State of the Cryosphere 2023

Two Degrees Is Too High

We cannot negotiate with the melting point of ice.

NOVEMBER 2023

www.iccinet.org/statecryo23

State of the Cryosphere 2023

Two Degrees Is Too High

We cannot negotiate with the melting point of ice.

NOVEMBER 2023

www.iccinet.org/statecryo23

International Cryosphere Climate Initiative

Contact: info@iccinet.org
Twitter/X: @iccinet
www.iccinet.org

State of the Cryosphere 2023 – Two Degrees Is Too High
We cannot negotiate with the melting point of ice.

Cover Photo: A 3AM "sunrise" over Ekström Ice Shelf, Dronning Maud Land, East Antarctica; taken from the icebreaker RV Polarstern, January 2023. Antarctic sea ice hit a record low minimum extent about a month later. (Credit: James Kirkham, British Antarctic Survey/ICCI and AMI Chief Science Advisor)

DEDICATION

This Report is dedicated to the memory of two towering figures lost to us in 2023, both from the early years of climate negotiations, both from Bangladesh and both passionately engaged: Quamrul Chowdhury (1959–May 2023) and Professor Dr. Saleemul Huq (1952–October 2023).

Both were also deeply and persuasively involved in efforts to make the connection between global cryosphere loss and the 1.5°C limit clear to global leaders as well as countries seemingly far removed from cryosphere, such as Bangladesh, quite literally till the last days of their lives.

They are both deeply missed; but their inspiring work lives on, including in these pages.

Contents

Scientific Reviewers

1. The Hope of Low Emission Pathways and Cryosphere

Julie Brigham-Grette, University of Massachusetts Amherst
Andrea Dutton, University of Wisconsin-Madison
Matthew Gidden, IIASA
Joeri Rogelj, IPCC CLA AR5, SR1.5 and AR6, Imperial College London
Martin Siegert, University of Exeter
Michiel Schaeffer, GAI, IPCC AR5
Drew Shindell, IPCC CLA SR1.5, Duke University

2. Ice Sheets and Sea-level Rise

Richard B. Alley, Pennsylvania State University, IPCC AR2, AR3, AR4
Jonathan Bamber, University of Bristol, IPCC AR6 WG1, AR5 Review Editor, AR4 Review Editor
Julie Brigham-Grette, University of Massachusetts-Amherst
Robert DeConto, University of Massachusetts-Amherst, IPCC SROCC
Andrea Dutton, University of Wisconsin-Madison, IPCC SROCC
Carlota Escutia, Spanish High Council for Scientific Research and University of Granada
Carl-Friedrich Schleussner, Climate Analytics
Martin Siegert, University of Exeter
Michael Schaeffer, IPCC AR5 LA, Global Center on Adaptation, IPCC AR5
Chris Stokes, Durham University
[Roderik van de Wal, Utrecht University, IPCC AR3, AR4, AR5 Review Editor, SROCC]

3. Mountain Glaciers and Snow

Carolina Adler, Mountain Research Initiative, Lead Author IPCC AR6 WGII and SROCC
Guðfinna Aðalgeirsdóttir, University of Iceland, IPCC AR6
Daniel Farinotti, ETH-Zurich, WSL
Matthias Huss, ETH-Zurich, WSL
Regine Hock, University of Oslo, Norway, University of Alaska Fairbanks, IPCC AR4, SROCC coordinating Lead Author, AR6
Miriam Jackson, ICIMOD, IPCC AR6
Georg Kaser, University of Innsbruck, IPCC AR4, AR5, SROCC and AR6 Review Editor
Michael Lehning, EPFL, IPCC SROCC
Ben Marzeion, University of Bremen, IPCC AR5, SROCC, AR5 and AR6 WG1
Fabien Maussion, University of Bristol
Ben Orlove, Columbia University, IPCC SROCC, AR6 WG2
David Rounce, Carnegie Mellon University
Heidi Sevestre, University of Svalbard
Heidi Steltzer, Fort Lewis College, IPCC SROCC
Philippus Wester, IPCC AR6 WG2

4. Permafrost

Benjamin W. Abbott, Brigham Young University
Julia Boike, Alfred Wegener Institute (AWI)
Sarah Chadburn, University of Exeter
Gustaf Hugelius, Bolin Centre for Climate Research, Stockholm University
Hugues Lantuit, AWI
Susan Natali, Woodwell Climate Research Center
Paul Overduin, AWI
Vladimir Romanovsky, University of Alaska-Fairbanks
Christina Schädel, Woodwell Climate Research Center
Ted Schuur, IPCC LA SROCC, Northern Arizona University
Merritt Turetsky, INSTAAR / University of Guelph

5. Sea Ice

Jennifer Francis, Woodwell Climate Research Center
Ronald Kwok, Polar Science Center, Applied Physics Laboratory, University of Washington
Robbie Mallett, University of Manitoba
Walt Meier, National Snow and Ice Data Center
Dirk Notz, University of Hamburg, Germany
Martin Sommerkorn, IPCC SROCC CLA, WWF-Arctic
Julienne Stroeve, University College London/University of Manitoba/NSIDC
Paul Wassmann, UiT - The Arctic University of Norway (emeritus)

6. Polar Ocean Acidification, Warming and Freshening

Nina Bednaršek, National Institute of Biology, Slovenia
Richard Bellerby, East China Normal University/Norwegian Institute for Water Research
Elise S. Droste, Alfred Wegener Institute (AWI) Helmholtz Centre for Polar and Marine Research
Sam Dupont, University of Gothenburg
Helen S. Findlay, Plymouth Marine Laboratory
Humberto E. González, University Austral of Chile/Fondap IDEAL
Sian Henley, University of Edinburgh
Peter Thor, Swedish Meteorological and Hydrological Institute (SMHI)
Paul Wassmann, UiT – The Arctic University of Norway (Emeritus)

Chapter Editors (ICCI)

James Kirkham (Ice Sheets, Sea Ice, Mountain Glaciers and Snow)
Lydie Lescarmontier (Polar Oceans)
Amy Imdieke (Permafrost)
Morgan Seag (Mountain Glaciers and Snow)

Acknowledgements

The extensive time and invaluable contributions of Reviewers are hereby acknowledged, and deeply appreciated.

Great thanks also to the International Centre for Integrated Mountain Development (ICIMOD) for its review and support.

Special thanks to Tyler Kemp-Benedict for extensive work with figures, design and layout.

Final content is the responsibility of ICCI.

Preface

1.5°C Is the Only Option

This year is the year of climate disasters. Global temperatures, including sea surface temperatures are at record high. The sea ice around Antarctica is at an all-time low; and, in the Arctic, icecaps and Iceland's vital glaciers continue to melt. Chile has seen a year of brutal wildfires, intense rains, devastating floods. We are not in an era of global warming; but as UN Secretary General Guterres says, "global boiling." This year we will come close to reaching 1.5°C of warming, for the first time in human history.

And the Cryosphere – Earth's frozen water in ice sheets, sea ice, permafrost, polar oceans, glaciers and snow – are at ground zero, beginning to reach the boundary where adaptation becomes loss and damage, irreversible on any human timescale. From the Cryosphere point of view, 1.5°C is not simply preferable to 2°C or higher, it is the only option.

We do see some positives. Iceland will not issue any licenses for oil exploration in its exclusive economic zone, and has put into legislation that it should become carbon-neutral no later than 2040. Chile, along with Fiji, was the first developing country to legislate carbon neutrality by 2050, and hopefully much sooner.

But we can and need to do much more, heading for a future where non-renewable energy is no longer an option. The only way through this climate crisis is to finally leave fossil fuels behind and resist greenwashing. After all, the melting point of ice pays no attention to rhetoric, only to our actions.

