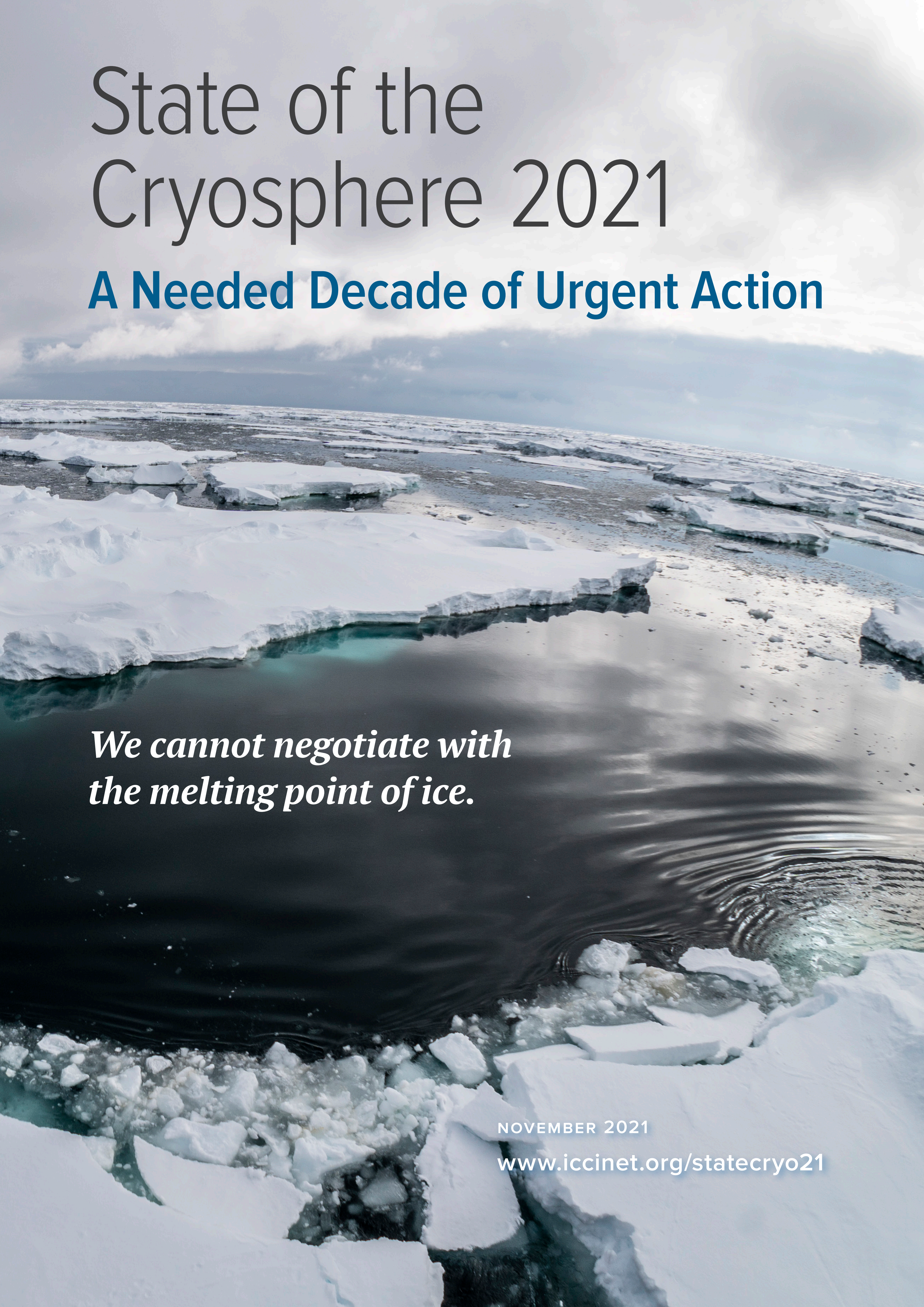
State of the Cryosphere 2021

A Needed Decade of Urgent Action



We cannot negotiate with the melting point of ice.

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Cover photo: Break-up of sea ice in the Ross Sea, Antarctica
(credit: Heidi Sevestre)

DEDICATION

This report is dedicated to all those who have given their lives in service of research in these snow-and-ice covered regions of the world, in particular Konrad (Koni) Steffen (August 2020, Greenland).

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Introduction

State of The Cryosphere: A Needed Decade of Urgent Action

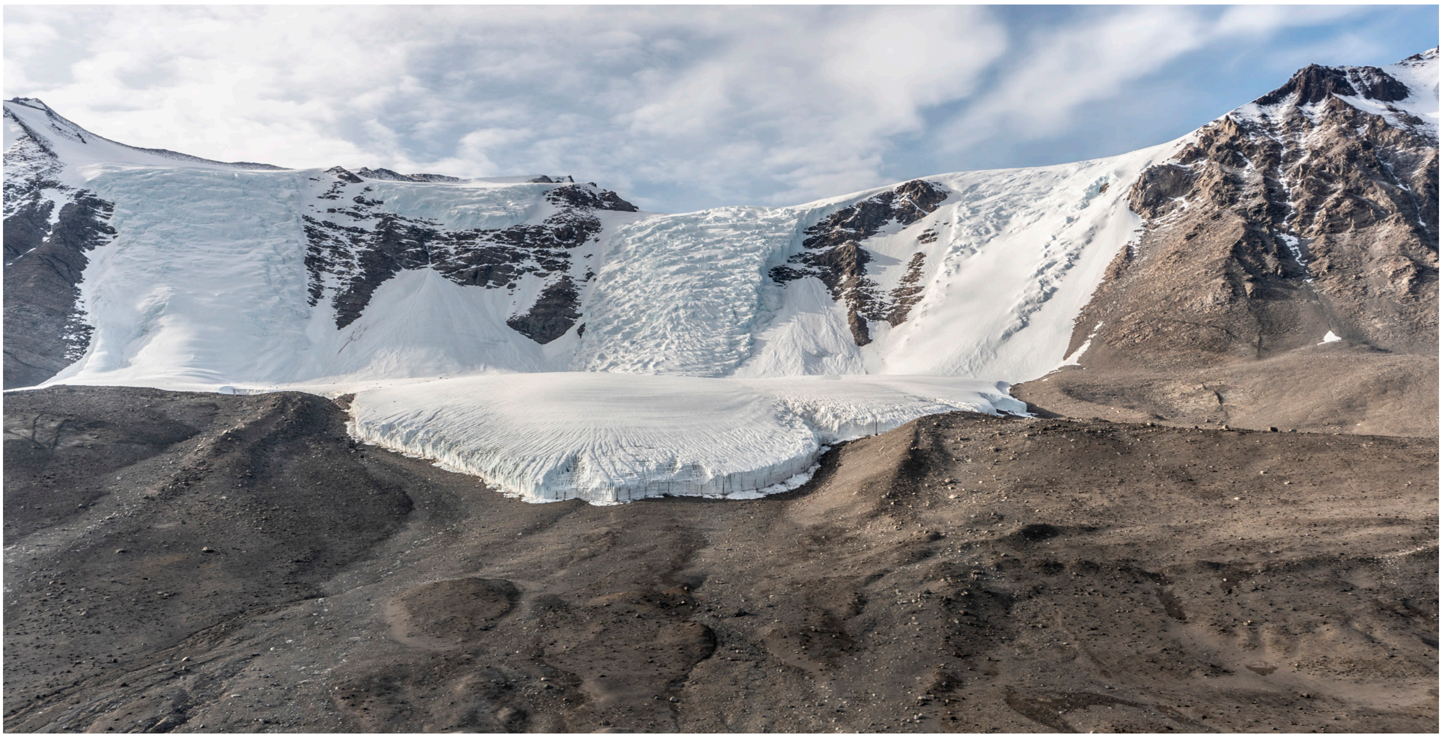
Over the past three decades, research into the Cryosphere – Earth's snow and ice regions, ranging from ice sheets, glaciers and permafrost, to sea ice and the polar oceans – has virtually exploded. Advanced satellites, deeper cores from polar ice and soils, and a better understanding of Earth's past have made these advances possible.

Cryosphere scientists are committed to research in these often barely accessible places – sometimes, at the cost of their lives – because of the rapid changes in these polar and mountain regions, long seen as an early signal of climate change.

What has clearly emerged over the past 20 years is an understanding that:

- **These cryosphere changes, if allowed to continue, will be permanent on all human timescales;**
- **Many, perhaps most of these essentially permanent changes would be triggered already by the 2°C maximum temperature rise in the Paris Agreement, but could be slowed or possibly averted if we remain close to the aspirational 1.5°C target; and**
- **The impacts, including loss and damage in human communities, are global and overwhelming in scale.**

The last point is among the most important: these essentially permanent impacts, ones that will grow with each successive incremental rise in temperature, are no longer just of concern for Arctic and mountain peoples and ecosystems. If caused to occur by continued irresponsible CO_2 emissions, the scale of loss and damage will be felt everywhere on the planet – all because of the irrefutable melting point of the Earth's ice.



Heidi Sevestre

Thinning Glacier in the Dry Valleys of Antarctica, McMurdo Sound

To their increasing alarm, this realization among cryosphere scientists has yet to penetrate the highest levels of government and industry, let alone among the general public. A false sense of complacency – that we can allow temperatures to rise for just a bit longer, prioritizing today's economic concerns over future and more to the point, permanent economic loss and damage – continues to prevail. As CO_2 emissions continue to rise unabated, even through the Covid-19 pandemic, the permanent response from global cryosphere melting grows ever more apparent and unavoidable.

In part, this may be the fault of the scientific community itself. The Intergovernmental Panel on Climate Change (IPCC) focused its "long-term" modeling projections on the year 2100 already in its first Assessment Report (1990). This was largely a matter of convenience: at the time, emission scenarios were difficult to develop even beyond 2030, and with the computers of the day, climate models had serious limitations predicting over multiple decades and centuries.

Those scientists and government representatives never meant for 2100 to be seen as an end point for climate change, however. Climate change will continue just as much in 2101; and, if we allow it, for many centuries beyond.

Nevertheless, that 1990 decision to focus on 2100 has continued to define the "end point" of nearly all policy evaluations of climate change impacts for the past three decades – including those dealing with the cryosphere.

The problem however is that the Earth's cryosphere at first responds incredibly slowly to temperature rise, and this has been difficult to capture, especially in models limited – often by available funding – to 2100. At the same time, there is increasing evidence of how glaciers, ice sheets, sea ice and permafrost have changed in the distant past, at times when CO_2 or temperatures were similar to today.

In 2100, even with high emissions, the cryosphere response to global warming, especially that of Earth's great ice sheets, is really only just getting started. However, once triggered by rising global mean temperatures – or even, in the case of permafrost thaw, by a single summer heat wave – that response soon becomes both inevitable, and essentially permanent on human timescales, as the findings in this Report make clear:

- ***Polar ocean acidification, warming and freshening:*** The Arctic and Southern Oceans, and near-polar waters such as the North Sea absorb more CO_2, more quickly than all other oceans combined. Above 450ppm – which at current emissions, we will reach in about 14 years – current polar marine ecosystems (including valuable fisheries) may largely cease to exist. **Recovery from this is estimated to be 50,000–70,000 years.**

- ***Ice sheets and sea-level rise (SLR):*** Polar ice sheets have thresholds that commit the Earth system to sea-level rise lasting thousands of years. Even today, having already exceeded 1.2°C, the lower boundary of essentially permanent SLR is now 2–3 meters; but this can be slowed to occur over many centuries with a 1.5°C peak and steadily declining temperatures thereafter. However, 2 meters could be reached by 2100 with current emissions, and an ultimate 15–20 meters would occur should temperatures peak between 2–3°C. **Recovery from this would be greater than 10,000 years** and only with temperatures below pre-industrial: ice sheets cannot grow back except in ice age conditions.

- ***Mountain glaciers:*** Steep declines will continue even with low emissions, with no tropical glaciers and few mid-latitude glaciers outside the Himalayas by 2200 should temperatures reach 2°C; and 90% of even Himalayan ice and snow lost at 3°C. **Recovery from that is several hundred to over a thousand years**, with glacier re-growth of only a few percent per decade/century.

- ***Permafrost:*** Thawed permafrost will continue emitting CO_2 and/or methane for over 100 years after initial thaw, even if temperatures stabilize. **Recovery is several thousand years** for carbon drawdown into new permafrost soils.

