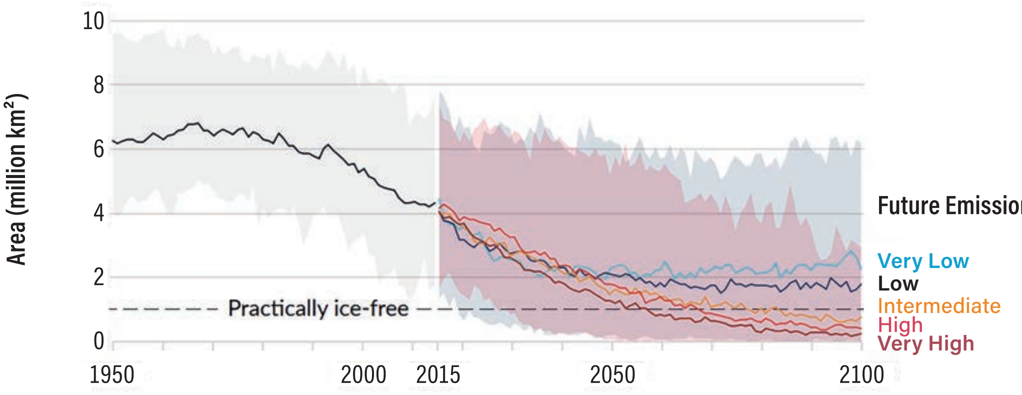
- The true rate of Arctic warming is three to four times faster than the global average, nearly double previous estimates, based on several decades of observational records. Arctic sea ice loss drives this cycle, increasing the amount of heat absorbed by the dark surface of the ocean. This feedback loop is most prominent in the Barents and Kara seas, where ocean warming has accelerated sea ice loss to unprecedented levels.[40]
- The decline of sea ice in the Barents-Kara Seas alone may account for up to one-third of winter warming over the Tibetan Plateau.[14] The Tibetan Plateau holds thousands of glaciers and serves as the source for many major rivers, including the Yellow and Yangtze Rivers, providing water for 40% of the world's population. Continued sea ice loss would exacerbate winter warming across nearly all regions of the Tibetan Plateau, endangering the reliability of seasonal water supply in much of China and southeast Asia. The rapid loss of Arctic sea ice may also intensify temperature and precipitation trends by 50% in Europe, North America, West Africa and South America.[11]
- In addition to losing nearly three-quarters of summer sea ice volume since the early 1980s, the Arctic has lost one-third of its entire winter sea ice volume in the past 20 years, mainly due to the loss of thick, multi-year ice. This once-prevalent multi-year ice has been replaced with thinner "seasonal" ice, which melts completely each summer. Since 2019, rising global temperatures have thinned Arctic multi-year ice by 0.5 meters – decreasing its total remaining volume by one-sixth in only three years.[24]
- This loss of multi-year sea ice also threatens Arctic marine life. Vulnerable regions such as the North Water polynya (NOW), a unique open-water ecosystem surrounded by sea ice between Greenland and Ellesmere Island in Canada, may no longer be able to serve as a winter refuge for keystone High Arctic mammals, or as central fishing and hunting ground for Inuit communities in the region as well as commercial fishing activities. Multiple lines of evidence now show increasing sea ice instability in this sector over the last two decades.[31,41]
- Arctic sea ice helps protect the Alaskan coastline from open ocean waves generated by strong winds in the Beaufort Sea. During the winter, this sea ice cover prevents waves from reaching the coastline. Over the past forty years, the "open-water" season – the warm period each year without the seasonal sea ice cover – has lengthened by more than three months, resulting in a five-fold increase in annual wave power and exposing Alaskan coastlines to erosion and collapse.[32]
- Sea ice also plays a role around Antarctica: along the coast of the Antarctic Peninsula, the accumulation of sea ice similarly provides a buffer that dampens approaching ocean waves, preventing them from smashing into the ice shelves that support the glaciers and ice sheet behind.[26] New research shows that rising air and ocean temperatures may decrease the amount of sea ice surrounding the Antarctic Peninsula.[8] Over the entire satellite record, the release of icebergs from the eastern Antarctic Peninsula almost always occurs during or shortly after some loss of sea ice.

Background

Arctic sea ice serves as the "global refrigerator," and an important regulator of global temperature. This large area of ice-covered ocean – the size of the U.S. and Russia combined – 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 ice, 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 the past 125,000 years.

The extent of Arctic sea ice that survives the entire summer, however, has declined by at least 40% since 1972, when reliable satellite measurements became available.[12,13,37] Estimates based on eyewitness accounts from ships and polar explorers places the decline since 1900 at well over 60%. In addition, until quite recently most of the sea ice in the Arctic was composed of mainly very thick multi-year ice, with an average lifetime of several years and an average winter sea ice thickness of 3 meters or more.[33,43] In contrast, today's sea ice mostly forms each winter and melts in summer, and is thinner than 2 meters.[13,33,46] The total volume of Arctic sea ice since the 1970s has therefore declined by nearly two-thirds: a much faster and greater decline than its area.