At COP28, we need a frank Global Stocktake, and fresh urgency especially due to what we have learned about Cryosphere feedbacks, worsening for each additional tenth of a degree in temperature rise. We need tangible results, and clear message about the urgency to phase out fossil fuels and for more robust financial mechanisms to finance climate action.

We have time, but not much time. Past alerts are today's shocking facts. Present warnings will be tomorrow's cascading disasters, both within and from the global Cryosphere, if we do not accelerate climate action and implement systemic change.

Change is hard, but change we must. Because of the Cryosphere, climate inaction is unacceptable.

Gabriel Boric,
President, Chile

Katrín Jakobsdóttir
Prime Minister, Iceland

Co-Chairs and Founding Members, Ambition on Melting Ice (AMI)
High-level Group on Sea-level Rise and Mountain Water Resources
www.ambitionmeltingice.org

Credit: J. Kirkham

High-altitude snow melt (5000 meters above sea level), Langtang Valley, Nepal, Himalayas. Melt at such high altitudes is becoming more frequent, as the Hindu Kush Himalaya warm at over twice the global average.

Scientist Foreword

2°C Is Too High

This has been a year of climate disasters and ice loss. A glacial lake outburst flood devastated Sikkim in India. Swiss glaciers lost 10% of their remaining ice over just two years. Sea ice around Antarctica hit all-time-low summer and winter records. Unprecedented fires raged across Canadian permafrost. Parts of the Arctic and North Atlantic saw water temperatures 4–6°C higher than normal. It rained far inland on Antarctica, and Greenland saw its second-highest surface melt ever.

None of these tragic events surprised us, members of the global Cryosphere scientific community, because – despite all the climate pledges from Paris in 2015, to Egypt in 2022 – greenhouse gas concentrations in the air have continued their steady march upwards. This year, 2023, atmospheric carbon dioxide (CO_2) concentrations officially hit 50% above pre-industrial levels: 424 ppm, higher than at any point in at least 3 million years. 2023 will be the warmest year on record, probably by the largest margin ever.

Our message -- the message of the Cryosphere – is that this insanity cannot and must not continue. COP28, and December 2023 must be when we correct course. Some degree of planetary-wide damage from Cryosphere loss is already locked in. We must prevent even worse impacts from a collapsing Cryosphere for each additional tenth of a degree temperatures rise, especially past the "lower" Paris Agreement limit of 1.5°C.

The Cryosphere – Earth's ice sheets, sea ice, permafrost, polar oceans, glaciers and snow – is ground zero for climate change. This is because of the simple physical reality of the melting point of ice; or in the case of our rapidly acidifying polar oceans, the amount of CO_2 in the atmosphere absorbed and turned to carbonic acid.

The warming impact of CO_2, around 80% from fossil fuel use, already has led to steep glacier and ice sheet loss causing global sea-level rise; reduction of water resources from snowpack; growing CO_2 and methane emissions from thawing permafrost; dramatic reduction of sea ice, now alarmingly low in both polar oceans; and growing evidence of stress on keystone polar marine species, such as krill, salmon and cod, from polar ocean acidification, warming and freshening.

Enough. It is time to carve a line in the snow: because of what we have learned about the Cryosphere since the Paris Agreement was signed in 2015, 1.5°C is not merely preferable to 2°C. It is the only option.

At COP28, we call on global leaders to enshrine this reality in the Cover Decision: because of the Cryosphere response, even 2°C is too high. The Paris Agreement's "well below 2°C" can mean just one thing: 1.5°C alone. We therefore need a Stocktake with clear guidelines to make 1.5°C a reality; a path to phase out fossil fuels; and financial mechanisms to support climate action, as well as the adaptation, and loss and damage – most of it ultimately tied to irreversible Cryosphere loss -- now inevitable even below 1.5°C; but far worse above that. For regions like the Hindu Kush Himalaya, frankly even 1.5°C is too high.

Otherwise, world leaders are *de facto* deciding to burden humanity for centuries to millennia by displacing hundreds of millions of people from flooding coastal settlements; depriving societies of life-giving freshwater resources, disrupting delicately-balanced polar ocean and mountain ecosystems; and forcing future generations to offset long-term permafrost emissions.

This continued rise in CO_2 is unacceptable.

The melting point of ice pays no attention to rhetoric, only to our actions.

Dr. Pema Gyamtsho
Director General, International Centre for Integrated Mountain Development (ICIMOD), Nepal

Dr. Gustaf Hugelius
Vice Director
Bolin Centre for Climate Research, Stockholm University

Dr. Julie Brigham-Grette
Former Chair, U.S. Polar Research Board
Dept of Earth, Geographic and Climate Sciences, University of Massachusetts – Amherst

Dr. Chris Stokes
Durham University, UK

Dr. Martin Siegert
Vice President and Professor of Geoscience
University of Exeter, Cornwall, UK

Dr Helen Findlay
Senior Scientist, Plymouth Marine Laboratory;
Honorary Professor University of Exeter, UK

Dr. Twila Moon
National Snow and Ice Data Center
Cooperative Institute for Research in Environmental Sciences
University of Colorado Boulder

Why 2°C Is Too High

Executive Summary

ICE SHEETS

- 2°C will result in extensive, potentially rapid, irreversible sea-level rise from Earth's ice sheets; 3°C will further speed up this loss to within the next few centuries.
- A compelling number of new studies, taking into account ice dynamics, paleo-climate records from Earth's past, and recent observations of ice sheet behavior, all point to a threshold for both Greenland and parts of Antarctica well below 2°C, committing the planet to between 12–20 meters sea-level rise if 2°C becomes the new constant Earth temperature.
- The most recent projections show a slow, but continuing pattern of sea-level rise (SLR) for many centuries even with "low emissions" (SSP1-2.6). This is an emissions pathway that peaks at 1.8°C and returns close to 1.6°C by 2100; yet the models show SLR continuing at this slow pace, indicating some level of ice loss has been irreversibly triggered even by this brief period of overshoot.
- Many ice sheet scientists now believe that by 2°C, nearly all of Greenland, much of West Antarctica, and even vulnerable portions of East Antarctica will be triggered to very long-term, inexorable sea-level rise, even if air temperatures later decrease. This is due to a warmer ocean that will hold heat longer than the atmosphere, plus a number of self-reinforcing feedback mechanisms, so that it takes much longer for ice sheets to regrow (tens of thousands of years) than lose their ice.
- If global leaders cause temperatures to reach this point through continued fossil emissions, they are committing the planet to extensive coastal loss and damage well beyond limits of feasible adaptation.
- Latest projections show that only "very low" emissions and the 1.5°C Paris limit reliably maintains both ice sheets, preventing massive long-term sea-level rise.

MOUNTAIN GLACIERS AND SNOW

- Measurements now confirm that essentially all mountain glaciers worldwide are losing ice: some, such as those in the Alps, at distressingly rapid rates over the past two summers alone.
- 2°C will result in extensive, long-term, essentially irreversible ice loss from many of the world's glaciers in many major river basins, with some disappearing entirely. Snow cover also will greatly diminish. A rise of 3°C will spread and greatly speed up this loss.
- If 2°C warming is reached, projections show that nearly all tropical glaciers (north Andes, Africa) and most mid-latitude glaciers outside the Himalayas and polar regions will disappear, some as early as 2050. Others are large enough to delay complete loss until the next century, but have already passed a point of no return. Even the Himalayas are projected to lose around 50% of today's ice at 2°C.
- As glaciers melt, risks of catastrophic events – landslides, sudden ice shears, and in some cases glacial lake outburst floods – will rise, affecting entire communities.
- Winter snowpack at 2°C generally will decrease, but also become more volatile; with some years of hardly any snow, and others with record-breaking amounts that threaten infrastructure and lives.
- Losses in both snowpack and glacier ice will have dramatic impacts on downstream dry season water availability for agriculture, power generation, and drinking. Impacts may be extreme in especially vulnerable river basins, such as the Tarim in northwest China and the Indus.
- Continued warming, even through the brief 1.6°C peak of very low emissions (SSP1-1.9) still means that today's very fast ice loss in glaciers globally will continue through at least the 2050s. With very low emissions, this loss will begin to slow in at least some regions around 2060, and stabilize towards the end of this century.
- With very low emissions, some glaciers may even show slow re-growth in the 2100s, though this would occur extremely slowly (many decades to centuries). Such visible snow and ice preservation, and its benefits for freshwater resources, may be one of the earliest and visible signs to humanity that steps towards low emissions have meaningful results.