- ***Arctic sea ice:*** Occasional ice-free Septembers even at 1.5°C, but ice-free summer periods lengthening to several months by 2°C, with massive global feedbacks on weather and drought, Greenland melt and permafrost emissions. **Recovery time would be decades to centuries**, depending on peak temperature and how quickly the ocean can cool.

All of these dynamics except Arctic sea ice require a return to pre-industrial temperatures – or below – to enable at least some level of meaningful recovery.

On the global scale, as temperatures exceed 1.5°C, the levels of essentially permanent coastal flooding and damage; loss of water resources from snowpack and glaciers; weather disturbances related to polar temperature amplification; resulting threats to infrastructure and food security; and many other worldwide impacts from cryosphere loss will preclude any possibility of sustainable economic development.

Cryosphere science increasingly points to ≈1.5°C and ≈450ppm as upper guard rails for peak temperature and CO_2 concentrations to prevent "dangerous anthropogenic interference[1]" in the Earth's cryosphere and therefore, the global climate system; with a need to return to lower temperatures as soon as possible.

This first Report on the State of the Cryosphere summarizes the best scientific understanding of its reviewers – many of them IPCC authors, others leading and cutting-edge researchers in their fields – of what the results will be if we instead choose to exceed 1.5°C or more. Importantly, it does not take as its benchmark the next few years, or 2100, but the ultimate cost of inaction to the planet and human communities.

Today's most optimistic climate pledges will still allow 2.1°C of temperature rise. Actually adopted legislation, regulations and policies – if fully implemented – will result in 2.7–3.1°C[2]. Both of these peak temperatures, even if temporary will cause many (perhaps most) of these cryosphere thresholds to be passed, with essentially permanent global consequences.

Worse yet, if human emissions – which were not meaningfully paused even by the Covid-19 pandemic – continue at today's levels, that will mean temperatures will be around 4–5°C by 2100, and still rising. This is approaching the temperatures when both polar ice sheets were essentially gone, with almost no permanent ice on Earth at all: the "hothouse" planet that last existed over 50 million years ago, with sea levels 70 meters (over 200 feet) higher than today.

Today, 2100 is no longer so far away. Children born in this year of 2021 will be 79 in 2100. Their children – the grandchildren of today's parents – will only be in their 40's and 50's. It is time the world face reality, and cease ignoring scientific evidence that the time to put other considerations before preventing dangerous climate change is well past, because we cannot delay or negotiate with the melting point of ice.

The Intergovernmental Panel on Climate Change has set 2030 as a benchmark year for emissions to reach around 50% reductions globally to allow any chance of remaining close to 1.5°C, with only a slight and temporary overshoot.

The IPCC has not only stated however that a 1.5°C 'guardrail' will avert a great deal of loss and damage. It has shown how this can be done.[3] Contrary to many pushing questionable and environmentally damaging "alternative" geo-engineering solutions, the IPCC has also stated that this goal remains physically, technologically, economically and environmentally

1 UN Framework Convention on Climate Change

2 Climate Action Tracker May 2021 Update, https://climateactiontracker.org/global/temperatures/

3 Special Report on Global Warming of 1.5°C (2019)

feasible today. The only thing missing is societal support and political will. Translated, that means all levels of human society from government and industry, to the individual voter and consumer.

This report will come out annually every year until 2030, summarizing our rapidly-evolving cryosphere science and outlining what the Earth gains if we meet the 1.5°C challenge; or, what we will lose should we continue with actions – in particular, use of fossil fuels – that cause temperatures to rise well above that.

If the world community – from governments, to individuals – refuses to act in accordance with the science of cryosphere, at least we cannot say that we didn't know the disastrous consequences of our inaction.

Yet again: we cannot negotiate with the melting point of ice.

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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 and declining)

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 stabilizes by 2040–2080, with slow continued emissions from permafrost for one-two centuries and some loss of ice sheets for several hundred, to thousands of years, but likely not exceeding 3 meters of global sea-level rise.

Fulfillment of "Optimistic" NDCs[1] (2.1°C in 2100 and rising)

Countries meet all current pledges or Nationally Determined Contribution (NDCs), including 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 are 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.

Currently Implemented NDCs and Policies[1] (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 Emissions Growth (2–3ppm per year, 2100 temperature 4°–5°C 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.

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.

1 Based on Climate Action Tracker May 2021 Update, https://climateactiontracker.org/global/temperatures/

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+

The two lowest emissions pathways are the only ones with any possibility of preventing the essentially permanent impacts outlined in this report. A decision to exceed these limits is a de facto decision to cause these changes to occur.

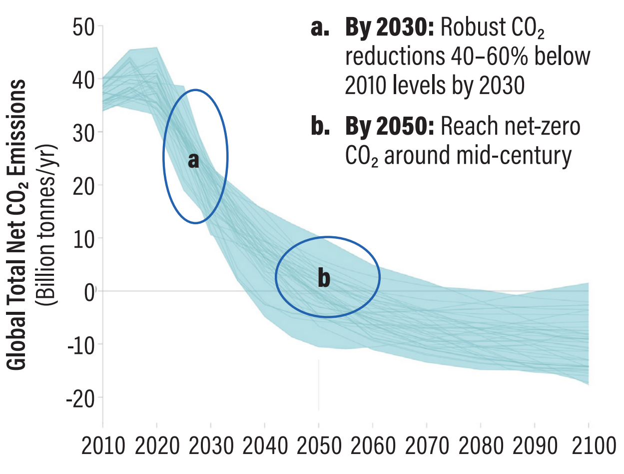
Paleo-climatologists, who study the behavior of Earth's climate, can trace this interaction between temperature, CO_2 concentration and the history of sea-level rise and (sometimes) glaciers going back many millions of years through studying the geologic recorded in rocks and ancient shorelines. Temperature, and concentrations of CO_2 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 15,000 years or so was a fairly consistent ≈180 ppm (Ice Age) and ≈280 ppm (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 300 ppm around 1910, 320 ppm in the 1960's and then accelerated to 400 ppm around 2015. It exceeded a 420ppm daily average twice in 2021, and continues to grow by 2–3ppm each year, despite existing climate pledges that in accordance with the 2015 Paris Agreement, were to result 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 Islands to the Netherlands, depends entirely on how high humanity decides is acceptable for temperatures and CO_2 concentrations to rise.

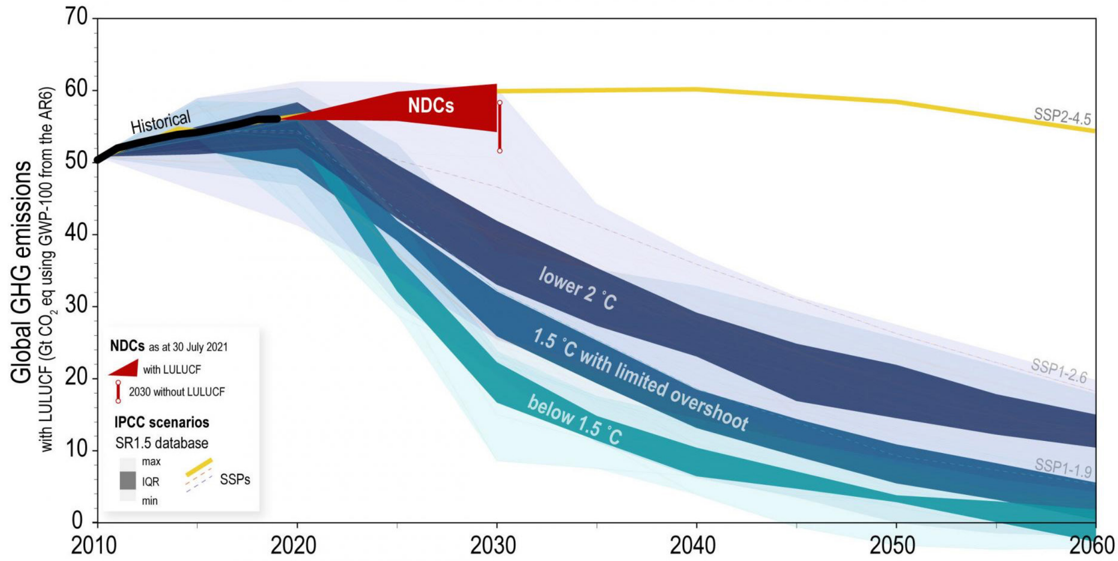
This is not however a pre-determined outcome. In its Special Report on 1.5°C of Warming (SR1.5) from 2018, as well as its Sixth Assessment (AR6, currently underway), the IPCC outlined the range of choices facing governments, industry and other stakeholders. The table below lists the range of possible carbon emission pathways as outlined in the latest IPCC report, the Working Group 1 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.

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



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

FIGURE 1-2. **September 2021 UNFCCC Synthesis Report**



SOURCE: UNFCCC NDC SYNTHESIS REPORT, SEPTEMBER 2021

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 10-30 ppm, 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.

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 nine 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, at least along the lines of the response to the Covid-19 pandemic, and 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 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?

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

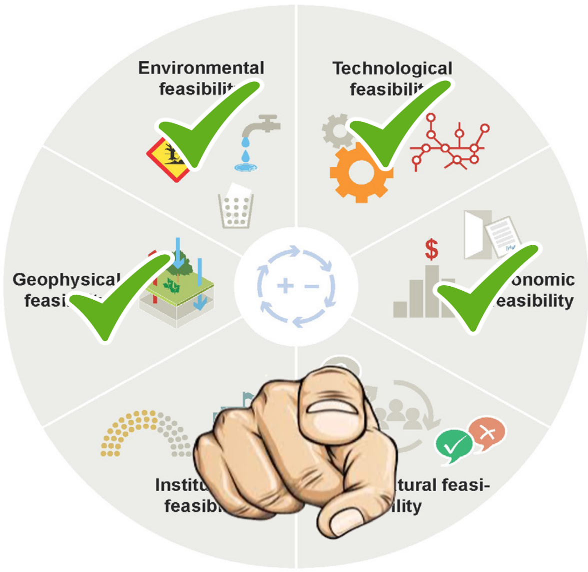
Country commitments, or "Nationally Determined Contributions" (NDCs) were first made in connection with the Paris Agreement in 2015, and scheduled to be updated by February 2020 or at the latest, COP-26 in November 2020. Due to the Covid-19 pandemic, as well as the delay of COP-26 to November 2021, many countries have not yet updated their NDCs; but the UNFCCC issued a report on pledges to-date in September 2021. Some of these NDCs consist of concrete measures backed up by regulation or legislation; others are merely goals, such as "carbon neutrality by 2050," without any specifics as to how the respective governments plan to achieve this goal.

This Report uses the calculations of the Climate Action Tracker (CAT), produced by a consortium of European research institutions[2] 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" NDCs (backed up by actual policies, such as legislation or other measures) and "optimistic" NDCs, including stated goals not yet reported under the Paris Agreement. These will result in approximately 2.1°C, and 2.7–3.1°C by 2100, respectively.

In its September 2021 Synthesis Report on submitted NDCs, the UNFCCC found a resulting temperature of 2.7°C (above). It is important to note however that both that finding, and those of the CAT rely on full implementation of the noted NDCs or concrete policies. Several countries with the greatest current legislated ambition, such as Sweden, Germany, Denmark and the UK have formal climate councils tasked with evaluating compliance. Nearly all of these have determined that even these legislated goals are not being met, which would push temperatures higher.

More alarming however is the reality that in 2021, emissions are not changing sufficiently 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 ends up above 4°C in 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 2021, no clear decline in human emissions can be seen.

FIGURE 1-3. **The 1.5° Target: Feasibility?**



Feasibility depends on societal acceptance and political will.

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

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 420 pmm. 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, the window of prevention is closing.

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, the window of prevention is closing.

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CHAPTER 2

Ice Sheets and Sea-level Rise

Loss of Many Coastal Communities Now Inevitable, But Can Be Slowed – and Many Still Saved

Very Low and Low Emissions (Peak 1.6°–1.8°C and declining)
Global sea levels will continue to rise for centuries, but very slowly, reaching around 2–3 meters above today in the next 2000 years, with about half a meter occurring early in the next century. This assumes ice sheets respond to warming in a steady manner, adding to sea-level rise from land glacier loss and ocean thermal expansion.

Fulfillment of "Optimistic" NDCs (2.1°C in 2100 and rising)
Primarily because of a relatively slow collapse of portions of the West Antarctic Ice Sheet (WAIS), as well as accelerated Greenland ice loss and the rapid decline and loss of nearly all land glaciers, global sea levels eventually will reach 3–6 meters above today. Even higher levels cannot be ruled out; the last time temperatures exceeded the 2°C threshold, sea-level rise likely was well above 6 meters. Sea levels would reach around 0.75 meters above today early in the next century. At this higher temperature however, a steady predictable rate of sea-level rise from ice sheets is less certain, and the rate and amount could be greater already by 2100.