FIGURE 5-1. **September Arctic Sea Ice Area Projections**



Only low and very low emissions will allow Arctic sea ice to stabilize above ice-free conditions, though at least one ice-free summer is inevitable even with these pathways, likely before 2050.

SOURCE: IPCC AR6 WGI 2021

This extreme loss of summer sea ice is a primary 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.[16,40,46] It also carries significant weather, ecological, and economic consequences. These include loss of traditional livelihoods for Indigenous people dependent on stable sea ice for hunting and fishing. It may also include influences on 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 a more "wobbly" jet stream.[2,6,10,15,47]

Continued sea ice loss will also cause Arctic Ocean ecosystem disruption. Many marine species 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.[43,46] Even with low emissions, this is projected to occur at least once before 2050.[13,33,34,37] This will have a lasting effect on the entire Arctic food chain, and perhaps beyond.

Although this chapter focuses on Arctic sea ice due to its greater extent and global feedbacks, sea ice around Antarctica in contrast has been comparatively stable over the past several decades of satellite observations, growing in some regions and decreasing in others. However, recent observations document very sharp declines beginning in 2014, equal to or exceeding those in the Arctic but occurring over the space of only a few years, rather than decades.[39] If this trend holds, sea ice-dependent habitats along Antarctica's coast and in the Southern Ocean would begin to show similar negative impacts as those in the Arctic.[3,8]

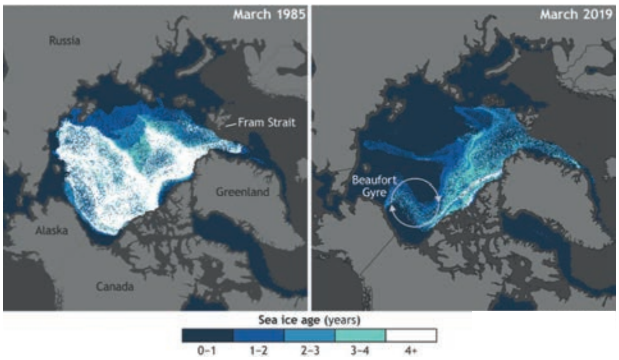
Summer Arctic sea ice extent has often been considered a bellwether of climate change, with great attention paid to the September minimum extent each year. In reality, however, sea ice thickness and extent have declined in all months; the consensus of sea ice scientists is that the ice cover has already fundamentally changed, crossing a threshold to a new state.[1,38,46] 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.[24,25,46] This "ecosystem of ice" no longer exists. 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 on average for only 1–3 years.[46]

Only under both very low and low emissions scenarios would summer sea ice extent likely stabilize.

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 Holocene spike in warming after the last ice age 8,000 years ago, and possibly not since the warm Eemian period 125,000 years ago. Today's temperatures almost equal those during the Eemian, when sea level was 4–6 meters (13–20 feet) higher than today. This is the current trajectory of the Earth's climate; and CO_2 levels from human emissions today are higher than at any point in 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.[4,5,12,28,29,49] It is likely that a near-complete loss of summer sea ice (defined as dipping below 15% of

FIGURE 5-2. **Just 1% of Today's Ice Pack is Old, Thick Ice**



For a NASA video showing the rapid loss of multi-year ice since 1984, see: https://www.50x30.net/disappearance-of-summer-arctic-sea-

IMAGE SOURCE: NOAA CLIMATE.GOV; DATA: ARC 2019

the Arctic Ocean's area, or 1 million square kilometers) 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 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.[9,33,35]

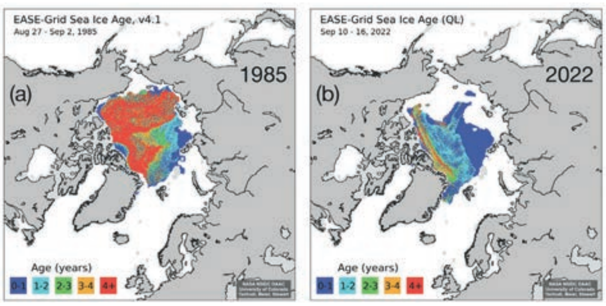
The occurrence of the first ice-free summer is therefore unpredictable, but scientists now believe it is inevitable, and likely to occur at least once before 2050 even under a "very low" emissions scenario.[13,33,34,37] However, under both very low and low emissions scenarios, summer sea ice extent would 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 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.[4]

On the other hand, even intermediate 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,[9,34,35,45] eventually stretching from July-October at 2°C.[22,35] 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.[9,46]

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.[2,7,10,15,47,50,53,54] 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; 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.[6] 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 governments declare that an ice-free summer Arctic will bring 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 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.[2,6,9,44,47] Such profound, adverse impacts almost certainly will eclipse any temporary economic benefits brought by an ice-free summer Arctic.

FIGURE 5-3. **Multi-year Ice at Summer Minimum, 1985 and 2022**



As recently as 1985, most of the Arctic Ocean was covered in thick multi-year ice even in summer, most of it more than four years old. In 2022, this multi-year ice is almost gone.

CREDIT: NSIDC

With greater ocean warming from a 3.1°C peak, recovery of Arctic sea ice will take centuries.