Why 2°C Is Too High

Executive Summary (continued)

SEA ICE

- Perhaps more so than for any other part of the cryosphere, 2°C is far too high to prevent extensive sea ice loss at both poles, with severe feedbacks to global weather and climate.
- By 2°C, the Arctic Ocean will be sea ice-free in summer not occasionally, but almost every year; and for periods of up to four months (July–October). The most recent projections show frequent ice-free conditions by 2050 even with "low emissions" (SSP1-2.6), a carbon pathway that peaks at 1.8°C.
- Open water in the Arctic for several months will absorb more heat from polar 24-hour sunlight conditions. A warmer Arctic will increase coastal permafrost thaw – adding more carbon to the atmosphere – and speed Greenland Ice Sheet melt and resulting sea-level rise.
- It also means that any Arctic sea ice recovery may take many decades, even with a subsequent return to lower atmospheric temperatures, because the water will hold that heat far longer.
- In the Antarctic, complete loss of sea ice every summer seems plausible at 2°C if current trends continue, and would almost certainly speed up loss from the Antarctic ice sheet and resulting sea-level rise. Record-low conditions in 2023 around much of Antarctica indicate that its threshold for complete summer sea ice loss might be even lower than for the Arctic.
- Studies consistently indicate that Arctic sea ice will still melt almost completely some summers even at 1.5°C, but not each year and only for a brief period (days to a few weeks) when it does. Only "very low" emissions (SSP1-1.9, which peaks at 1.6°C) can maintain summer Arctic sea ice, and lead to some recovery by 2100, when temperatures begin to decline below 1.4°C.
- Negative impacts on sea ice-dependent Indigenous communities and ecosystems will still be significant, however, since at least one ice-free summer is now inevitable before 2050 even with "very low" emissions, according to the IPCC.

PERMAFROST

- 2°C – and even 1.5°C – is too high to prevent extensive permafrost thaw and resulting CO_2 and methane emissions that will cause temperatures to continue to rise, even once human emissions reach zero, unless offset by extensive negative emissions/carbon drawdown; but 1.5°C will decrease the size of such emissions significantly.
- 2°C means 4–8°C in the Arctic where most permafrost is located, with parts of the Arctic warming 2–4 times faster than the rest of the planet. In addition, up to half of recent permafrost thaw has occurred during extreme heat events of up to 12°C above average, as a result of "abrupt thaw" processes where coastlines or hillsides collapse, or lakes form; exposing much deeper and greater amounts of permafrost to thaw.
- Once thawed, permafrost begins emitting CO_2 or methane, even if temperatures later drop below freezing. These emissions are irreversibly set in motion and will not slow for 1–2 centuries, meaning that future generations must offset them (draw down carbon) at scales the size of a major emitter.
- At 2°C, annual total permafrost emissions (both CO_2 and methane) would probably total the size of the entire European Union's emissions from 2019 (≈200Gt total by 2100 and about twice that by 2300). Permafrost thaw at 2°C might also be accelerated further by loss of Arctic sea ice in summer for several months, as the open water absorbs more heat; and by increased wildfires in Siberia and North America.
- Even at 1.5°C, studies indicate significant permafrost thaw and related emissions, but these will be less in scale since temperatures will "only" average 3–4°C higher than today in the Arctic. "Very low" emissions (SSP1-1.9 also result in temperatures declining to below 1.4°C by the end of this century, preventing most additional new thaw.
- Annual permafrost emissions will still need to be offset by future generations, but should be 30–50% less, more on the scale of India in 2019 (150Gt by 2100).

Why 2°C Is Too High

Executive Summary (continued)

POLAR OCEANS

- 2°C will result in year-round, essentially permanent corrosive ocean acidification conditions in extensive regions of Earth's polar and some near-polar seas; with widespread negative impacts on key fisheries and species.
- This is because all 2°C emissions pathways lead to CO_2 levels in the atmosphere well above 450 ppm, the critical level for polar oceans identified decades ago by marine scientists. The Arctic and Southern Oceans already are bearing the brunt of acidification impacts because they absorb CO_2 faster. Some near-polar oceans, especially the Barents, North and Baltic seas, also would have acidification levels rivaling that of the poles.
- Shell-building animals, and commercial fisheries that rely on them in the food chain – valuable species such as krill, cod, salmon, lobsters, king crab, to name just a few – may not survive in the wild or when cultivated in these corrosive waters. With warmer ocean temperatures and lack of protective sea ice for several months each summer, marine heat waves and extreme acidification events will cause additional losses.
- These "overshoot" corrosive conditions, set by peak atmospheric CO_2 levels, are essentially irreversible, lasting 30–70,000 years.
- The "very low" emissions pathways resulting in temperatures close to the 1.5°C Paris limit would on the other hand reliably maintain atmospheric CO_2 well below 450 ppm; the most ambitious (SSP1-1.9) sees CO_2 levels peak at 430 ppm. This will limit corrosive stressing conditions to mostly seasonal damage in smaller sections of the Arctic and Southern Oceans, spreading marginally from what is already seen as shell damage today.
- This 430 ppm threshold is very close however: the May 2023 monthly average CO_2 level at Mauna Loa Observatory was 424 ppm. Destructive compound events combining marine heatwaves and extreme acidification have already caused population crashes even at today's 1.2°C.

CHAPTER 1

The Hope of Low Emission Pathways and Cryosphere

Very Low Emissions Can Still Prevent the Greatest Loss And Damage: But Time Is Very Short

Background

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

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

It cannot be over-emphasized how much more slowly these shifts in temperature and CO_2 concentrations occurred compared to today's warming from human greenhouse gas emissions. CO_2 levels an Ice Age were around 180 ppm, and 280 ppm during warm periods or "interglacials," including the past 10,000 years. The CO_2 peak of 424 is completely off-the-charts for the entirety of human existence, going back 3 million years; and as of 2023 is officially 50% above pre-industrial levels.

Most worryingly, CO_2 continues to rise in the atmosphere by 2–3 ppm each year, despite existing climate pledges that in accordance with the 2015 Paris Agreement, should aim to peak and stabilize concentrations, with that peak occurring before 2030 especially in 1.5°C-consistent emissions scenarios. By continuing to emit CO_2 and other greenhouse gases without pause, the world's nations and industrial sectors have pushed the planet into a risk zone. Today's 1.2°C above pre-industrial already has caused massive drops in Arctic and Antarctic sea ice; loss of glacier ice in all regions across the planet;

Summary

Very Low Emissions (Peak 1.6° and declining by 2100): Requires 1) at least 43% greenhouse gas reductions from 2019 levels by 2030, primarily from steep declines in fossil fuel use; 2) carbon neutrality (net zero CO_2 emissions) by 2050; and 3) net negative emissions (carbon drawdown) afterwards. Cryosphere generally begins to stabilize in 2040–2080. Slow CO_2 and methane emissions from permafrost continue for one-two centuries, then cease. Snowpack stabilizes, though at lower levels than today. Steep glacier loss continues for several decades, but slows by 2100; some glaciers still will be lost, but others begin to show re-growth. Arctic sea ice stabilizes slightly above complete summer loss. Year-round corrosive waters for shelled life are limited to scattered polar and near-polar regions for several thousand years. Ice sheet loss and sea-level rise will continue for several hundred, to thousands of years due to ocean warming, but likely not exceed 3 meters globally and occur over centuries.