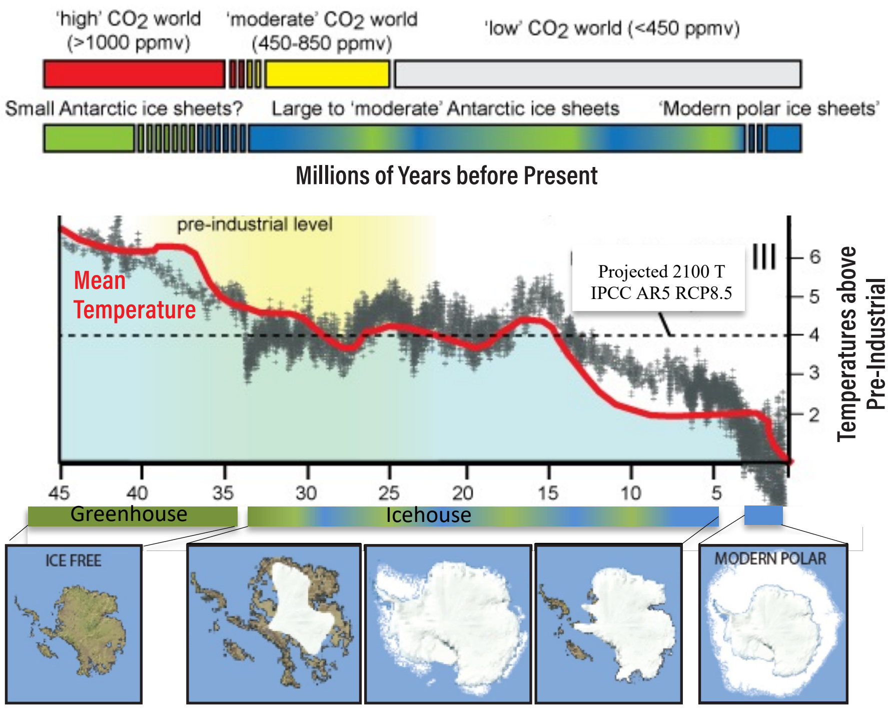
Currently Implemented NDCs and Policies (2.7–3.1°C in 2100 and rising)
This scenario would push ice sheets in ways not seen since the end of the last Ice Age. West Antarctic Ice Sheet collapse is likely to be rapid once temperatures exceed 3°C, with some involvement of portions of East Antarctica and greater loss from Greenland. WAIS collapse would be well along by 2300, with almost no glaciers remaining anywhere on the globe. Sea-level rise will continue at a relatively rapid pace for many centuries and be essentially permanent on human timescales, ending at 15–20 meters or more above today. Sea-level rise of more than 1 meter already by 2100 is possible. This rate of temperature rise will push ice sheets in ways not seen in the Earth system since large deglaciation events 125,000 years ago.

Current Emissions Growth (2–3ppm per year, 2100 temperature 4°–5°C and rising)
Loss of large portions of both polar ice sheets and all land glaciers will occur. West Antarctic Ice Sheet collapse will 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 complete loss of the Greenland ice sheet. Such a rapid rise in CO_2 concentrations and temperature has no counterpart in Earth's geologic record, but Antarctica has ice-free conditions at 6°C. Restoration of the polar ice sheets can only begin with temperatures well below pre-industrial (induction of a new Ice Age).

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 and likely parts of East Antarctica. While some of these changes occurred very slowly in the past, over thousands of years, there have

FIGURE 2-1. **Antarctica with Past CO_2 Concentrations and Temperature**



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also been periods where extremely rapid sea level rises (around 4 meters per century) have 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 15–18 meters in just 350 years.

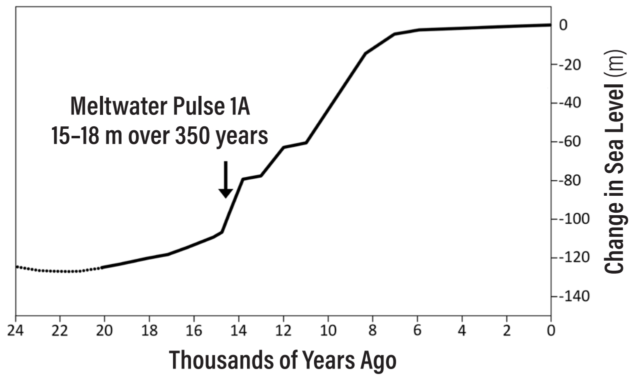
The observed human-induced global temperature rise over the past decades is much faster than anything documented in Earth's past. CO_2 increases in the last 50 years are 200 times greater than during the end of the last Ice Age, which means that future rates of ice sheet loss and sea-level rise (SLR) could increase even further over the acceleration that has been observed over the past few decades, and potentially be more rapid than at any other time in the past 130,000 years. Better understanding of ice sheet behavior, especially interactions between the ice and surrounding, warming oceans informs us that ice sheet collapse, and potentially rapid sea-level rise cannot be ruled out, especially should warming ever exceed 3°C. This is especially the case for the West Antarctic Ice Sheet (WAIS), for which some studies show the threshold for collapse may already have passed at around 0.8°C global warming, although the WAIS may hold stable for many more centuries unless greater 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.

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 rises. 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 balance mass gain via snowfall. Observations now confirm that this equilibrium has been lost on Greenland, the West Antarctic Ice Sheet (WAIS) and 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 sea level. During ice age periods, when the ice sheets expanded significantly, sea level was more than 120 meters lower than today. During periods of warming, when the ice sheets lost mass, sea level rose accordingly. This is what occurred rapidly during the meltwater pulse noted above, when warming as the last Ice Age ended caused sea levels to rise between 15–18 meters in 350 years, probably as part of the Laurentide Ice Sheet over Canada collapsed.

Greenland and parts of the Antarctic ice sheet have certain thresholds where irreversible melt becomes

FIGURE 2-2. **Rapid Sea-level Rise in the Past**



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

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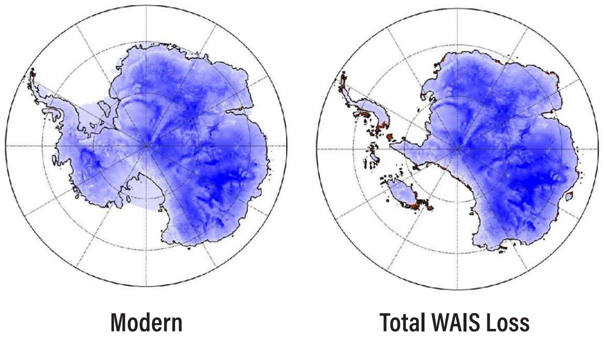
FIGURE 2-3. **West Antarctic Ice Sheet Collapse**



inevitable, and (in the case of the WAIS) potentially relatively rapid. In Earth's past, several of these thresholds (paced by slow Earth's orbital changes, but driven by related slow rises in atmospheric greenhouse gases) have occurred somewhere between 1 and 2 degrees of warming: about 1° for the WAIS and Antarctic Peninsula (containing 5 meters SLR); and between 1.5°C and 2°C for Greenland (7 meters SLR). 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. This combination likely explains why, in the Earth's past, sea levels peaked at around 12-20 meters higher than today during sustained periods when temperatures reached 2°C. During the height of the Pliocene 3 million years ago, when CO_2 levels were comparable to today and temperatures stabilized at 2°–3° higher than pre-industrial, sea levels may have peaked at around 20 meters above today.

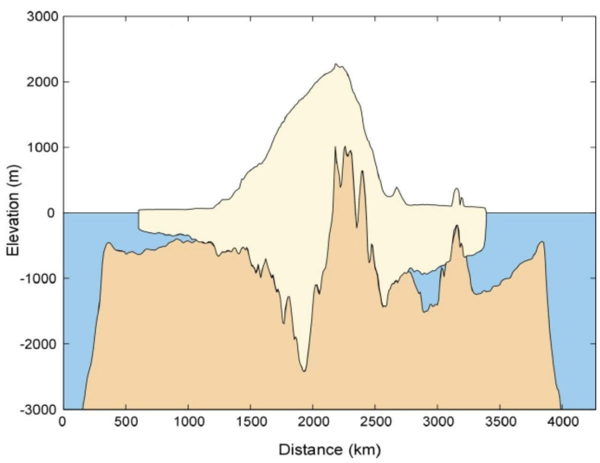
Greenland responds more predictably to warming atmospheric temperatures, but also reaches a significant tipping point once melting lowers its altitude. The Greenland ice sheet is over 3000 m thick and above 3000 m altitude in the interior. If the height of this ice sheet is lowered through surface melting 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. The first recorded rain at the highest point of Greenland occurred in August 2021, during several days with temperatures often above freezing.

The WAIS is a very different story: much of it does not really sit over land, but a vast archipelago of islands separated by extremely deep ocean basins. Much of its ice rests on bedrock that is up to 2.5 km below sea level, sloping downwards toward its center (Figure 2-4).

As warm water melts the edges of the ice sheet, it 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 to occur over a few centuries or less. 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 learned.

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 can transfer heat around the planet. Changes in the height and extent of Earth's ice sheets, together with incursion of new cold and fresh water into ocean currents from ice sheet

FIGURE 2-4. **Cross-section of 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

melt, cause changes not only in weather patterns near the poles, but also at lower latitudes; as well as large changes in nutrient supplies in marine ecosystems globally.

The main question for scientists and policy makers is the rate of change, and at what point 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 – as fast as 5 cm a year from Antarctica by 2150,

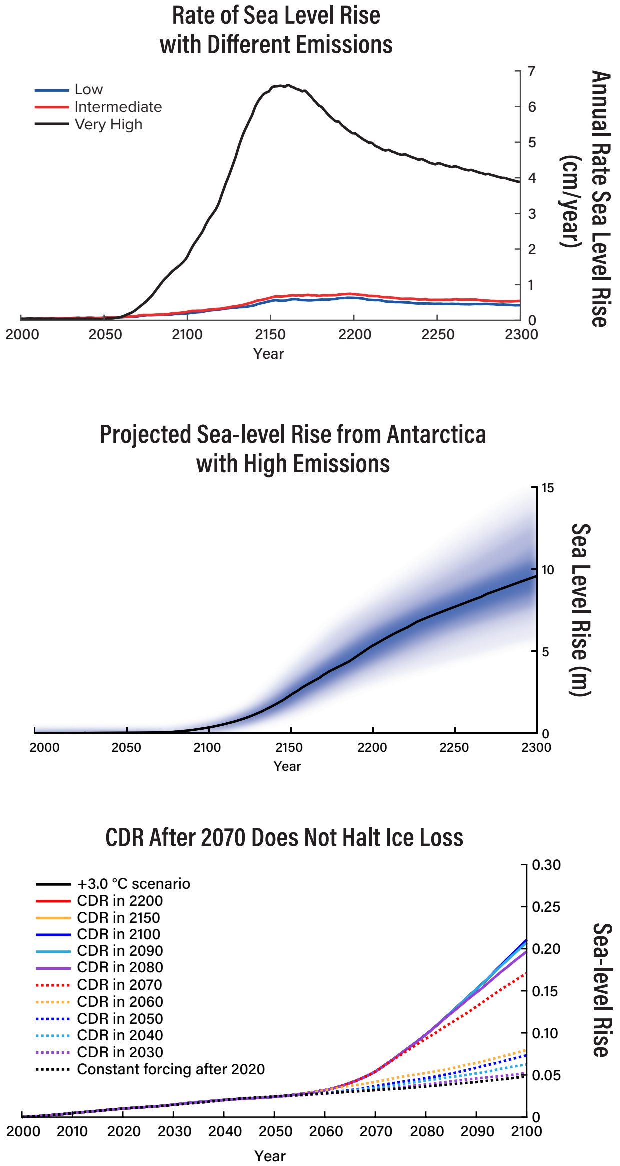
As ice sheet melt processes accelerate at higher temperatures, they cannot be stopped or reversed for many thousands of years, even once temperatures decrease.

should today's emissions continue and cause temperature rise to exceed 4° by 2100.