The Arctic Ocean has never been ice-free in modern human existence. With the determination by the IPCC that at least one ice-free summer is now inevitable due to human CO2 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.

Even very low emissions can no longer prevent complete loss of multi-year Arctic sea ice and at least one ice-free summer, likely before 2050.

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CHAPTER 6

Polar Ocean Acidification, Warming and Freshening

Very Low Emissions – the Only Means to Save Many Polar Species and Ecosystems

Very Low and Low Emissions (Peak 1.6–1.8°C, declining by 2100): At least 50% reductions by 2030 will raise CO_2 levels to a peak of between 440–480 ppm, depending on the scale of permafrost emission feedbacks. In large portions of the Arctic and Southern Oceans, this will lead to prolonged ocean acidification: very long-term (tens of thousands of years) corrosive conditions that stress all marine organisms, especially those with shells (made of calcium carbonate). Isolated marine heatwaves and related marine die-off events are likely to occur each year, until temperatures decrease to at least today's levels, sometime after 2200. Freshening from polar glacier and ice sheet melt may decrease the availability of needed nutrients in surface waters, causing changes in the food web. The Atlantic Meridional Overturning Circulation (AMOC) is likely to slow further, but not collapse.

Fulfillment of All 2022 Pledges/NDCs (1.9°C in 2100, overshoot >2°C post-2100): With the disappearance of sea ice for several months each summer, Arctic and near-Arctic waters will warm significantly faster, and hold heat longer. CO_2 concentrations will be greater than 500 ppm, resulting in harmful long-term acidification levels spreading throughout much of the Arctic and Southern Oceans, as well as impacting important fisheries in the Barents, Bering, Beaufort and Amundsen Seas. Such conditions, which will persist for several thousand years, may also begin to appear seasonally in other "hot spots" further from the poles, such as the North Sea and waters off western Canada, Iceland and the Canadian Maritimes. The impact of multiple stressors – increased acidification, marine heat waves, and greater freshening from meltwater off both polar ice sheets – on food webs and fisheries in these regions could be significant. Impacts on the AMOC and other ocean currents will be greater than at low emissions.

Implemented Policies as of 2022 (2.7–3.1°C in 2100 and rising): With CO_2 concentrations nearing 600 ppm, ocean acidification and multiple stressors will spread southward and persist for longer periods each year. Significant extinctions of cold-water polar species will become more likely, as waters both warm and become more corrosive for tens of thousands of years. With acceleration of Greenland melt, severe slowing and even shutdown of the AMOC cannot be ruled out. This would lead to severe and unpredictable disturbances to global weather patterns, which at this temperature level would already be more extreme from a warmer and wetter atmosphere.

Current Growth in CO_2 (2–3ppm per year, temperature 4–5°C in 2100 and rising): CO_2 levels, especially with permafrost emissions feedbacks, could reach between 650–800 ppm or more by 2100. Few of today's polar species, especially shell-building species and those associated with sea ice, are likely to survive the radical change in environment on multiple fronts.[41] In addition to acidification and sea ice loss, this would include much warmer water from atmospheric warming as well as from incursion of warm water from the mid latitudes; as well as much fresher waters from accelerating ice sheet melt, with potentially rapid collapse of the West Antarctic Ice Sheet. Mass extinction of many polar and near-polar species will be the result. Economically important species such as cod, herring and salmon are extremely unlikely to survive in the wild, especially as food webs are likely to be less diverse and resilient. Ocean currents, and related weather impacts from this rapid incursion of ice sheet meltwater would likely be extreme and unpredictable.

2022 Updates

- Mounting research indicates that that a high emissions scenario would lead to catastrophic polar marine species loss already by 2300. The scale of loss would be on par with the five mass ocean extinction events in Earth's past, with polar and near-polar oceans particularly vulnerable.[35]
- Warming and acidifying oceans reduce habitat options for many marine species, including Pacific salmon, Arctic-native whale species and mussels.[5,7,42]
- Exposure to new stressors such as nanoplastics could worsen the effects of acidification for polar marine species.[28]
- Areas of the Arctic ocean are increasingly separating into layers based on their temperature, salt content and depth. If temperatures continue to rise and this separation continues, this could have profound impacts for nutrient availability and therefore the Arctic food web.[25]
- Increasing permafrost melt from rising temperatures provides another source of acidification, as organic carbon is released into Arctic waterways.[27]
- Westerly winds have shifted closer to the Antarctic continent, causing water eddies to erode the base of ice sheets and increase meltwater into the ocean. This shift may have negative impacts on Southern Ocean ecosystems and species, and it underscores the influence this ice sheet holds over local ecosystems as well as the global climate system.[34]
- Sea ice loss is increasing the uptake of atmospheric carbon dioxide by surface water and driving rapid acidification of the western Arctic Ocean at a rate three to four times higher than that of the other ocean basins.[36]
- pH changes through a seasonal cycle. Presently, the lowest pH in the Arctic Ocean occurs in winter. This lowest pH point could shift to the summer in the future due to increasing warming and ice loss. These findings mean that the Arctic ecosystem, already stressed in summer due to higher temperatures, will also have to contend with additional acidification.[33]