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

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+

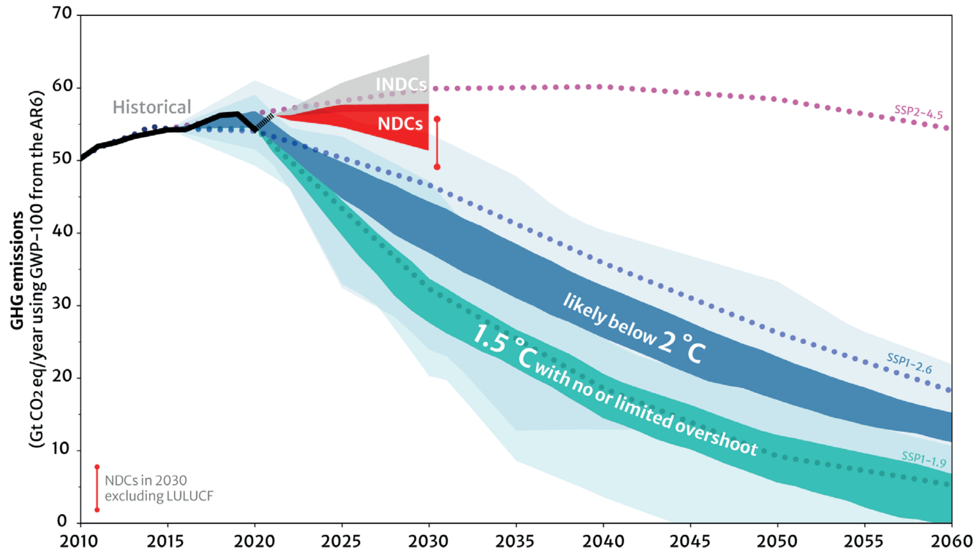
accelerating loss from both the Greenland and Antarctic ice sheets; extensive permafrost thaw; and rising polar ocean acidification. The global impacts of these losses at today's 1.2°C include extreme weather and disturbed ocean currents; floods, landslides and loss of snow and ice water resources; accelerated sea-level rise; infrastructure damage and permafrost greenhouse gas emissions; and damage to shelled polar organisms. Nearly all of these changes cannot be reversed on human timescales, and they will grow with each additional tenth of a degree. Well before 2°C, they would become devastating due to the physical reality of the cryosphere's response.

This is not however a pre-determined outcome. A variety of reports and independent analyses have shown the way to a 1.5°C future, beginning with the IPCC's Special Report on 1.5°C of Warming (SR1.5) from 2018. The IPCC Sixth Assessment, with its Synthesis Report released in March 2023, updated these findings, and outlined an even greater variety of pathways (see Table below). Other expert groups, especially the International Energy Agency (IEA), Climate Analytics, and initiatives from UN Secretary General Guterres have outlined how 1.5°C can be achieved. All these 1.5°C-consistent solutions however involve very sharp cuts in fossil fuel emissions within the next few years, so that CO_2 emissions peak before 2030 and no later.

Scenarios that would keep temperatures within or very close to 1.5°C remain physically, technologically, and economically feasible and even advantageous to both human populations and ecosystems, especially because many of their elements greatly improve human health outcomes. Most of the early emissions decline

Only a strong, emergency scale course-correction towards 1.5°C can slow and eventually halt these cryosphere impacts.

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



SOURCE: UNFCCC NDC SYNTHESIS REPORT, OCTOBER 26, 2022 would take place in the transport and power sectors. In particular, nearly all use of fossil fuels – especially coal, with oil and natural gas clearly declining – must be phased out, and certainly not expanded. Non-OECD countries especially must receive support to develop in a carbon-neutral manner. After 2050, "negative emissions" – pulling carbon out of the atmosphere through changes in agricultural practices or mechanical carbon removal technologies, will help CO_2 levels decline more rapidly, with temperatures beginning to lower by the end of this century. Some benefits – such as slight decreases in extreme weather – may begin to be felt around 2040.

The issue therefore is not that global leaders do not have 1.5°C solutions available. The issue is that those leaders, and humanity collectively, must decide to implement them. The most recent 2023 analysis show that the remaining carbon budget, and window to act has become very, very small. As of 2023, some of the very lowest emission pathways from IPCC no longer remain possible. Only a strong, emergency scale course-correction towards 1.5°C – emissions following the remaining "very low" pathways – can avert higher temperatures, to slow and eventually halt these cryosphere impacts within adaptable levels.

As the chapters in this Report describe, each tenth of a degree above 1.5°C matters. The various parts of the cryosphere will respond in future to our decisions today, based on the simple physical reality of the melting point of ice.

SCIENTIFIC REVIEWERS

Julie Brigham-Grette, University of Massachusetts Amherst

Andrea Dutton, University of Wisconsin-Madison

Matthew Gidden, IIASA

Joeri Rogelj, IPCC CLA AR5, SR1.5 and AR6, Imperial College London

Martin Siegert, University of Exeter

Michiel Schaeffer, GAI, IPCC AR5

Drew Shindell, IPCC CLA SR1.5, Duke University

LITERATURE AND ADDITIONAL READING

Briner, J., Cuzzone, J., Badgeley, J., Young, N., Steig, E., Morlighem, M., . . . Nowicki, S. (2020). Rate of mass loss from the Greenland Ice Sheet will exceed Holocene values this century. Nature, 70–74.

Christ, A., Bierman, P., Schaefer, J., Dahl-Jensen, D., Steffensen, J., Corbett, L., . . . Southon, J. (2021). A multimillion-year-old record of Greenland vegetation and glacial history preserved in sediment beneath 1.4 km of ice at Camp Century. Proceedings of the National Academy of Sciences of the United States of America.

Climate Action Tracker. Global Update, September 2022. https://climateactiontracker.org/climate-target-update-tracker-2022/

DeConto, R., Pollard, D., Alley, R., Velicogna, I., Gasson, E., Gomez, N., . . . Dutton Andrea. (2021). The Paris Climate Agreement and future sea-level rise from Antarctica. Nature, 83–89.

Dutton, A., Carlson, A., Long, A., Milne, G., Clark, P., DeConto, R., . . . Raymon, M. (2015). Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science.

Grubler A, Wilson C, Bento N, et al., 2018, A low energy demand scenario for meeting the 1.5 degrees C target and sustainable development goals without negative emission technologies, *Nature Energy*, Vol:3, ISSN:2058-7546, Pages:515–527

Höhne N, den Elzen M, Rogelj J, et al., 2020, Emissions: world has four times the work or one-third of the time., *Nature*, Vol:579, ISSN:0028-0836, Pages:25–28

Hoepner AGF, Rogelj J, 2021, Emissions estimations should embed a precautionary principle, *Nature Climate Change*, Vol:11, ISSN:1758-678X, Pages:638–640

IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty[V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R.Shukla,A. Pirani, W. Moufouma-Okia, C.Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield(eds.)].

IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.