A key message for policy makers and coastal communities is that as ice sheet melt processes accelerate at higher temperatures, they cannot be stopped or reversed for many thousands of years, even once temperatures decrease. The geologic sea level record clearly shows 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. For a growing number of ice sheet experts therefore, the true "guardrail" to prevent dangerous levels and rates of sea-level rise is not 2° or even 1.5°, but 1° above pre-industrial.

FIGURE 2-5. **Potential Sea-level Rise from Antarctica**



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.

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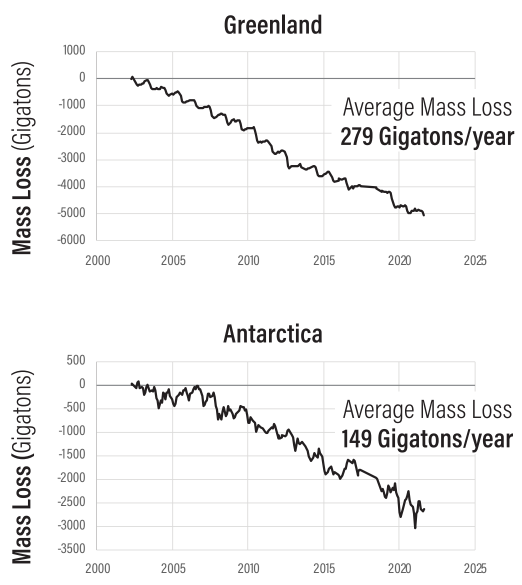
FIGURE 2-6. **Ice Mass Changes**

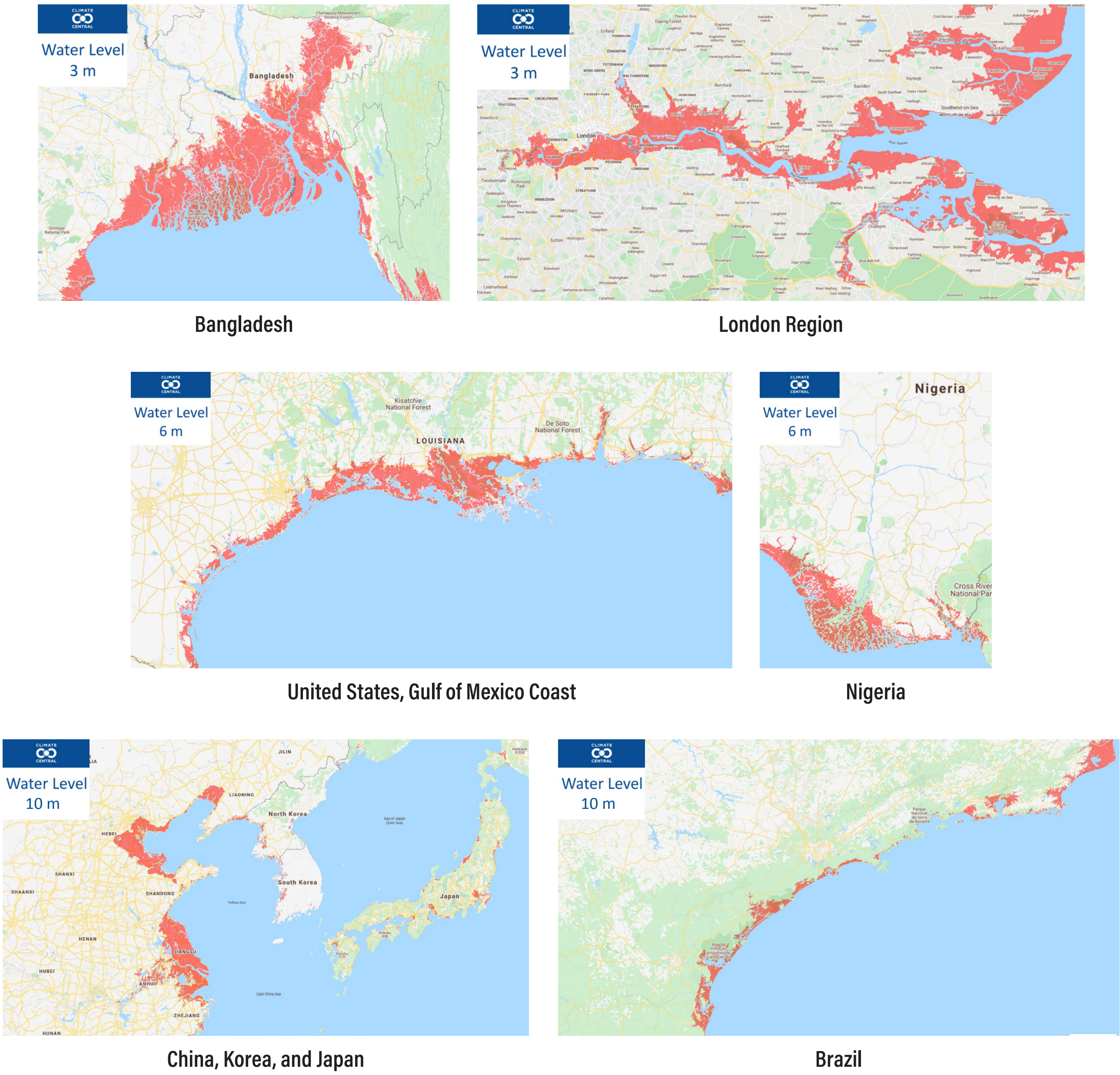


DATA FROM NASA; GRAPHIC: TYLER KEMP-BENEDICT

For these scientists, a key argument in favor of very low emissions, staying close to the 1.5° limit is that it will allow us to return more quickly to the 1° level, drastically slowing global impacts from land ice loss, and WAIS collapse especially. 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°, CO_2 emissions must be halved by 2030. 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.

FIGURE 2-7. **Sea-level Rise with Ice Sheet Loss**



Sea-level rise at 3 meters in Bangladesh and around London; 6 meters along the Texas-Louisiana coast, and coastal Nigeria; and at 10 meters in coastal Brazil, China, Korea and Japan.

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CHAPTER 3

Mountain Glaciers and Snow

Current Loss and Damage Can Be Slowed and Reversed Only with Very Low Future Emissions

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

Glaciers and snowpack have been declining extremely rapidly for the past several decades. That rapid decline will continue, especially outside polar regions, but with very low emissions losses 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 of the Andes, East Africa and Indonesia by 2100 is now difficult to avoid. They may not recover until temperatures fall below re-industrial, or the next Ice Age.

Fulfillment of "Optimistic" NDCs (2.1°C in 2100 and rising)

Once two degrees is passed, by 2300 the only 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 one-half or one-third of their current size. Snowfall also will become more rare outside these regions, falling instead as rain that may at times be extreme in this warmer climate, leading to increased erosion, flooding and landslides. In the Himalayas, this loss of glaciers and snowpack will radically affect seasonal water supplies in some river systems, for example the Tarim in northwestern China.

Currently Implemented NDCs and Policies (2.7–3.1°C in 2100 and rising)

Virtually no glaciers will remain anywhere on the globe outside the Arctic, Patagonia and Himalayas, where only 20–35% of ice will remain. Snowfall will become more rare outside the polar regions and high altitudes. With such very high ice and glacier loss exposing bare ground, glacier re-growth (even with temperatures returning to those of today) will likely take thousands of years, though snowpack would return as soon as temperatures decline.

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

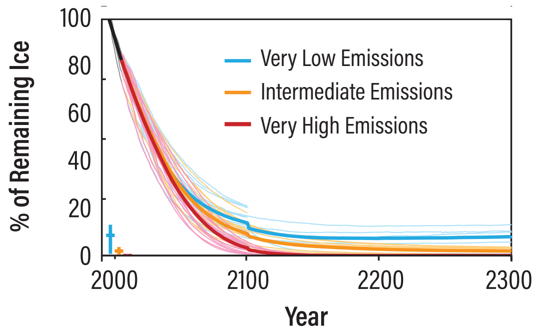
Virtually no glaciers will remain anywhere on the globe by 2200, with mid-latitude glaciers 90% gone by 2100. Snowfall by 2100 will be extremely limited outside polar regions and high altitudes.

Background

Most 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. 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.

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 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

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)

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 remnants remaining. Some projections even show slow re-growth beginning between 2100 and 2300, but only with very low emissions entailing 50% reductions by 2030, and essentially zero emission by 2050.

Any emissions higher than this will eventually result in essentially complete loss of all land glaciers on Earth outside High Mountain Asia and high latitude polar regions, which include Alaska, northern Canada and Patagonia. With high emissions, and global mean temperature rise exceeding 4°C by 2100, any substantial seasonal snowpack will become a rarity outside the polar regions and very highest mountain ecosystems.

In those "high altitude and high latitude" regions, around 30-50% of glacier volume will remain by the end of this century under high emissions scenarios. If we have followed 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 temperatures above 2°C, losses will continue; and with very high emissions similar to our growth rate today, this loss would be quite rapid.

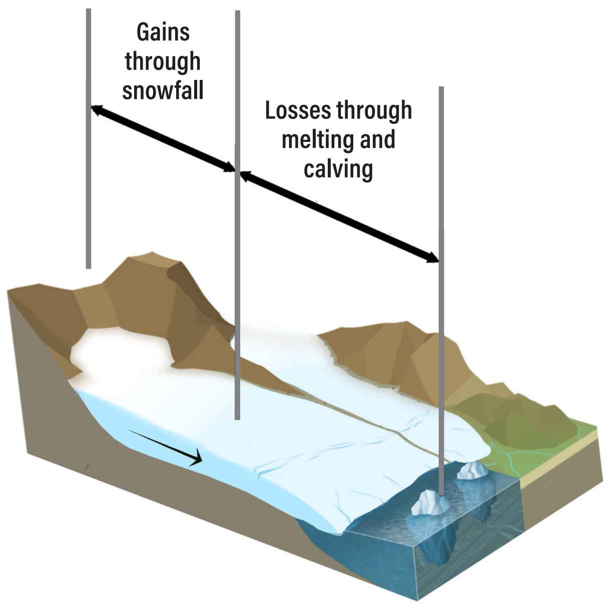
Glaciers are showing that they can melt, and even disappear completely over the space of just decades or a century. When Glacier National Park in the U.S. was created in 1910, it had around 150 glaciers; today, less than 30 remain, and those have shrunk by about two-thirds. From 1901 to 2018, glaciers outside Antarctica contributed nearly 7 cm to global sea-level rise; most of this over the past 4 decades. While such melt has been demonstrably rapid, large glaciers grow back only slowly, especially at temperatures above pre-industrial. "Restoration" will be a matter of many centuries or even millennia: on human timescales therefore, an essentially permanent change to the mountain landscape. Very low emissions are key to ensuring as little ice as possible is lost during this current period of rapid decline, preserving the ecosystem services glaciers provide.

In addition to glaciers, mountains actually hold far more seasonal water in the form of snow. Snowfall has however become more unreliable in many mountain watersheds, with extremes of snow drought alternating with high amounts that increase risk of avalanche and flood. In many mountain snow systems, it now appears that snow generally is following the same downward trajectory as the glaciers: smaller amounts, with more snow today instead falling as rain. This carries economic harm for farming and tourism; as well as sufficient water supplies for large urban populations, such as in the southwestern United States where rising temperatures have paired with snowpack loss, leading to ever more severe drought conditions.