Background

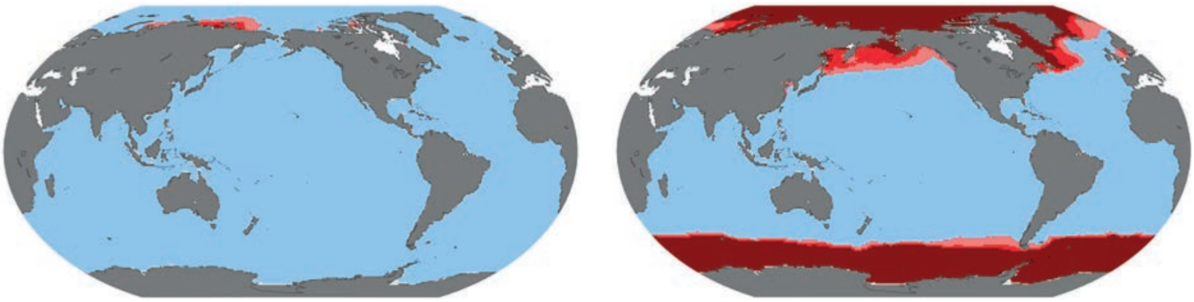
Increasing CO_2 concentration leads not only to climate change, but also to increasing rates of acidification of the world's oceans. Oceans provide a vital service to the global climate system by absorbing CO_2; limiting global warming, despite sharp increases in human carbon emissions. However, such ocean carbon absorption comes with a price: when dissolved into seawater, CO_2 forms carbonic acid. This phenomenon is known as ocean acidification; and rates of acidification today are faster than at any point in the past 300 million years.[17]

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. By some estimates, polar waters have absorbed up to 60% of the carbon taken up by the world's oceans thus far. This makes them an important carbon sink, helping to hold down global heating. This "sink" comes at a cost for polar marine environments, however, 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 build and maintain their structures, while in all water-dwelling organisms ocean acidification also increases the energy costs to maintain pH in the cells and tissues. In this way, ocean acidification harms key organisms such as marine gastropods and pteropods, sea urchins, clams, and crabs.[24] Polar organisms are adapted to stable pH conditions that have existed for several million years. They are sensitive to even small changes in seawater chemistry, and will be strongly and quickly impacted by the more rapid and greater ocean acidification of polar waters.

A high emissions scenario would lead to catastrophic polar marine species loss on par with the five mass ocean extinction events in Earth's past.

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



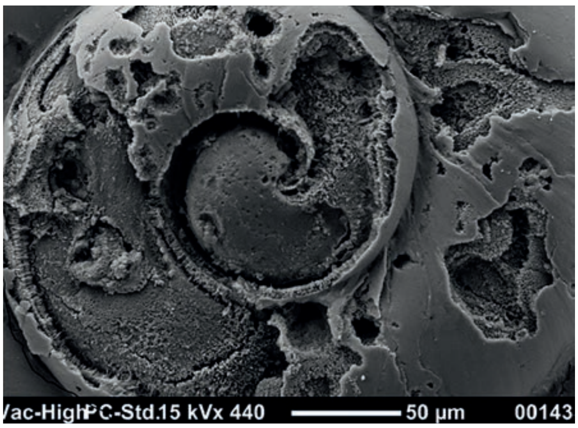
Difference between acidification levels in a 1.5° world (RCP2.6) (left map), and a 3–4° world (RCP8.5) (right map) by 2100. Red shows "undersaturated aragonite conditions," a measure of ocean acidification meaning that shelled organisms will have difficulty building or maintaining their shells, leading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

IMAGE SOURCE: IPCC SROCC (2019).

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 the acidity from 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 50–70,000 years to bring acidification and its impacts back to pre-industrial levels, following the weathering of rocks on land into the ocean. This very long lifetime of acidification in the oceans is one 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.[30] This represents an additional 30% increase in acidification globally, with higher levels again projected in polar waters. However, current pledges (even if completely fulfilled) will result in CO_2 levels above 500 ppm, and temperatures of around 2.1°C. At that point, acidity will have more than doubled in polar oceans.

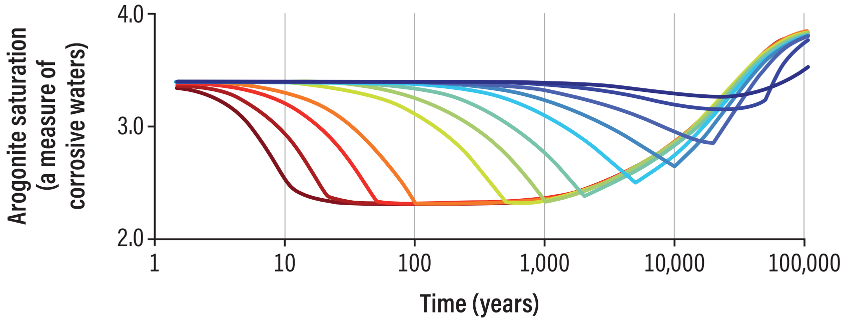
Atmospheric CO_2 levels above 500 ppm are projected to cause widespread areas of corrosive waters in both polar oceans. The Arctic Ocean appears to be most sensitive: already today, it has large regions of persistent corrosive waters. These corrosive areas in the Arctic Ocean began expanding in the 1990s. 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.[1] In the Southern Ocean, the ability of some vulnerable organisms to build shells declined by around 4% between 1998 and 2014.[11] Pteropods – tiny marine snails known as "sea butterflies" – are particularly susceptible



Top: Healthy living pteropod. Bottom: Observed severe shell damage (Arctic).