IPCC, 2022*: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

IPCC, 2023: *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35–115, doi: 10.59327/IPCC/AR6-9789291691647

Lamboll, R.D., Nicholls, Z.R.J., Smith, C.J. *et al.* Assessing the size and uncertainty of remaining carbon budgets. *Nat. Clim. Chang.* (2023). https://doi.org/10.1038/s41558-023-01848-5

Mengel M, Nauels A, Rogelj J, et al., 2018, Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action, *Nature Communications*, Vol:9, ISSN:2041-1723

Noël, B., Kampenhout, L. van, Lenaerts, J. T. M., Berg, W. J. van de, & Broeke, M. R. van den. (2021). A 21st Century Warming Threshold for Sustained Greenland Ice Sheet Mass Loss. *Geophysical Research Letters*, *48*(5). https://doi.org/10.1029/2020gl090471

Rogelj J, Popp A, Calvin KV, et al., 2018, Scenarios towards limiting global mean temperature increase below 1.5 degrees C, *Nature Climate Change*, Vol:8, ISSN:1758-678X, Pages:325-+

Rogelj J, Geden O, Cowie A, et al., 2021, Net-zero emissions targets are vague: three ways to fix, *Nature*, Vol:591, ISSN:0028-0836, Pages:365–368

CHAPTER 2

Ice Sheets and Sea-level Rise

2°C Risks Triggering Long-term Sea-level Rise and Loss of Coastlines on Massive Global Scale

Why 2°C is Too High for Ice Sheets: A compelling number of new studies, taking into account ice dynamics, paleo-climate records from Earth's past, and recent observations of ice sheet behavior, all point to a threshold for both Greenland and parts of Antarctica well below 2°C, committing the planet to between 12–20 meters sea-level rise if 2°C becomes the new constant Earth temperature. The most recent projections show a slow, but continuing pattern of sea-level rise (SLR) for many centuries even with "low emissions" (SSP1-2.6). This is an emissions pathway that peaks at 1.8°C and returns close to 1.6°C by 2100; yet the models show SLR continuing at this slow pace, indicating some level of ice loss has been irreversibly triggered even by this brief period of overshoot. Many ice sheet scientists now believe that by 2°C, nearly all of Greenland, much of West Antarctica, and even vulnerable portions of East Antarctica will be triggered to very long-term, inexorable sea-level rise, even if air temperatures later decrease. This is due to a warmer ocean that will hold heat longer than the atmosphere, plus a number of self-reinforcing feedback mechanisms, so that it takes much longer for ice sheets to regrow (tens of thousands of years) than to lose their ice.

Preserved at 1.5°C: Latest projections show that only "very low" emissions and the 1.5°C Paris limit reliably maintains both ice sheets, preventing massive long-term sea-level rise. The "very low" pathway (SSP1-1.9) means fossil fuel emissions decline 40% by 2030, and global temperature peaks at 1.6°C. Sea-level rise slows by 2100 because temperatures have declined to around 1.4°C, heading towards 1°C. There are clear indications that should the planet remain at 1.5°C for too long (several decades), sea-level rise from Greenland, West Antarctica and possibly even East Antarctica will continue for several millennia; in Earth's past, a 1.5°C global temperature resulted in sea levels 6–9 meters above today.

Today's Emissions Aiming Towards 3°C+: If atmospheric CO_2 continues to increase at today's pace, which has not paused despite current pledges, global temperatures will reach at least 3°C by the end of this century. Once 3°C is passed, ice loss from Greenland and West Antarctica may become extremely rapid. Together with extensive ice loss from parts of East Antarctica, annual sea-level rise may reach 5 cm per year by 2150. Three meters might be passed early in the 2100s, wiping out entire low-lying nations and coastlines; with five meters passed by 2200 and up to 15 m sea-level rise possible by 2300. While in the seeming far future, this massive scale of coastal inundation will have been made inevitable by decisions made in the next two decades causing temperatures to pass the critical 3°C threshold.

The 2°C Takeaway: 2°C will result in extensive, potentially rapid, irreversible sea-level rise from Earth's ice sheets; 3°C will further speed up this loss to within the next few centuries. If global leaders cause temperatures to reach this point through continued fossil emissions, they are committing the planet to extensive coastal loss and damage well beyond limits of feasible adaptation.

2023 Updates

- A new integrated model including the complex interactions between ice sheets, oceans and the atmosphere found that West Antarctica and Greenland will cross irreversible thresholds if global temperatures reach 1.8°C even temporarily, committing these ice sheets to increased ice loss and accelerating sea-level rise for several centuries. Only the very low greenhouse gas emissions scenario, with temperatures peaking around 1.6°C and leveling off below 1.5°C by the end of this century, avoids long-term acceleration of sea-level rise from the Earth's two great ice sheets. With high emissions, by 2150 Greenland is contributing about 1 cm/year SLR and Antarctica about 2 cm/year (3 cm/year total from ice sheets alone). Even though warming begins to slow after 2100 under medium and high emissions scenarios, ice sheet melting and related sea-level rise continue to accelerate.[46]
- A state-of-the-art model suggests that extensive West Antarctic ice shelf melting, including in regions crucial for maintaining ice sheet stability, is now inevitable, even with very low emissions. This is because water temperatures in the Amundsen Sea could be up to 2°C warmer than pre-industrial temperatures by 2100 even if atmospheric warming is held near 1.5°C, causing many buttressing ice shelves to melt and collapse. This means that the opportunity to preserve much of the West Antarctic Ice Sheet, with its potential 5 meters of sea-level rise, has probably passed. Its loss can be slowed, but not prevented entirely.[41]
- Between 1992 and 2022, the Earth's ice sheets lost 7,560 billion tons of ice: enough to cover the entire U.S. with a 1 m thick layer of ice. The seven worst years of ice loss have all occurred in the last decade. If the recent observed acceleration of loss in Greenland were to continue, it would track above the upper range predicted by the IPCC (2021) for this decade.[44]
- Thwaites Glacier, the keystone of the West Antarctic Ice Sheet, may be more sensitive to warm ocean waters than previously estimated. The water driving present-day ice loss is actually cooler than expected given today's high retreat rate, demonstrating that even moderately warm water can trigger instability.[16,55] Thwaites has retreated at twice its current rate in the past, highlighting its potential for pulses of rapid loss and correspondingly rapid sea level rise in future.[25]
- Long-term sediment records from Pine Island and Thwaites glaciers show that ice loss rates observed today are unprecedented within the last 11,000 years.[14] Irreversible collapse in the Amundsen Sea Embayment sector of West Antarctica appears not yet inevitable, but even current forcing may be sufficient to force irreversible retreat if today's temperatures are sustained.[31,50]
- Increasing meltwater discharge from Antarctica could reduce the strength of the Antarctic overturning circulation by more than 40% by 2050, potentially leading to the collapse of this important ocean conveyor system. The resulting subsurface warming would lead to further ice shelf collapse, ice sheet loss and resulting sea-level rise in a region that is already vulnerable.[36]
- Observations have revealed that mid-depth Circumpolar Deep Water has warmed by up to 2°C over the last few decades off parts of East Antarctica, a trend which is likely to persist into the 21st Century.[30] Mass loss in this region, known as Wilkes Land, is now ten times higher than it was a decade ago.[62] Furthermore, the third fastest grounding line retreat anywhere in Antarctica is currently in Wilkes Land, suggesting that the same processes driving mass loss in West Antarctica are now also impacting East Antarctica.[48]

continued on next page

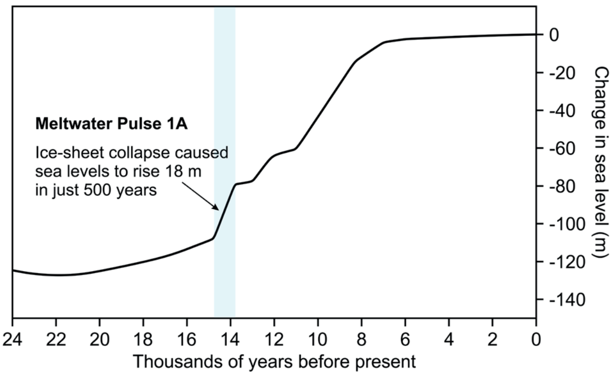
Only the very low greenhouse gas emissions scenario, with temperatures peaking around 1.6°C and leveling off below 1.5 °C by the end of this century, avoids long-term acceleration of sea-level rise.