Glaciers "work" by gaining snow at higher altitude, and losing it as meltwater at lower altitude. Global warming means that a given glacier will experience a net loss of ice every year at higher and higher elevations, so that the

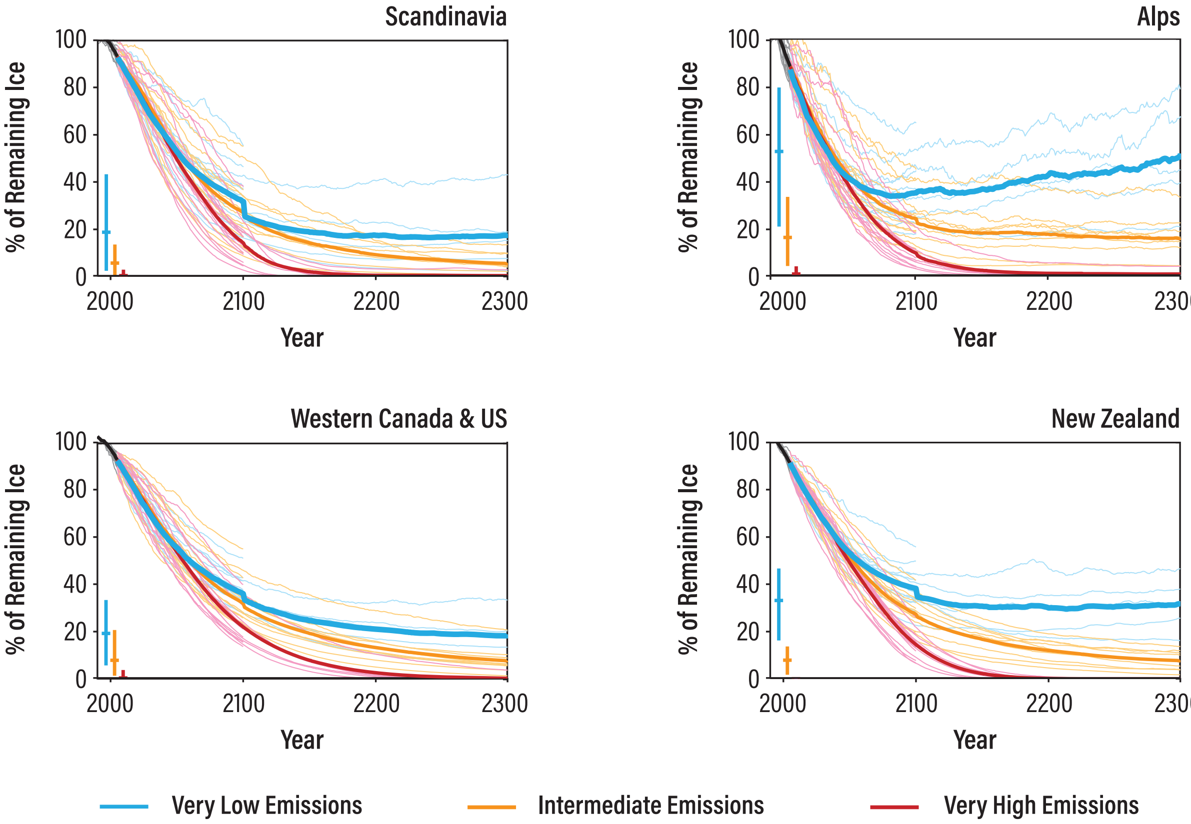
"Restoration" will be a matter of many centuries or even millennia: on human timescales therefore, an essentially permanent change to the mountain landscape.

FIGURE 3-2. **How Glaciers Work**



GRAPHIC: HEIDI SEVESTRE

FIGURE 3-3. **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)

annual gain by snowfall turning to ice decreases, and the gain is outpaced by an increasing loss from melting 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.

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. Glaciers in some regions, such as the Andes or the Indus and Tarim basins in the Greater Himalaya region, contribute an unusually high amount of water to human 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 continued shrinking, may make certain economic activities – and even continued human habitation – impossible. Indeed, most glacier regions outside high latitude polar regions and the Himalayas have already passed this period of “peak water,” or peak melting. 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.

Snowpack, an even greater source of seasonal water supplies than glaciers, appears to be following a similar

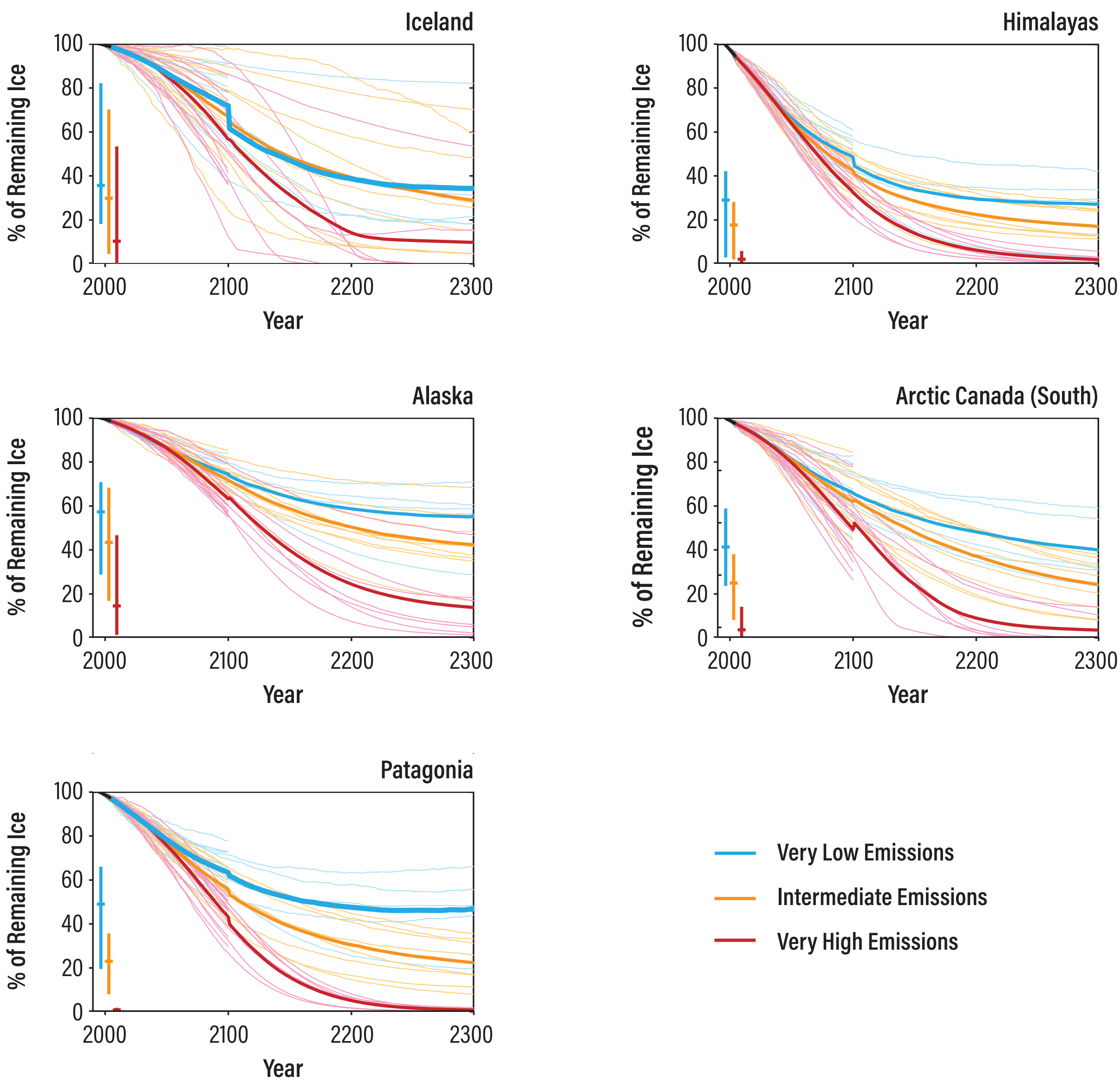
ZUMA Press, Inc. / Alamy Stock Photo

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

path of loss as mountain glaciers: with more swings and extremes of high snowfall and snow drought, but overall loss as temperatures rise above freezing at higher and higher altitudes. This means that precipitation that would have fallen as snow in past decades, increasingly comes down as rain. At lower elevations and latitudes, snow will fall less often or not at all. Seasonal snowpack will not form, resulting in loss of stored water in the snow itself and in underground aquifers.

Mountain snow sustains water supplies for people far beyond mountain regions, travelling great distances across grasslands and deserts to densely populated coastal regions. People in cities such as Los Angeles, Marrakech and in the Ebro-Duero basin of northern Spain and Portugal are especially dependent on the water from snow. In both the Arctic and mountain regions, the well-being of people and many species depends on seasonal snow cover. For reindeer-based Arctic indigenous cultures, increasing numbers of animals are lost to starvation when rain falls on snow, forming a layer of ice that makes it impossible for the reindeer to scrape snowpack away to graze. In addition to threatening water supplies, decreases in snow cover

FIGURE 3-4. **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)

mark ferguson / Alamy Stock Photo

Aviemore ski resort, Scotland, Winter 2014

negatively impact snow tourism, especially in the U.S. West, New England and central Europe. 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.

A sharp strengthening of climate pledges in 2021 towards 1.5°C, including preferably stronger commitments in the near-term 2030–2040 time frame, could make the difference between rapid and disruptive loss of regionally-important snow and glacier systems, and significant slowing of glacier loss that allows local communities time to adapt, even in those equatorial regions where glaciers are doomed to disappear completely at 1.5°C. This will have greatest benefit for communities in the Andes and Central Asia that are most dependent on glaciers as a seasonal source of water for drinking and irrigation; and on economies dependent on glaciers and associated snowpack for power generation, agriculture and revenue from snow tourism, such as the Alps and North American West.

A sharp strengthening of climate pledges in 2021 towards 1.5°C could make the difference between rapid and disruptive loss of snow and glacier systems, and significant slowing of glacier loss that allows local communities time to adapt.

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Permafrost

Higher Human Emissions Mean Higher Permafrost Emissions for Centuries after Peak Temperature

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

Permafrost thaw will add carbon dioxide and methane emissions to those of humans of about the size of Canada today, totaling around 150–200 Gt CO_2* by 2100. Once permafrost experiences its first thaw, emissions can continue for centuries; so these permafrost emissions will continue after peak temperature is reached 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.

Fulfillment of "Optimistic" NDCs (2.1°C in 2100 and rising)

Permafrost thaw will add carbon dioxide and methane emissions to those of humans of about the size of the European Union today, totaling around 220–300 Gt CO_2 by 2100. These emissions will continue for one-two 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 emissions until they cease, simply to hold temperatures steady. Permafrost soils will disappear in extensive regions above the Arctic Circle, as well as below, and nearly all existing infrastructure built on vulnerable permafrost soils will require replacement.

Currently Implemented NDCs and Policies (2.7–3.1°C in 2100 and rising)

Permafrost thaw will add carbon dioxide and methane emissions to those of humans of about the size of the U.S. today, totaling around 350–400 Gt CO_2 by 2100. These emissions will continue for one-two centuries after peak temperature is reached between 2150–2170. 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 have disappeared by the time of this peak. Extensive erosion, due to permafrost thaw, sea ice-free conditions and more violent storms will require extensive replacement of coastal and riverside Arctic infrastructure, especially in Russia and Canada.

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

Permafrost thaw will add carbon dioxide and methane emissions to those of humans of about the size of China today, totaling around 400–500 Gt CO_2 by 2100. These emissions will continue for one-two 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 soils will largely disappear globally with massive impacts on infrastructure and population in the permafrost region.

* Actually CO_2 equivalents (CO_2-e) – this means carbon emissions coming from permafrost as both CO_2 and methane, with their climate "forcing" or impact converted to the same impacts that would come from these emissions as CO_2 alone. In this chapter, we simply use "CO_2" to express overall carbon emissions, but it's important to recall that some of these emissions come from permafrost as methane.

Background

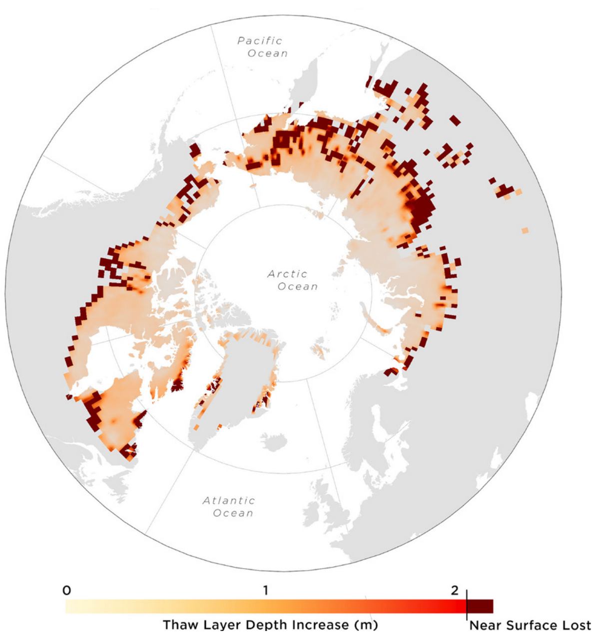
Permafrost is ground that remains frozen through the year. The permafrost region It covers 22% of the Northern Hemisphere land area, and holds vast amounts of ancient organic carbon. Observations confirm that it is rapidly warming, and releasing part of that thawed carbon into the atmosphere as both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

Permafrost stretches across vast regions of Arctic and tundra and taiga forest, especially in Siberia, and also occurs in high mountain regions globally. Of greatest concern is surface permafrost (what scientists refer to as "near-surface permafrost," eg the first few meters below the surface). However, permafrost sometimes extends to depths of over a thousand meters. It is actually a frozen mixture of soil, rocks, ice and organic material, holding about twice as much carbon as currently exists in the Earth's atmosphere. Cold temperatures have protected this organic matter from thawing, decomposing and releasing its stored carbon for many thousands of years.