Images, top: Dr. Nina Bednaršek; bottom: Niemi et al., 2020, Frontiers in Marine Science

FIGURE 6-2. **Over Ten Thousand Years for Recovery from Ocean Acidification**



Ocean acidification recovery time, ranging from very high emissions (red) to very low emissions (blue). Note logarithmic scale: for ocean species, acidification is essentially permanent, with full recovery taking 50,000–70,000 years.

ADAPTED FROM HONISCH ET AL (2012)

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.[3] Pteropods are hugely important in the polar food web, serving as an important source of food for young salmon, Arctic cod and char and other species.

Global ocean acidity has been relatively stable over the past several million years. Today's rate of change is unprecedented however 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. The speed of today's acidification is therefore a key part of its threat: it is occurring far too quickly to allow species of today to evolve and survive.

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

This is especially the case in the Arctic, where in addition to rising acidification, warming has been unusually rapid. 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 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.[32] 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. 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 west of the Antarctic Peninsula. This Southern Ocean warming seems increasingly important in overall global ocean heat increase.

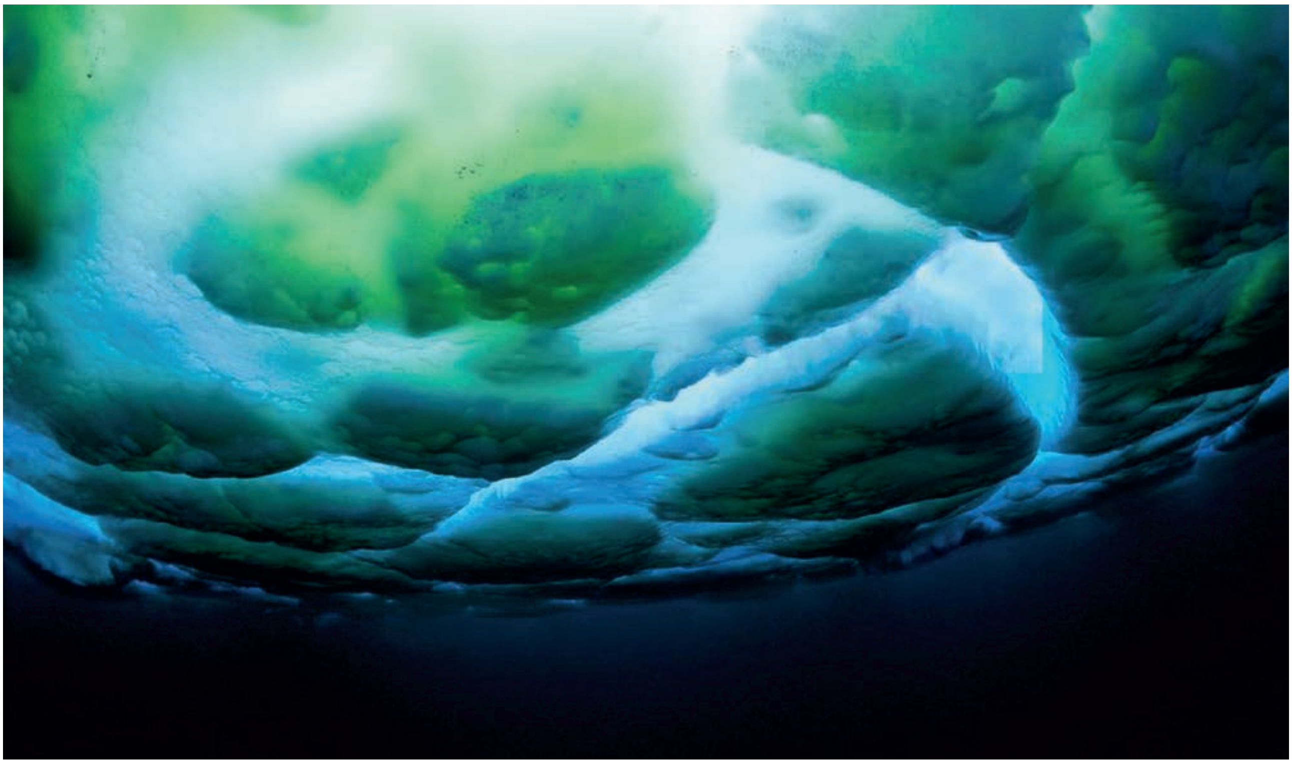
It will take some 50,000–70,000 years to bring acidification and its impacts back to pre-industrial levels.