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 preindustrial levels has reshaped the Earth's coastlines in the past due to extensive melting of the West Antarctic Ice Sheet (WAIS), Greenland[4,32] and by 1.5°C, possibly parts of East Antarctica.[61] While some of these changes occurred very slowly in the past, over thousands of years, there have also been periods where extremely rapid sea level rise (around 3.5 to 4 meters per century) has occurred due to rapid ice sheet collapse. Termed "meltwater pulses," the last of these events took place around 14,500 years ago when vulnerable sectors of Antarctica and the ice sheets which used to cover North America and Scandinavia collapsed, causing global sea levels to rise by 12–18 meters in about 350 years.[21,37]

The observed human-induced global temperature increase over the past few decades is much faster than anything documented in Earth's past. CO_2 increase in the last 50 years is 200 times greater than during the end of the last Ice Age. This means that future rates of ice sheet loss and sea-level rise (SLR) could increase even further beyond the acceleration that has already been observed over the last few decades, and could potentially be more rapid than at any other time in the past 130,000 years.[59] The latest investigations of ice sheet behavior, especially

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



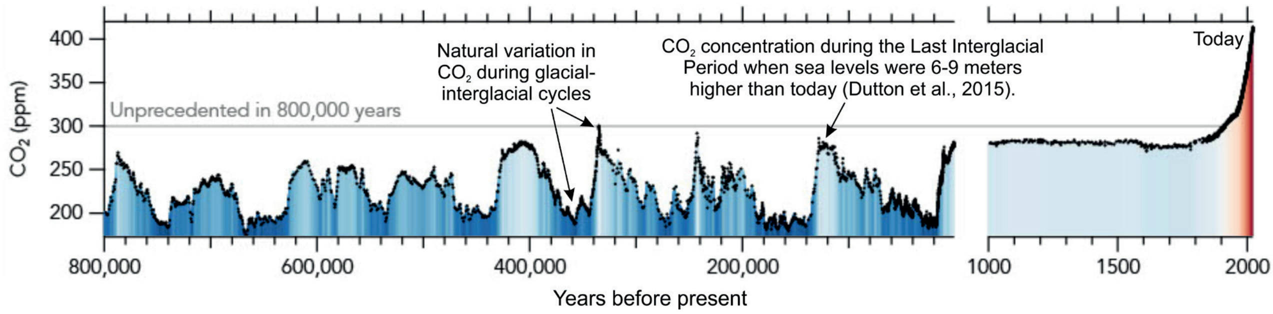
Over just ≈350 years, sea levels rose by 18 meters (3.5 to 4 meters per century). This massive sea-level rise probably came mostly from melt of the Laurentide Ice Sheet then covering Canada; but shows an ice sheet can collapse quite quickly.

ADAPTED FROM ROBERT A. RODE FROM PUBLISHED DATA

2023 UPDATES (CONTINUED)

- New ocean sediment records indicate that parts of the East Antarctic Ice Sheet contributed 40 to 80 cm (and possibly more) to sea-level rise during the Last Interglacial (130,000–115,000 years ago), further highlighting the vulnerability of the marine-based sectors of this ice sheet at temperatures similar to today.[33]
- The occurrence and severity of extreme events in Antarctica, such as heatwaves, all-time low sea ice conditions, ice shelf collapse, and species population crashes, appear to be increasing and will continue to do so unless radical action is taken to reduce greenhouse gas emissions to net zero by 2050.[58]
- The frequency and intensity of extreme events is also increasing over Greenland. Rainfall on the Greenland Ice Sheet has grown by a third since 1991, and the frequency of extreme deluges are increasing.[9] Water quickly drains into the ice sheet through vast networks of micro-cracks that may run hundreds of meters deep, carrying surface water to deeper parts of the ice sheet and melting it from within.[12] These extreme melt events may increase sea level rise projections from Greenland by up to 14% over previous worse-case scenarios by the year 2300,[7] contributing as much as 3.74 meters to global sea-level rise.
- Evidence from ancient soil recovered from beneath today's ice sheet in northwest Greenland shows that 400,000 years ago, the ice sheet retreated over 200 km inland, causing at least 1.4 m sea-level rise from this section of Greenland alone, when CO_2 concentrations were only 280 ppm (1.5 times less than today). This period of moderate warming, similar to today, persisted for 30,000 years. More likely, however, is that nearly the entire Greenland ice sheet melted at that time.[13]
- Overall: continued improvements in numerical modeling and scientific understanding of ice sheet processes shows that the Greenland and Antarctica ice sheets are more sensitive to warming than previously thought, and have the potential to release greater and more rapid sea-level rise and at lower global mean temperatures than previously estimated.

FIGURE 2-2. **Ice Sheets and CO_2**



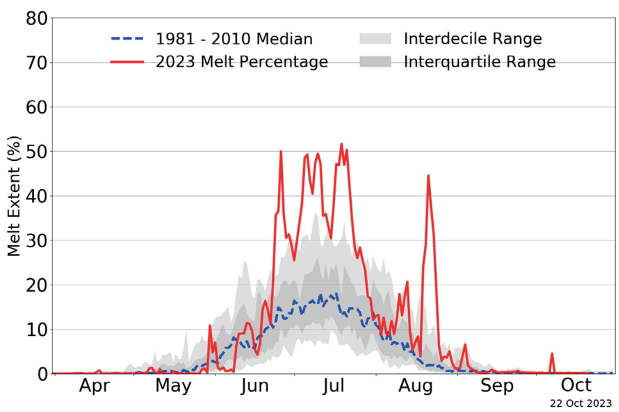
Current atmospheric CO_2 concentrations are unprecedented in over 800,000 years and far beyond any natural variation. Even during past warm periods, CO_2 never exceeded 300 ppm; in 2023, it reached 424ppm. Data is from gases trapped within Antarctic ice cores.

SOURCE: BRITISH ANTARCTIC SURVEY, ICE CORE DATA

interactions between the ice and the warming oceans that surround them, informs us that ice sheet collapse and rapid sea-level rise cannot be ruled out[5,15,17,18,57] especially if peak warming exceeds 2°C. This is especially the case for the WAIS: some studies show that the threshold for WAIS collapse may already have been passed at around 0.8°C above pre-industrial,[34,41,52] although the WAIS could hold stable for some centuries prior to collapse unless further warming occurs.[50] Even if ice sheet loss is inevitable once thresholds are crossed, this can be slowed to take place over longer timescales if temperatures remain close to 1.5°C, with an aim to return below that level as soon as possible. This would give coastal communities greater time to adapt to rising sea levels.

Greenland may contribute 3.74 meters to global sea-level rise by 2300 with high emissions.

FIGURE 2-3. **Greenland Surface Melt Extent in 2023**



Total 2023 surface melt was the second highest in the 45-year satellite record, at over 30 million square kilometers.

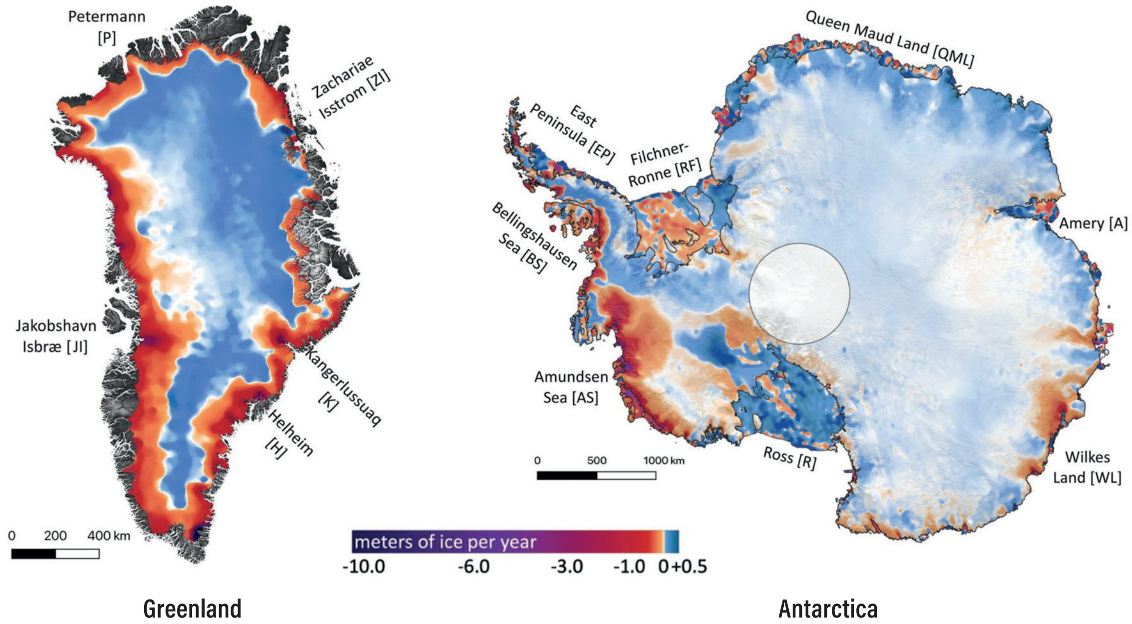
SOURCE: NSIDC (2023)