Permafrost also occurs in shallow seabeds that were inundated at the end of the last Ice Age, especially off Eastern Siberia. This subsea permafrost is rapidly thawing, as it has been "prewarmed" by overlying seawater throughout the past 10–20,000 years, with elevated methane concentrations measured in these shallow coastal waters.

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. Today, at about 1.2°C, we are already committed to losing about 25% of surface permafrost. Scientists anticipate that 40% of permafrost area will be lost by 2100, even if we hold temperatures close to 1.5°C globally. Over 70% of the pre-industrial surface permafrost will thaw by 2100 should temperatures exceed 4°C.

FIGURE 4-1. **Loss of Permafrost Since Pre-industrial**

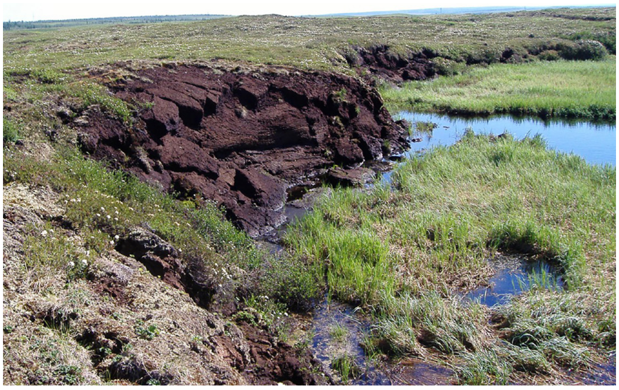


PERMAFROST THAW DATA (FIGURE) FROM CLM5 COUPLED CLIMATE MODEL SIMULATIONS AS PROVIDED FOR THE 6TH COUPLED MODEL INTERCOMPARISON PROJECT (EYRING, V., BONY, S., MEEHL, G. A., SENIOR, C. A., STEVENS, B., STOUFFER, R. J., AND TAYLOR, K. E.: OVERVIEW OF THE COUPLED MODEL INTERCOMPARISON PROJECT PHASE 6 (CMIP6) EXPERIMENTAL DESIGN AND ORGANIZATION, GEOSCI. MODEL DEV., 9, 1937–1958, DOI:10.5194/GMD-9-1937-2016, 2016). ANALYSIS BY SARAH CHADBURN AND ELEANOR BURKE. GRAPHIC DESIGN BY GREG FISKE.

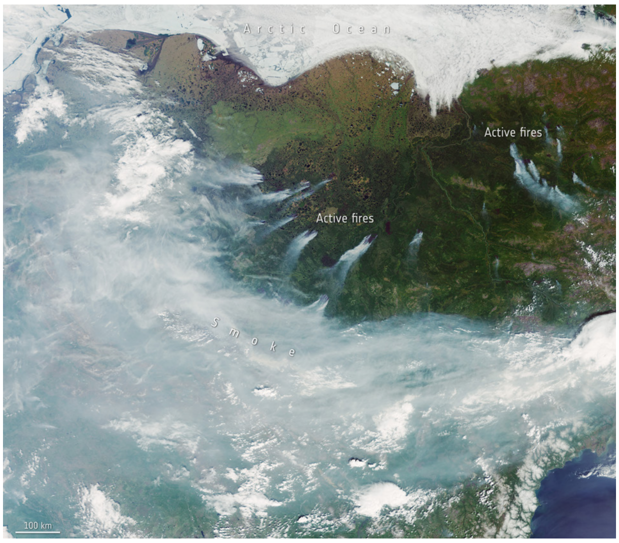
As temperatures have risen, permafrost has not only declined in area, but thawed to greater depth and volume; beginning to release its stored carbon. Most of this released carbon comes as CO_2. However, if permafrost thaws under wet conditions, such as under wetlands or lakes, some of that carbon enters 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,

Credit: Gustaf Hugelius

Cliff collapse



Thermokarst lake



Source: ESA

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

and nearly 100 times more over 20 years, leading to faster and more intense warming globally.

Permafrost thaw occurs gradually over its entire region, but is also vulnerable to abrupt thaw events that can result in land erosion (called "thermokarst" processes). This causes collapse along hillsides and cliffs, often with rapid formation of new lakes or wetlands. As permafrost on coastlines thaws, increased erosion also threatens thousands of kilometers along the coasts of Alaska, Canada and Russia. Current global estimates of permafrost emissions have not included such abrupt thaw processes, which expose deeper frozen carbon previously considered immune from thawing for many more centuries. The collapsed ground rapidly exposes ever-deeper carbon pools, and further accelerates thaw rates.

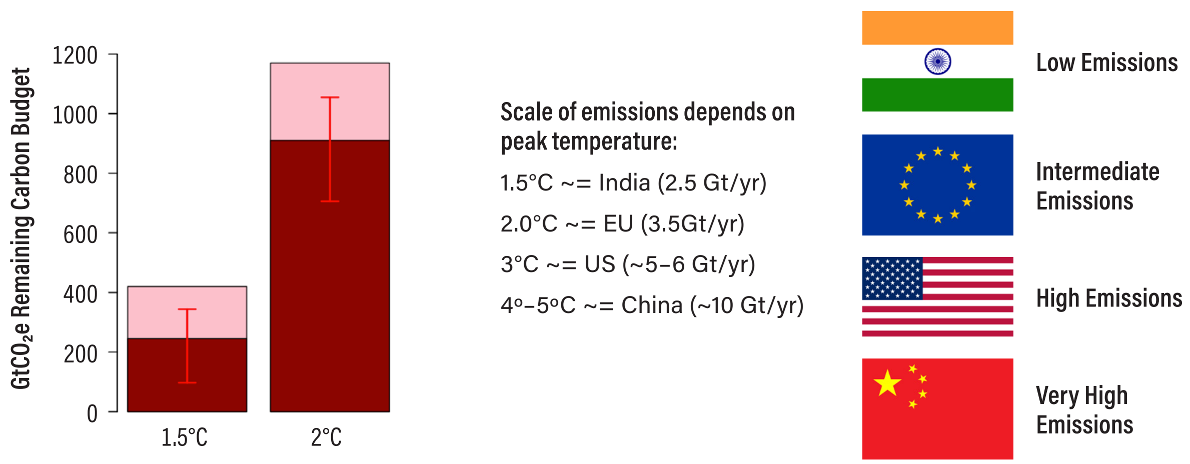
The number of these rapid thaw events has increased as the Arctic warms, and might increase permafrost carbon emissions by as much as 40% as the planet warms to 1.5°C or more. Increasing wildfires in the Arctic due to warmer and drier conditions also cause deeper and more rapid thawing post-fire. Like emissions from other abrupt thaw events, these fire-related emissions have not necessarily been included in past global models.

Once triggered, emissions from permafrost thaw processes are most often permanent on human timescales, because the long-term drawdown of carbon to re-build new permafrost soils with a colder climate takes centuries to thousands of years. While new vegetation growing on thawed former 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 the Arctic greening stimulated by 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. Its current and future contribution to carbon emissions

Emissions from permafrost are permanent on human timescales, because the long-term drawdown of carbon to re-build new permafrost soils takes centuries to thousands of years.

FIGURE 4-2. **Permafrost Emissions**

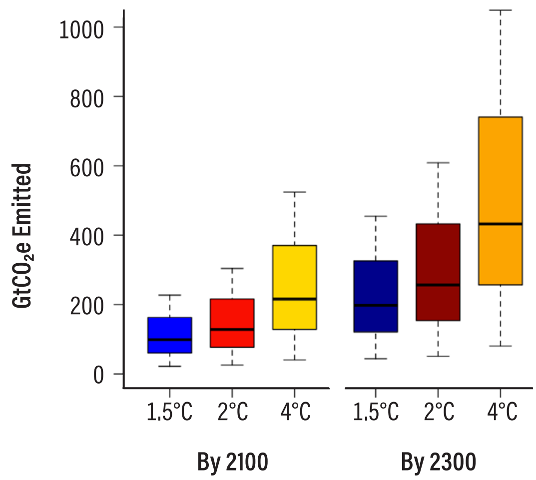


DATA SOURCES: IPCC SR15, GASSER ET AL. (2018), TURETSKY ET AL. (2019)

remains uncertain, but could be significant. Recent estimates range from an additional 150–250 Gt by 2100, especially at higher temperatures with additional Arctic Ocean warming. In addition, methane clathrates (frozen methane, often in very deep seabed or below permafrost on land) represent an additional potential source of methane emissions, with the most vulnerable part at around 300–400 m depth along the upper continental slope off Eastern Siberia. Such clathrates may have contributed to rapid warming events in Earth's deep past, around 85 million years ago or more. The degree to which such deep seabed methane emissions was caused by warming, as opposed to geologic processes such as undersea movement or volcanic activity, remains highly uncertain but cannot be excluded. Some of the extensive methane releases observed both on the East Siberian Shelf Seas, and in sinkholes on the Yamal peninsula are hypothesized to come from collapsing methane hydrates.

Permafrost emissions today and in the future are on the same scale as large industrial countries, 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 (around 150–200 Gt CO_2-eq). Should we instead reach 2°C, permafrost emissions will about equal those of the entire European Union, about 220–300 Gt CO_2-eq by 2100. Even higher temperatures, exceeding 4°C by 2100, will however likely result in up to 400–500 Gt CO_2-eq additional carbon release, adding the

FIGURE 4-3. **Multi-generational Permafrost Emissions**



ADAPATED FROM GASSER, ET AL. (2018)

Permafrost emissions today and in the future are on the same scale as large industrial countries, but can be minimized if the planet remains at lower temperatures.

Ashley Cooper / Alamy Stock Photo Adam Jones Traditional Wooden House Leans in Permafrost - Tomsk - Siberia – Russia

House collapsed in Alaska due to thawing permafrost equivalent of another United States or China to the global carbon budget.

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. This is because once thawed, former permafrost may continue to emit carbon for centuries; thereby committing future generations to continually offset permafrost carbon emissions through negative emissions even after temperatures stabilize.

Thawing permafrost also damages infrastructure, like roads, pipelines and houses, as the ground sinks unevenly beneath them. Coastal permafrost erosion has already required some communities in Alaska to relocate their 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 up to $100 billion by 2050 if current warming continues.

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. Warming in the Arctic already is occurring three times faster than the rest of the planet, due in part to the loss of snowpack, glaciers and sea ice. 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 4º–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, which also minimizes negative emissions efforts required by future generations. This will greatly decrease the amount of additional carbon entering the atmosphere from permafrost thaw, and minimize the long-term burden of negative emissions laid on future generations.

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.

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CHAPTER 5

Arctic Sea Ice

Ice-Free Periods Now Inevitable, but Low Emissions Can Make Them Less Frequent and Damaging

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

At least 50% reductions by 2030 will not prevent at least one ice-free summer before 2050; but as temperatures stabilize just above 1.5°C and then decline, Arctic summer sea ice can stabilize just above total loss conditions (defined as less than 1 million km^2). The number of ice-free summers will also decline, helping stabilize global climate and feedbacks such as sea-level rise from Greenland and Arctic glaciers, and permafrost emissions.

Fulfillment of "Optimistic" NDCs (2.1°C in 2100 and rising)

Summer sea ice will disappear nearly every September 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.

Currently Implemented NDCs and Policies (2.7–3.1°C in 2100 and rising)

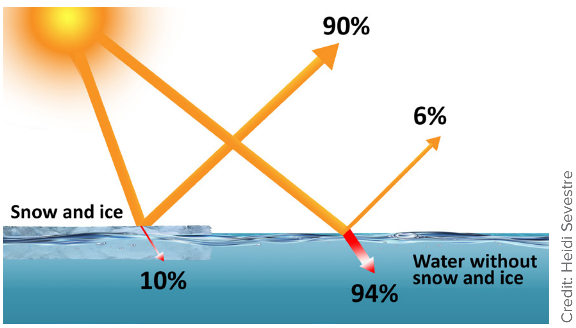
The 1.7°C summer loss threshold will be reached far earlier, by ~2040. Ice-free conditions during much of spring and fall, as well as summer will further accelerate sea-level rise and permafrost emissions further. Ecosystem disruption will extend farther south, reaching also into near-Arctic waters such as the Barents, Bering, and North seas., in concert with Lower salinity due to extensive meltwater and growing ocean acidification 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 Emissions Growth (2–3ppm per year, 2100 temperature 4°–5°C and rising)

The conditions of ecosystem collapse noted above will be apparent by 2030, spreading south along the coastlines of all Arctic nations and beyond. Depending on peak global mean temperatures, recovery of Arctic sea ice to today's conditions would likely take over 1000 years.