Warming of polar waters is also resulting in more frequent extreme heat events, with temperatures that go beyond levels that polar species evolved to survive, essentially trapping these polar endemic species with nowhere else to migrate. At the same time, warming waters bring competition from invasive species that are moving poleward, following their own preferred temperature range.

Warming waters result in a poleward movement of other species, while reducing the range of polar species and increasing competition for food resources.[1,7] In some

Gtravel / Shutterstock

Krill is an important component in the Southern Ocean ecosystem, as well as a protein-rich commercial product.

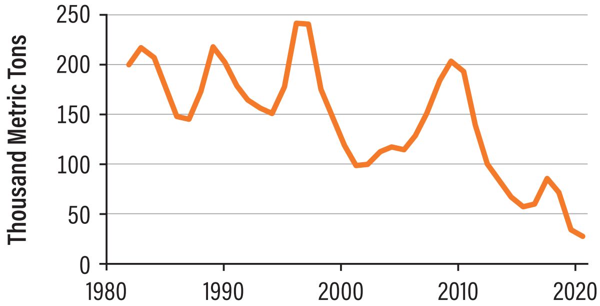


Peter Thor, SMHI

Thick, multi-year ice provides a rich ecosystem not visible from above.

instances, especially where extreme heatwaves occur in the ocean, 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 (plants) and animals also are being lost as sea ice declines due to warming. Ocean pollution, particularly that from plastics, add another layer of stress to polar species.[28] 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.[3,45]

FIGURE 6-3. **Male Snow Crab Abundance, Eastern Bering Sea (Alaska)**



DATA FROM NOAA FISHERIES; GRAPHIC: TYLER KEMP-BENEDICT, ADAPTED FROM THE WASHINGTON POST (2022)

Increased run-off from glaciers and ice sheets into the oceans is also freshening the surface waters of the polar oceans. This colder, fresher water sits like a lid on top of the deeper, warmer and saltier levels below, preventing nutrients from reaching the surface where most species live.[10,34] This phenomenon of a freshwater "lid" can also impact ocean currents, especially the AMOC – the system of ocean currents carrying warm water from the tropics to the North Atlantic. It acts as a motor for currents in the North Atlantic, and in turn can affect currents worldwide. Similar freshwater incursion from the Antarctic ice sheet can change ocean currents, which has consequences for global circulation of important nutrients, gases and heat. Such freshening can also have negative physiological impacts or impair species movement.

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, and the fisheries and aquaculture that depend on them, beyond our recognition. A world kept close to 1.5°C or lower can limit these irreversible effects on polar ocean ecosystems and fisheries, though some losses unfortunately are now inevitable.

These impacts above 2°C are essentially irreversible, and will occur with all but the very lowest emissions pathways. These require 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 a critical ocean acidification chemical threshold. 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.

The only way to slow and eventually halt the acidification process is through rapid CO_2 emissions reductions and future carbon dioxide removal.

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Summary Projections

State of the Cryosphere 2022

Very Low and Low Emissions (Peak 1.6–1.8°C, declining by 2100)

ICE SHEETS AND SEA-LEVEL RISE

Global sea levels will continue to rise for centuries, reaching around 2–3 meters above today's level in the next few hundred years, with about half a meter occurring within the next 50–100 years. This assumes ice sheets respond to warming in a limited and steady manner, not adding substantially to sea-level rise from mountain glacier loss and ocean thermal expansion.

GLACIERS AND SNOWPACK

Glaciers and snowpack already have declined rapidly for several decades. That rapid decline inevitably will continue, especially outside the polar regions. With very low emissions, glacier losses will begin to slow slightly already around 2040, though many glaciers are not expected to stabilize until around 2200. Some glacier regions in the mid-latitudes, such as the Alps, may begin to show very slow re-growth (a few percent per decade) by 2100; others require temperatures closer to pre-industrial for recovery. With very low emissions, even low-latitude glaciers may begin to recover, though disappearance of nearly all near-equatorial glaciers by 2050 is plausible even with low emissions. They may not recover until temperatures fall below pre-industrial, or the next Ice Age.

PERMAFROST

Permafrost thaw is already adding carbon dioxide and methane emissions equal to those of Japan today, at 1.1°C of warming. Even with low emissions, thawed permafrost thaw will add carbon dioxide and methane to the atmosphere at a rate on par with human emissions from India today, totaling around 150–200 Gt CO_2 by 2100. Once permafrost thaw has occurred, its emissions can continue for centuries; so permafrost carbon release would continue well after 2100, even as atmospheric temperatures begin to decline sometime between 2060–2080. Future generations will need to deploy and continue carbon dioxide removal strategies to balance these long-term emissions until they cease, simply to hold temperatures steady. Surface permafrost will largely disappear below the Arctic Circle, and from nearly all mountain regions globally, with extensive infrastructure damage. Even in this low emissions scenario, such local impacts will force a number of Arctic communities to relocate entirely.