There is strong consensus that the risk of extensive melting from ice sheets increases as both the peak in global temperatures and the rate of warming rise. The massive Greenland and Antarctic ice sheets consist of compressed snow that fell, in the oldest sections, over a million years ago. In equilibrium, the calving of icebergs and outflow of meltwater into the ocean are balanced by mass gain via snowfall. Observations now confirm that this equilibrium has been lost on Greenland, the WAIS, and the Antarctic Peninsula; and potentially for portions of the tentimes-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 around 130 meters lower than it is today. During periods of warming, when the ice sheets lost mass, sea level rose accordingly, with clear evidence of meltwater pulses (noted above) largely as a result of catastrophic collapse of the Laurentide Ice Sheet over North America.[28,37]

Antarctic ice shelves also play an important role in ice loss because they hold back, or "buttress," the ice upstream. Loss of this buttressing effect through ice shelf thinning and break-up can accelerate the rate of ice flow from the land into the sea.[51] From 1997 to 2021, Antarctic ice shelves experienced a net loss of 36,701 ± 1,465 km², equal to the size of the country Guinea-Bissau.[27] Antarctic ice shelf thinning has also accelerated over recent decades, driven by the intrusion of warmer ocean currents.[45,49] Reduced ice-shelf buttressing driven by such

FIGURE 2-4. **Current Ice Loss Regions – Greenland and Antarctica**



Both ice sheets are overall losing mass at record levels.

SOURCE: SMITH ET AL. (2020)

A compelling number of new studies all point to a threshold for both Greenland and parts of Antarctica well below 2°C.

warm ocean incursions accounts for a significant portion of Antarctic mass loss[29,60] and could drive increasingly significant sea-level rise in the future.[6,27,41,51]

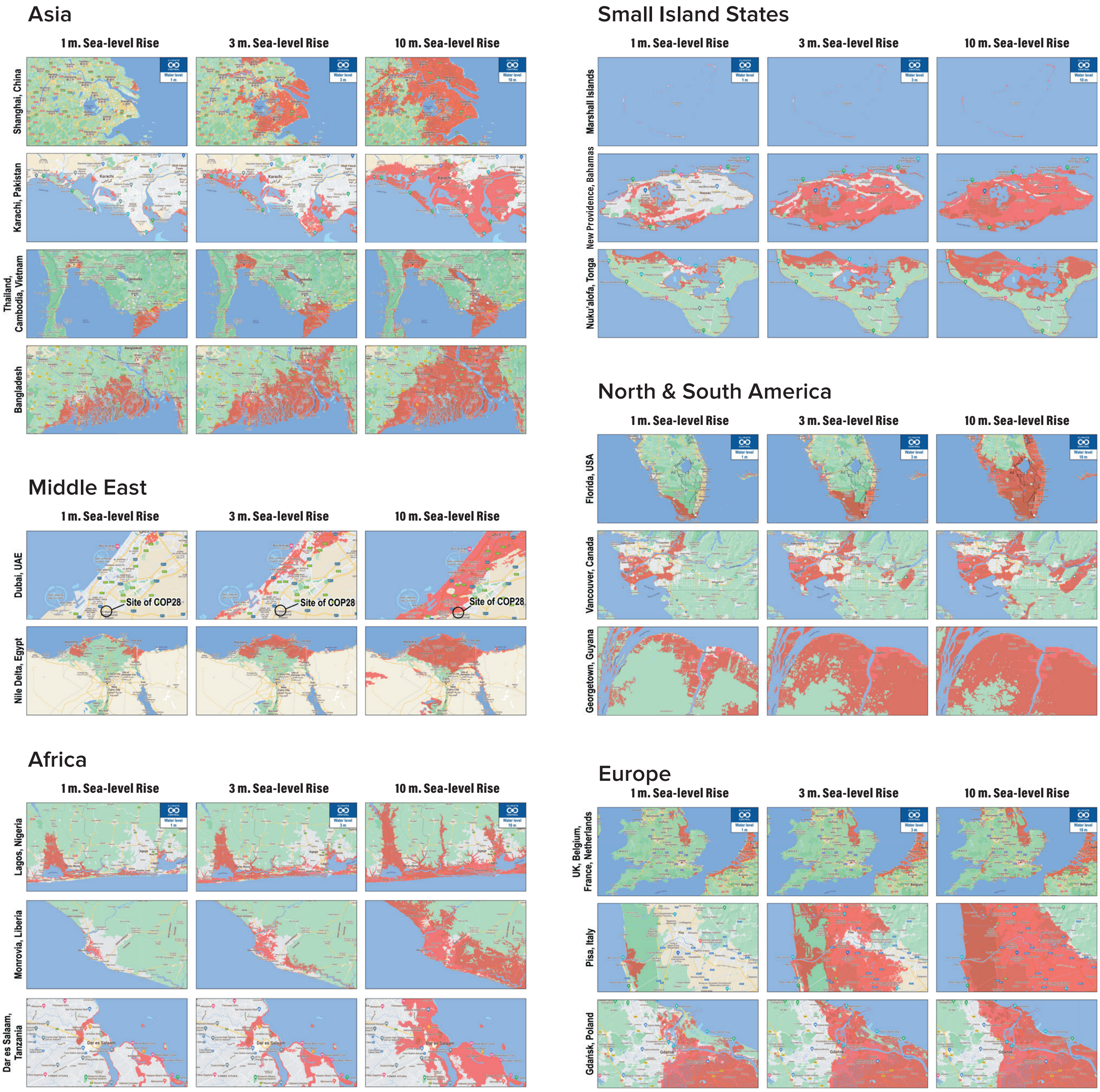
Ice sheets in Greenland and (parts of) Antarctica have certain thresholds where irreversible melt becomes inevitable and, in the case of the WAIS and Greenland Ice Sheet, potentially rapid.[17,25,39,54] In Earth's past, several of these thresholds have occurred somewhere between 1 and 2 degrees of warming: about 1°C for the WAIS and Antarctic Peninsula (containing about 5 meters SLR); and between 1.5°C and 2°C for Greenland (approximately 7 meters SLR). (It should be noted that changes around past thresholds were driven by slow increases in atmospheric greenhouse gases but were paced by slow changes in Earth's orbit - unlike today's rapid, human-caused rates of change.) Parts of East Antarctica, especially the massive Wilkes and Aurora Basins (at least 8 meters of potential SLR), may also have a threshold around or just beyond 2°C.[3,61]

Because of the existence of these thresholds, when temperatures reached 2°C above pre-industrial in the Earth's past, sea levels peaked at around 12–20 meters higher than present-day levels. During the height of the Pliocene 3 million years ago, when CO_2 levels were comparable to today and temperatures stabilized at 2–3°C higher than pre-industrial, sea levels may have peaked at around 20 meters higher than today's.[19,20,26,40] Such extensive sea level rise would be catastrophic for today's coastal communities — yet we are currently on track for even higher temperature peaks than those that drove these past sea level rises.