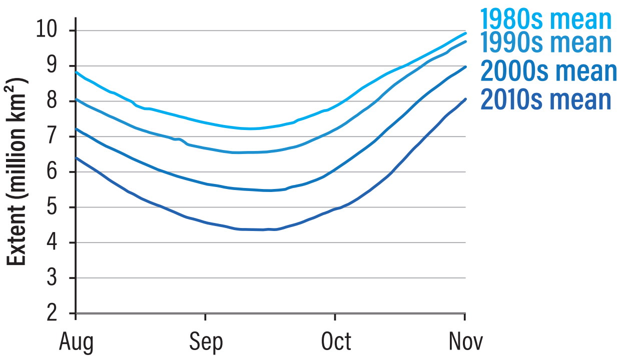
Background

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 over 125,000 years.



Arctic sea ice reflects the sun's rays, cooling the Arctic region, and therefore the entire planet.

FIGURE 5-1. **Arctic Sea Ice Extent**



DATA: JAXA AMSR, 2002–2021 (ARCTIC DATA ARCHIVE SYSTEM, NPR)
SOURCE: HTTPS://ADS.NIPR.AC.JP/VISHOP/#/EXTENT
GRAPHIC: TYLER KEMP-BENEDICT

The extent of Arctic sea ice that survives the entire summer has however declined by at least 40% since 1972, when reliable satellite measurements became available. 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. In contrast, today's sea ice mostly forms each winter and melts in summer, and is thinner than 2 meters. The total volume of Arctic sea ice since the 1970's has therefore declined by nearly two-thirds: a much faster and greater decline than its area.

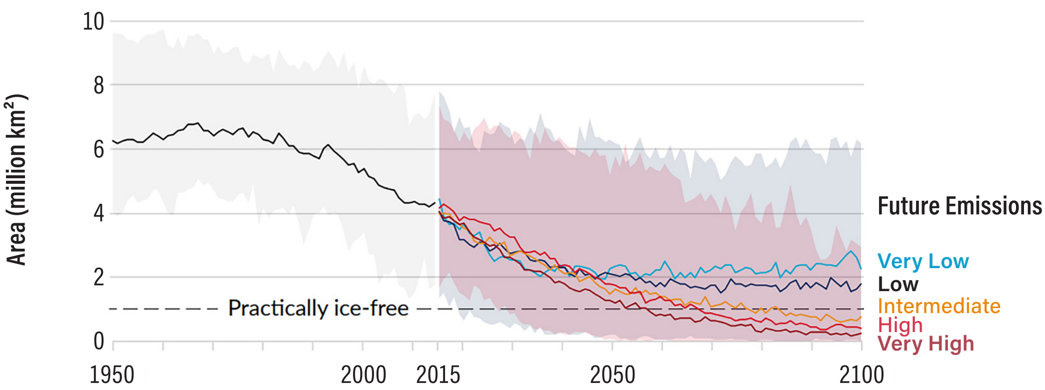
This extreme loss of summer sea ice is a primary cause of "Arctic amplification", which refers to the greater rise in temperature that has been observed in the high latitudes of the northern hemisphere compared to the rest of the globe. It also carries significant weather, ecological, and economic consequences. 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 .

Continued sea-ice loss will also cause Arctic Ocean ecosystem disruption. Many small 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, in the first ice-free summer event. Even with low emissions, this is projected to occur at least once before 2050. This will have a lasting effect on the entire Arctic food chain.

Sea ice around Antarctica 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. 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.

Summer Arctic sea ice extent has often been considered a bellwether of climate change, with great attention paid to the September minimum each year. In reality however, sea ice thickness and extent have declined in all months; and the consensus of sea ice scientists is that the ice cover has already fundamentally changed, crossing a threshold to a new state. Thinner and younger ice has replaced much of the multi-year ice that used to circulate

FIGURE 5-2. **September Arctic Sea Ice Area Projections**



SOURCE: IPCC AR6 WGI 2021

FIGURE 5-3. **Just 1% of Today's Ice Pack is Old, Thick Ice**

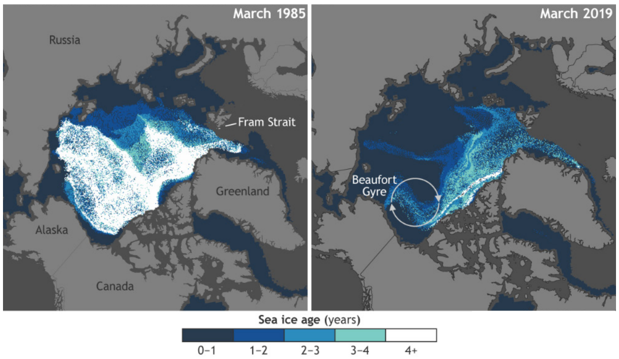


IMAGE SOURCE: NOAA CLIMATE.GOV; DATA: ARC 2019

The consensus of sea ice scientists is that the ice cover has already fundamentally changed, crossing a threshold to a new state.

over several years around the North Pole, before being discharged into the North Atlantic Ocean. 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.

Despite this fundamental change already observed at today's heightened temperatures, public focus remains on when the first ice-free summer will occur: something which 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, and sea level then was 4–6 meters (13–20 feet) higher than today. This is the current trajectory of the Earth's climate.

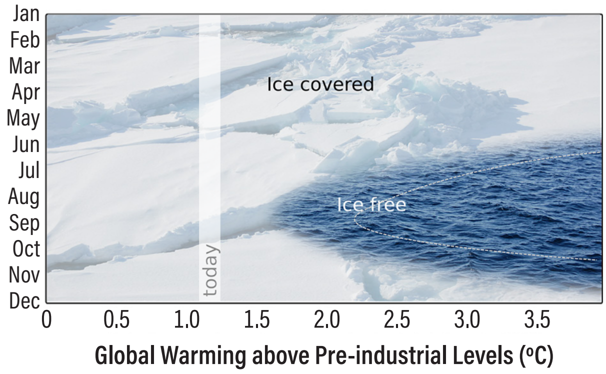
Like many impacts of climate change, Arctic sea-ice loss over the past three decades has not occurred gradually, but rather in abrupt loss events when combinations of wind and warmer temperatures drove lower ice extents. It is likely that a near-complete loss of summer sea ice (defined as dipping below 15% of the Arctic Ocean, 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, become the norm for some portion of each summer, with ice-free conditions ultimately extending into spring and autumn.

The occurrence of the first ice-free summer is therefore very unpredictable, but scientists now project it will occur at least once before 2050 even under very low emissions scenarios. However, under both very low and low emissions scenarios, summer sea ice extent would likely stabilize, with occasional ice-free years, but remaining generally above ice-free conditions. Greater amounts of sea ice would then begin to occur, slowly increasing on decadal scales due to a warmer Arctic Ocean, as temperatures decrease below 1.5°C and towards at least today's temperatures.

On the other hand, even intermediate emissions will lead to ice-free conditions each summer, and the length of this ice-free state would increase alongside emissions. These ice-free summers would start somewhere around 1.7°C of global warming, with longer ice-free periods each summer by 2°C, eventually stretching from July-October. 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.

The global impact of complete Arctic summer sea ice loss will therefore include accelerated global warming and its impacts. Given the greater absorption of solar heat from 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. Unusual weather patterns likely will involve persistent conditions (drought, heatwaves, cold spells, or stormy periods), such as the extreme multi-year drought in the U.S. Southwest; extreme heatwaves in northwestern North America in June 2021; and the summer 2018 drought in Scandinavia that

FIGURE 5-4. **Ice-free Conditions by Month and Temperature**



Latest research projects ice-free conditions ranging from briefer periods in September around 1.7°C, to several months by 2°C.

BASED ON NOTZ AND STROEVE, 2018

spalla67 Adobe Spark

contributed to extensive wildfires and agricultural losses. Additional 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 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. Such profound, adverse impacts almost certainly will eclipse any temporary economic benefits brought by an ice-free summer Arctic.

The Arctic Ocean has never been ice-free in modern human existence.

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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 and declining)

At least 50% reductions by 2030 still 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 nevertheless 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 heat waves 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 AMOC (Atlantic Meridional Overturning Circulation) is likely to slow further, but not collapse.

Fulfillment of "Optimistic" NDCs (2.1°C in 2100 and rising)

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.

Currently Implemented NDCs and Policies (2.7–3.1°C in 2100 and rising)

With CO_2 concentrations above 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 Emissions Growth (2–3ppm per year, 2100 temperature 4°–5°C and rising)

CO_2 levels, especially with permafrost emissions feedbacks, would reach 800 ppm 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 caused by such a rapid and extreme rise in acidification, in combination with much warmer and fresher waters from extensive and accelerating ice sheet melt, including potentially rapid collapse of the West Antarctic Ice Sheet. Mass extinction of many sea ice-associated polar and near-polar species will be the result; and fish such as cod, herring and salmon are extremely unlikely to survive in the wild.

Background

Increasing CO_2 concentrations lead 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 three million years.

The Arctic and Southern Oceans have absorbed the lion's share of this excess CO_2, mostly because colder and fresher waters take up carbon more readily. By some estimates, these 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.

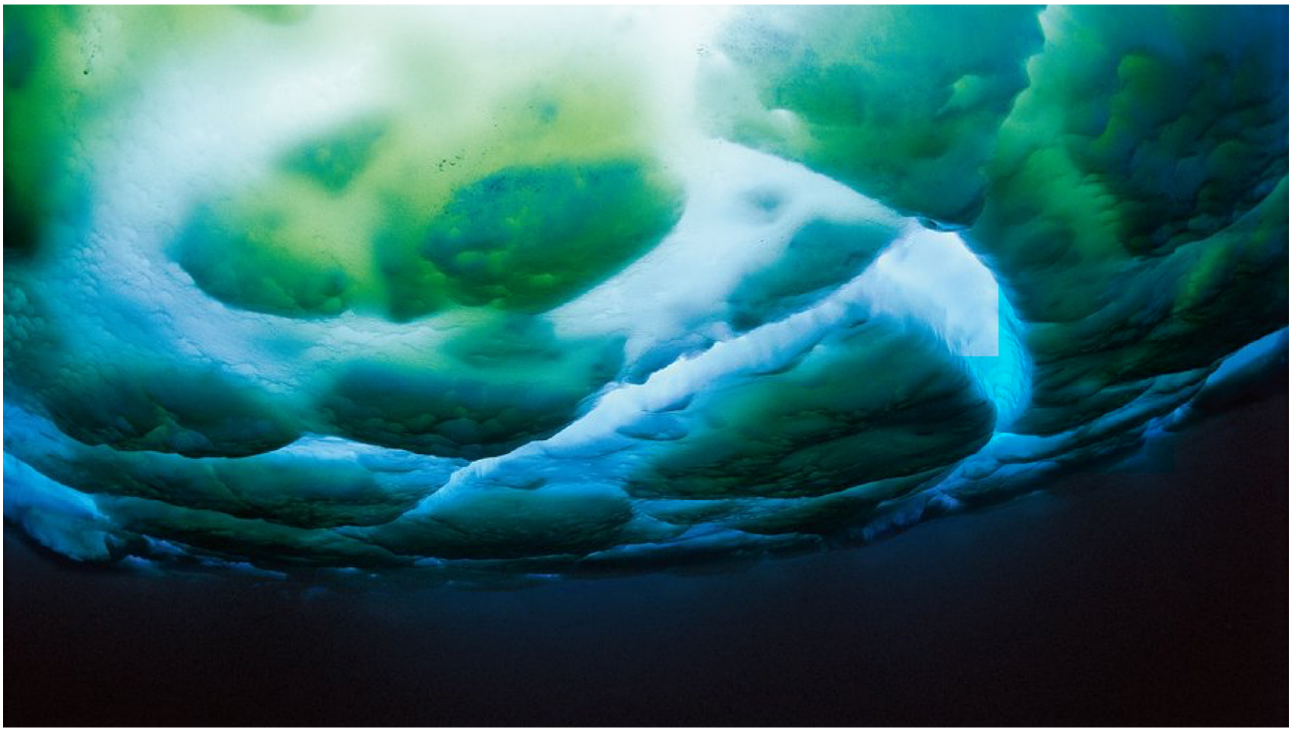
This "sink" comes at a cost for polar marine environments, however, because it also results in higher rates of acidification than anywhere else on Earth; and at a time when species there face extreme stress from other climate change impacts, especially in the Arctic. Summer surface water temperatures there have increased by around 2°C since 1982, primarily due to sea ice loss and an 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. 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, where many species at the base of the Arctic food chain live. 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 Arctic and Southern Oceans have absorbed the lion's share of excess CO_2, by some estimates up to 60% of the carbon taken up by the world's oceans.