POLAR OCEANS

At least 50% reductions by 2030 will raise CO_2 levels to a peak of between 440–480 ppm, depending on the scale of permafrost emission feedbacks. In large portions of the Arctic and Southern Oceans, this will lead to prolonged ocean acidification: very long-term (tens of thousands of years) corrosive conditions that stress all marine organisms, especially those with shells (made of calcium carbonate). Isolated marine heatwaves and related marine die-off events are likely to occur each year, until temperatures decrease to at least today's levels, sometime after 2200. Freshening from polar glacier and ice sheet melt may decrease the availability of needed nutrients in surface waters, causing changes in the food web. The Atlantic Meridional Overturning Circulation (AMOC) is likely to slow further, but not collapse.

ARCTIC SEA ICE

Even very low emissions can no longer prevent complete loss of multi-year Arctic sea ice due to at least one ice-free summer, likely before 2050. The crossing of this first global cryosphere threshold is now inevitable. However, if temperatures stabilize just above 1.5°C and then decline in line with these low and very low emissions pathways; Arctic summer sea ice most years could stabilize just above total loss conditions (defined as less than 1 million km^2). The number of ice-free summers will then slowly decline, helping stabilize global climate and feedbacks such as sea-level rise from melting of the Greenland ice sheet and Arctic glaciers, and permafrost emissions.

Summary Projections

State of the Cryosphere 2022 (continued)

Fulfillment of All 2022 Pledges/NDCs (1.9°C in 2100, overshoot >2°C post-2100)

ICE SHEETS AND SEA-LEVEL RISE

Primarily because of a relatively slow collapse of portions of the West Antarctic Ice Sheet (WAIS), as well as accelerated Greenland ice loss, plus loss of nearly all glaciers, global sea levels eventually will reach 3–6 meters above today's. Even higher levels cannot be ruled out: the last time temperatures exceeded the 2°C threshold, sea-level rise was 6–9 meters. Sea levels would reach at least 0.75 meters above today's level early in the next century. More troublingly, at this higher temperature, a steady predictable rate of sea-level rise from ice sheets is less certain, and so the rate and amount of sea-level rise by 2100 could be greater.

GLACIERS AND SNOWPACK

Under this scenario, by 2300, the only surviving glaciers of any substantial size will be limited to the polar regions and highest mountains, such as the Himalayas. Even in these regions, glaciers may shrink to 30–50% of their current size. Snowfall will become scarcer, falling instead as rain that may at times be extreme in this warmer climate, leading to increased erosion, flooding and landslides. In regions such as the western Americas and Himalayas, the loss of glaciers and diminishing snowpack will radically affect seasonal water supplies in some river systems, for example the Colorado, Indus, and Tarim Rivers.

PERMAFROST

Permafrost thaw will add carbon dioxide and methane to the atmosphere at a rate on par with human emissions from the European Union today, totaling around 220–300 Gt CO_2 by 2100. These permafrost emissions will continue for centuries after peak temperature is reached between 2120–2140. Future generations will need to deploy and continue carbon dioxide removal strategies equal to these long-term permafrost emissions until they cease, simply to hold temperatures steady. Near-surface permafrost will disappear in extensive regions below as well as above the Arctic Circle, and most existing infrastructure built on vulnerable permafrost will require replacement.

POLAR OCEANS

With the disappearance of sea ice for several months each summer, Arctic and near-Arctic waters will warm significantly faster, and hold heat longer. CO_2 concentrations will be greater than 500 ppm, resulting in harmful long-term acidification levels spreading throughout much of the Arctic and Southern Oceans, as well as impacting important fisheries in the Barents, Bering, Beaufort and Amundsen Seas. Such conditions, which will persist for several thousand years, may also begin to appear seasonally in other "hot spots" further from the poles, such as the North Sea and waters off western Canada, Iceland and the Canadian Maritimes. The impact of multiple stressors – increased acidification, marine heat waves, and greater freshening from meltwater off both polar ice sheets – on food webs and fisheries in these regions could be significant. Impacts on the AMOC and other ocean currents will be greater than at low emissions.

ARCTIC SEA ICE

Summer sea ice will disappear most Septembers starting at ~1.7°C global warming, and the autumn freeze-up process will begin later. By the 2.2°C peak, ice-free conditions will occur as early as June and persist well into November. This will greatly accelerate sea-level rise from melting of the Greenland ice sheet and Arctic glaciers, as well as carbon emissions from thawing permafrost. Today's Arctic ecosystem will be lost, with Arctic species replaced by those invading from the south as the Arctic Ocean becomes more like its southern counterparts.

Summary Projections

State of the Cryosphere 2022 (continued)

Implemented Policies as of 2022 (2.7–3.1°C in 2100 and rising)

ICE SHEETS AND SEA-LEVEL RISE

This scenario will push ice sheets in ways not seen since the end of the last Ice Age, 20–10,000 years ago. WAIS collapse is likely to be rapid once temperatures exceed 3°C, with involvement of portions of East Antarctica (such as Wilkes) and greater loss from Greenland. WAIS collapse would be well along by 2300. Sea-level rise will continue at a relatively rapid pace for many centuries and be essentially permanent on human timescales, reaching 15–20 meters or more above today's level. Sea-level rise of more than 1 meter before 2100 becomes highly probable in this scenario.

GLACIERS AND SNOWPACK

Rapid losses will continue in nearly all glacier regions for the next two centuries; by 2300, virtually no glaciers will remain anywhere on the globe outside the polar regions, Patagonia and Himalayas, where only 20–35% of ice will remain. Snowfall will become more rare outside the polar regions and the highest altitudes. With such very high levels of snowfall and glacier loss, glacier re-growth (even with temperatures returning to those of today) to scales present in the middle of the 1900's will likely take many centuries or in some cases even millennia, though snowpack would return as soon as temperatures decline.

PERMAFROST

Permafrost thaw will add carbon dioxide and methane to the atmosphere at a rate on par with human emissions from the United States today, totaling around 350–400 Gt CO_2 by 2100. These emissions will continue for centuries, even after peak temperature is reached between 2150–70. Future generations will need to deploy and continue carbon dioxide removal strategies equal to these long-term emissions until they cease well past 2300, simply to hold temperatures steady. Over 70% of original pre-industrial surface permafrost globally will disappear. Extensive erosion, due to permafrost thaw, ice-free conditions in northern seas, and more violent storms will require extensive replacement or relocation of coastal and riverside Arctic infrastructure in Russia, Canada and Alaska.

POLAR OCEANS

With CO_2 concentrations nearing 600 ppm, ocean acidification and multiple stressors will spread southward and persist for longer periods each year. Significant extinctions of cold-water polar species will become more likely, as waters both warm and become more corrosive for tens of thousands of years. With acceleration of Greenland melt, severe slowing and even shutdown of the AMOC cannot be ruled out. This would lead to severe and unpredictable disturbances to global weather patterns, which at this temperature level would already be more extreme from a warmer and wetter atmosphere.

ARCTIC SEA ICE

The 1.7°C summer loss threshold will be reached already by ~2040. Ice-free conditions during summer, as well as much of spring and fall, will further accelerate Greenland melt and related sea-level rise and permafrost emissions. Ecosystem disruption will become more pervasive, reaching also into near-Arctic waters such as the Barents, Bering, and North seas, in concert with lower salinity due to extensive meltwater and worsening ocean acidification. These changes will disrupt plankton and algae growth in summer, with cascading effects up the marine food web. With greater ocean warming from the 3.1°C peak, recovery of Arctic sea ice will take centuries.

Summary Projections

State of the Cryosphere 2022 (continued)

Current Growth in CO_2 (2–3ppm per year, temperature 4–5°C in 2100 and rising)

ICE SHEETS AND SEA-LEVEL RISE

Loss of large portions of both polar ice sheets and all glaciers will occur. WAIS collapse would be inevitable and potentially rapid, with sea-level rise of 2 meters possible by 2100, and up to 5 meters by 2150. 10 meters sea-level rise from all sources is likely by 2300. Sea-level rise will continue for many centuries even with temperature stabilization and slow decline, with the eventual complete loss of the Greenland ice sheet. Such a rapid rise in atmospheric CO_2 concentrations and temperature has no counterpart in Earth's geologic record, but Antarctica is known to have had essentially ice-free conditions at +6°C above today's level. Restoration of the polar ice sheets would only begin with temperatures well below pre-industrial (i.e., substantial global cooling).

GLACIERS AND SNOWPACK

Very few mountain glaciers will remain anywhere on the globe by 2200, with mid-latitude glaciers 90% gone already by 2100. Snowfall by 2100 will be extremely limited outside the polar regions and highest altitudes.

PERMAFROST

Permafrost thaw will add carbon dioxide and methane to the atmosphere at a rate on par with human emissions from the U.S. or China today (5–10Gt/year), totaling around 400–500 Gt CO_2 by 2100. These emissions will continue for some centuries after peak temperature is reached, which may not occur until well after 2200. Future generations will need to deploy and continue carbon dioxide removal strategies equal to these long-term emissions until they cease well past 2400, simply to hold temperatures steady. Surface permafrost will largely disappear globally with massive impacts on infrastructure and population in the permafrost region.

POLAR OCEANS

CO_2 levels, especially with permafrost emissions feedbacks, could reach between 650–800 ppm or more by 2100. Few of today's polar species, especially shell-building species and those associated with sea ice, are likely to survive the radical change in environment on multiple fronts.[41] In addition to acidification and sea ice loss, this would include much warmer water from atmospheric warming as well as from incursion of warm water from the mid latitudes; as well as much fresher waters from accelerating ice sheet melt, with potentially rapid collapse of the West Antarctic Ice Sheet. Mass extinction of many polar and near-polar species will be the result. Economically important species such as cod, herring and salmon are extremely unlikely to survive in the wild, especially as food webs are likely to be less diverse and resilient. Ocean currents, and related weather impacts from this rapid incursion of ice sheet meltwater would likely be extreme and unpredictable.

ARCTIC SEA ICE

The conditions of ecosystem collapse noted above will be apparent by 2030, spreading throughout the Arctic Ocean far more rapidly than with lower emissions. Depending on peak global mean temperatures, recovery of Arctic sea ice to even today's conditions (if temperatures return to around 1°C) would likely take over 1000 years as the Arctic Ocean will hold this heat for so long.


International Cryosphere
Climate Initiative