The Southern Ocean around Antarctica also has warmed more than other ocean regions, in particular the western Antarctic Peninsula; and seems increasingly important in overall global ocean heat increase.

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 following their own preferred temperatures polewards.

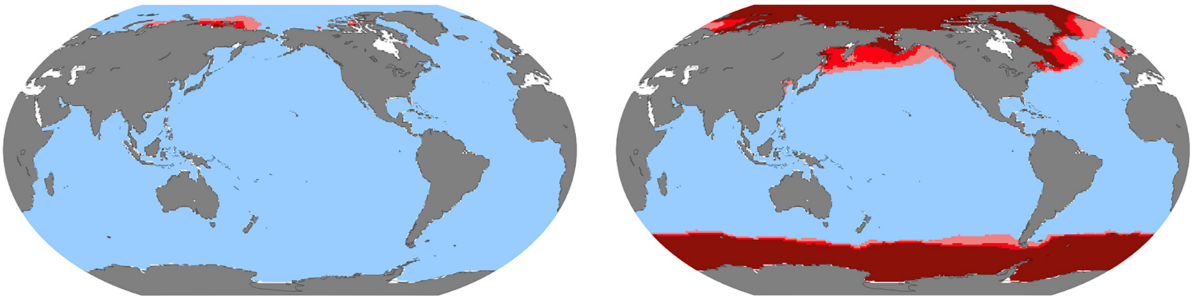
Other changes include freshening of polar waters from glacier and ice sheet melting, adding additional stress



Peter Thor, SMHI

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

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



Difference between acidification conditions in a 1.5° world (RCP2.6) (left map), and a 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.

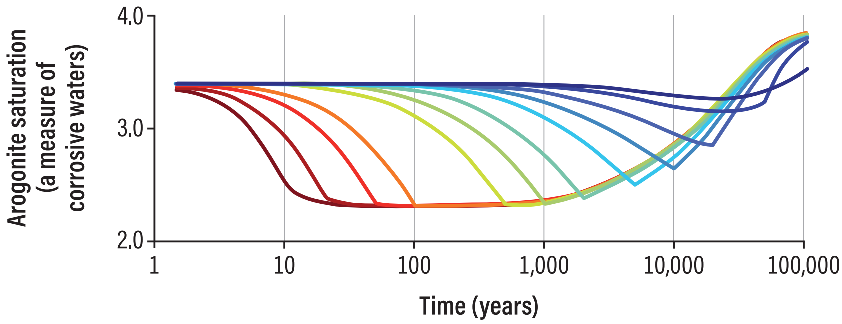
IMAGE SOURCE: IPCC SROCC (2019).

on high-latitude species and ecosystems, with effects seen already today. 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.

Ocean acidification makes it more difficult for shell-building animals to build and maintain their structures. More corrosive waters also increase the energy costs to maintain pH in the cells and tissues of all water-dwelling organisms. In this way, ocean acidification harms key organisms such as marine gastropods and pteropods, sea urchins, clams, and crabs. 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.

There is currently no practical way for humans to reverse ocean acidification, and 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.

FIGURE 6-2. **Long Time for Recovery from Ocean Acidification**



For ocean species, acidification is essentially permanent. Recovery time from acidification: 50,000–70,000 years

ADAPTED FROM HONISCH ET AL (2012)

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

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

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 2009 as an important threshold for serious global ocean acidification. 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. In the Southern Ocean, the ability of some vulnerable organisms to build shells declined by around 4% between 1998 and 2014. Pteropods – tiny marine snails known as “sea butterflies” – are particularly susceptible to these expanding corrosive waters, with shell damage documented in portions of the Gulf of Alaska, Bering and Beaufort seas; as well as regions in the Southern Ocean. 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.

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, CO_2 levels begin to fall sharply.

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 65 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.

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. This phenomenon of a freshwater “lid” can also impact ocean currents, especially the AMOC, which 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.

Warming waters result in a poleward movement of other species, while reducing the range of polar species and increasing competition for food resources. In some instances, especially where extreme heatwaves occur in the ocean, polar species have apparently even experienced lethal temperatures. Large die-offs of seabirds and gray

Credit: Jeremy Irons

1 million Common Murres died during this 2016 event, the largest known die-off of a single bird species ever, from starvation after a marine heat wave in the Bering Sea.

There is currently no practical way for humans to reverse ocean acidification, and these more acidic conditions will persist for tens of thousands of years.

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. 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.

The bottom line is that the combination of ocean acidification, warming and freshening, as well as invasion of lower latitude species will have earlier and greater impacts on polar ecosystems and organisms. These impacts are essentially irreversible above 2°C; and will occur with all but the very lowest emissions pathways, requiring 50% reduction in CO_2 emissions, motivated by high ambition and commitment toward global decarbonization by 2030, and essentially zero emissions by 2050.

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Summation

State of the Cryosphere 2021

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

ICE SHEETS AND SEA-LEVEL RISE

Global sea levels will continue to rise for centuries, but very slowly, reaching around 2-3 meters above today in the next 2000 years, with about half a meter occurring early in the next century. This assumes ice sheets respond to warming in a steady manner, adding to sea-level rise from land glacier loss and ocean thermal expansion.

GLACIERS AND SNOWPACK

Glaciers and snowpack have been declining extremely rapidly for the past several decades. That rapid decline will continue, especially outside polar regions, but with very low emissions losses 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 of the Andes, East Africa and Indonesia by 2100 is now difficult to avoid. They may not recover until temperatures fall below pre-industrial, or the next Ice Age.

POLAR OCEANS

At least 50% reductions by 2030 still 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 nevertheless will lead to prolonged ocean acidification: very long-term (tens of thousands of years) corrosive conditions that stress all marine organisms, especially those unable to build or maintain their shells. Isolated marine heat waves 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 AMOC (Atlantic Meridional Overturning Circulation) is likely to slow further, but not collapse.

PERMAFROST

Permafrost thaw will add carbon dioxide and methane emissions to those of humans of about the size of India today, totaling around 150-200 Gt CO2-eq by 2100. Once permafrost experiences its first thaw, emissions can continue for centuries; so these permafrost emissions will continue after peak temperature is reached 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.

ARCTIC SEA ICE

At least 50% reductions by 2030 will not prevent at least one ice-free summer before 2050; but as temperatures stabilize just above 1.5°C and then decline, Arctic summer sea ice can stabilize just above total loss conditions (defined as less than 1 million km^2). The number of ice-free summers will also decline, helping stabilize global climate and feedbacks such as sea-level rise from Greenland and Arctic glaciers, and permafrost emissions.

Fulfillment of "Optimistic" NDCs (2.1°C in 2100 and rising)

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 and the rapid decline and loss of many land glaciers, global sea levels eventually will reach 3–6 meters above today. Even higher levels cannot be ruled out; the last time temperatures exceeded the 2°C threshold, sea-level rise likely was well above 6 meters. Sea levels would reach around 0.75 meters above today early in the next century. At this higher temperature however, a steady predictable rate of sea-level rise from ice sheets is less certain, and the rate and amount could be greater already by 2100.

GLACIERS AND SNOWPACK

Once two degrees is passed, by 2300 the only 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 one-half or one-third of their current size. Snowfall also will become more rare outside these regions, falling instead as rain that may at times be extreme in this warmer climate, leading to increased erosion, flooding and landslides. In the Himalayas, this loss of glaciers and snowpack will radically affect seasonal water supplies in some river systems, for example the Tarim in northwestern China.

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 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.

PERMAFROST

Permafrost thaw will add carbon dioxide and methane emissions to those of humans of about the size of the European Union today, totaling around 220–300 Gt CO_2-eq by 2100. These emissions will continue for one-two 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 emissions until they cease, simply to hold temperatures steady. Permafrost soils will disappear in extensive regions above the Arctic Circle, as well as below, and nearly all existing infrastructure built on vulnerable permafrost soils will require replacement.

ARCTIC SEA ICE

Summer sea ice will disappear nearly every September 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.

Currently Implemented NDCs and Policies (2.7–3.1°C in 2100 and rising)

ICE SHEETS AND SEA-LEVEL RISE

This scenario would push ice sheets in ways not seen since the end of the last Ice Age. West Antarctic Ice Sheet collapse is likely to be rapid once temperatures exceed 3°C, with some involvement of portions of East Antarctica and greater loss from Greenland. WAIS collapse would be well along by 2300, with almost no glaciers remaining anywhere on the globe. Sea-level rise will continue at a relatively rapid pace for many centuries and be essentially permanent on human timescales, ending at 15–20 meters or more above today. Sea-level rise of 1-2 meters already by 2100 is possible. This rate of temperature rise will push ice sheets in ways not seen in the Earth system since large deglaciation events 125,000 years ago.

GLACIERS AND SNOWPACK

Virtually no glaciers will remain anywhere on the globe outside the Arctic, Patagonia and Himalayas, where only 20–35% of ice will remain. Snowfall will become more rare outside the polar regions and high altitudes. With such very high ice and glacier loss exposing bare ground, glacier re-growth (even with temperatures returning to those of today) will likely take thousands of years, though snowpack would return as soon as temperatures decline.

POLAR OCEANS

With CO_2 concentrations above 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.

PERMAFROST

Permafrost thaw will add carbon dioxide and methane emissions to those of humans of about the size of the U.S. today, totaling around 350–400 Gt CO_2-eq by 2100. These emissions will continue for one-two centuries after peak temperature is reached between 2150–2170. 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 have disappeared by the time of this peak. Extensive erosion, due to permafrost thaw, sea ice-free conditions and more violent storms will require extensive replacement of coastal and riverside Arctic infrastructure, especially in Russia and Canada.

ARCTIC SEA ICE

The 1.7°C summer loss threshold will be reached far earlier, by ~2040. Ice-free conditions during much of spring and fall, as well as summer will further accelerate sea-level rise and permafrost emissions further. Ecosystem disruption will extend farther south, reaching also into near-Arctic waters such as the Barents, Bering, and North seas., in concert with Lower salinity due to extensive meltwater and growing ocean acidification 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 Emissions Growth (2–3ppm per year, 2100 temperature 4°–5°C and rising)

ICE SHEETS AND SEA-LEVEL RISE

Loss of large portions of both polar ice sheets and all land glaciers will occur. West Antarctic Ice Sheet collapse will 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 complete loss of the Greenland ice sheet. Such a rapid rise in CO2 concentrations and temperature has no counterpart in Earth's geologic record, but Antarctica has ice-free conditions at 6°C. Restoration of the polar ice sheets can only begin with temperatures well below pre-industrial (induction of a new Ice Age).

GLACIERS AND SNOWPACK

Virtually no glaciers will remain anywhere on the globe by 2200, with mid-latitude glaciers 90% gone by 2100. Snowfall by 2100 will be extremely limited outside polar regions and high altitudes.

POLAR OCEANS

CO_2 levels, especially with permafrost emissions feedbacks, would reach 800 ppm by 2100. Few of today's polar species, especially shell-building species are likely to survive the radical change in environment caused by such a rapid and extreme rise in acidification, in combination with much warmer and fresher waters from extensive and accelerating ice sheet melt, including potentially rapid West Antarctic Ice Sheet collapse. Mass extinction of many sea ice associated polar and near-polar species will be the result; and fish such as cod, herring and salmon are extremely unlikely to survive in the wild. 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.

PERMAFROST

Permafrost thaw will add carbon dioxide and methane emissions to those of humans of about the size of China today, totaling around 400–500 Gt CO2-eq by 2100. These emissions will continue for one-two 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 soils will largely disappear globally with massive impacts on infrastructure and populations in the permafrost region.

ARCTIC SEA ICE

The conditions of ecosystem collapse noted above will be apparent by 2030, spreading south along the coastlines of all Arctic nations and beyond. Depending on peak global mean temperatures, recovery of Arctic sea ice to today's conditions would likely take over 1000 years.


International Cryosphere
Climate Initiative