Greenland responds in a more linear manner (more predictably) to increasing atmospheric temperatures. The Greenland Ice Sheet is over 3000 m thick in places and above 3000 m altitude in its interior. If the height of this ice sheet is lowered through surface melting and ice flow into the oceans, it eventually becomes exposed to above-freezing temperatures for longer time periods throughout the year, leading to the eventual unstoppable loss of most of the ice sheet.[2,8,11,24,35] The first recorded rain at the highest point of Greenland, Summit Station, occurred in August 2021 and lasted several days. Rainfall on the Greenland Ice Sheet has increased by 33% since 1991, and the frequency of extreme deluges is increasing.[9] These deluges drain quickly into the ice sheet through vast networks of micro-cracks that may run hundreds of

FIGURE 2-5. **Ice Sheets and Sea-level Rise: Our Decisions, Our Children's Future**

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



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

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

meters deep, carrying warm surface water to the interior of the ice sheet where it heats the ice internally, melting the ice sheet from within.[12] Evidence from ancient soil recovered from beneath the modern-day northwest Greenland shows that the ice sheet retreated over 200 km inland of its present position and caused 1.4 m of sea level rise when CO_2 concentrations of only 280 ppm (1.5 times less than today) were sustained for 30,000 years in the past.[13]

The WAIS is a very different story: much of it does not really sit over land, but rather over island archipelagoes separated by extremely deep (>2.5 km below sea level) and vast basins.[1,22] Much of its ice rests on a bed that slopes downwards toward its center. As warm water melts the marine edges of the WAIS, the ice retreats over these ever-deeper ocean basins. This exposes more and more of the underside of the ice sheet to warming waters, rapidly forcing further melting and eventually causing the ice sheet to become unstable. These processes may cause very rapid ice-sheet loss and resulting sea-level rise over just a few centuries. Indeed, Thwaites Glacier has experienced pulses of rapid retreat in the past in which the glacier stepped back at rates of over 2.1 km per year — twice the fastest rate observed between 2011 and 2019.[25] Comparably fast rates are expected to occur in the near future when the glacier migrates off stabilizing high points on the seafloor on which it currently sits.[25] 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.[38] Recent work also suggests that although the East Antarctic Ice Sheet was once considered relatively stable, parts of this vast ice sheet resemble vulnerable West Antarctic sectors, and could contribute substantially to sea level rise if temperatures rise above 1.8°C.[61]

Ice sheets have other global impacts in addition to sea-level rise. They influence both atmospheric and ocean circulation at high latitudes and globally, which transfer heat around the planet. Changes in the height and extent of Earth's ice sheets, together with the incursion of new cold and fresh water into ocean currents from ice sheet melt, cause changes in weather patterns near the poles and at lower latitudes. Additionally, these circulation systems affect nutrient supplies in marine ecosystems. Recent studies suggest that increasing meltwater discharge from Antarctica could reduce the strength of the Antarctic overturning circulation by more than 40% by 2050, potentially leading to collapse. The resulting subsurface warming would lead to an amplifying feedback in West Antarctica, leading to further ice shelf melting and sea-level rise in a region that is already vulnerable to irreversible retreat.[36]

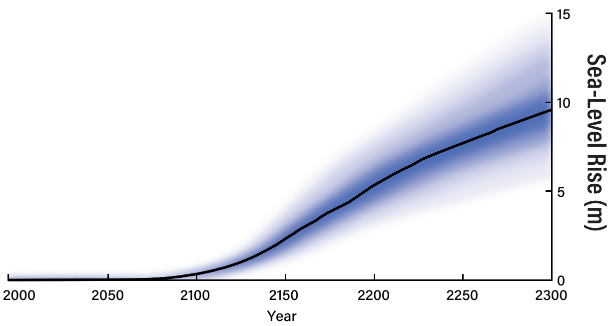
Continued fossil emissions are committing the planet to extensive coastal loss and damage well beyond limits of feasible adaptation.

The main questions for scientists and policy makers are (1) what is the future rate of sea level change? (2) how high will sea level go? and (3) at what point do future higher sea levels become locked in? In general, scientists agree that higher temperatures, sustained for longer periods of time, will result in both faster melt and more rapid rates of sea-level rise. This could be as much as 5 cm a year from Antarctica by 2150 should today's emissions continue, and cause temperature rise to exceed 3–4°C by 2100.[18]

A key message for policy makers and coastal communities is that once ice sheet melt accelerates due to higher temperatures, it cannot be stopped or reversed for many thousands of years, even once temperatures stabilize or even decrease with so-called net-zero emissions and/or carbon dioxide removal (CDR). Ice core and sea level records clearly show that it takes tens of thousands of years to grow an ice sheet, but two orders of magnitude less (100x less) time to shrink one. Sea level lowering from these new highs will not occur until temperatures go well below pre-industrial, initiating a slow ice sheet re-growth.[23] Overshooting the Paris Agreement goals would therefore cause essentially permanent loss and damage to the Earth's ice sheets, with widespread impacts that are not reversible on human time scales.

Regardless of the uncertainties surrounding the rates of future melt, we know that Greenland ice loss today is three times what it was 20 years ago, and Antarctica's contribution to sea level rise is six times greater than it was 30 years ago.[42,52,53,56,58] For a growing number

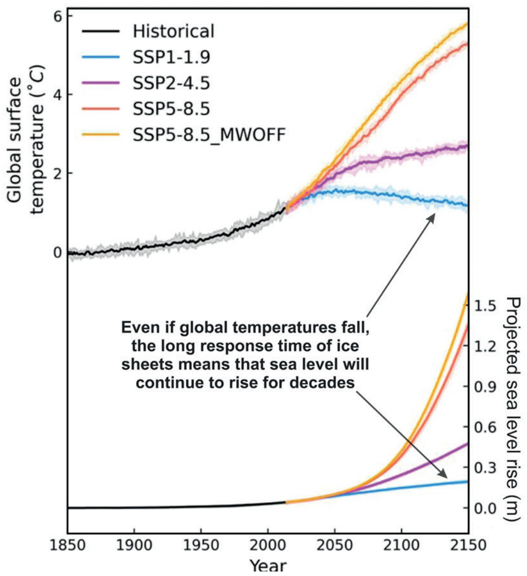
FIGURE 2-6. **Sea-level Rise from Antarctica If Today's Emissions Continue**



New models, including potential ice sheet collapse mechanisms, project high and irreversible sea-level rise from Antarctica with very high emissions; growing at exponential rates past 2°C and especially, past 3°C.

SOURCE: DECONTO ET AL. (2021)

FIGURE 2-7. **Projected Sea-level rise by 2150 with Different Emissions Pathways**



Even under "low emissions," where global temperatures peak at 1.8°C and then fall (purple line, SSP2-4.5), sea-level rise continues accelerating. Only "very low" fossil fuel emissions that peak before 2030 (blue line, peak temperature 1.6°C, SSP1-1.9) would slow and stabilize sea-level rise, preserving many coastal communities and giving others time to adapt.

SOURCE: PARK ET AL. (2023)

of ice sheet experts, the true "guardrail" to prevent dangerous levels and rates of sea-level rise is not 2°C or even 1.5°C, but 1°C above pre-industrial;[10,43,47] note that we are currently 1.2°C above pre-industrial. A key argument therefore in favor of very low emissions is that staying close to the 1.5°C limit will allow us to return more quickly to the 1°C level, drastically slowing global impacts from ice sheet loss and especially WAIS collapse.[63] This would reduce the risk of locking in significant amounts of long-term, irreversible sea-level rise. This will help to provide low-lying nations and communities more time to adapt through sustainable development, although some level of managed retreat from coastlines in the long term is tragically inevitable.

The decisions made by policymakers today on future emissions of greenhouse gases will determine the rate of future sea-level rise and associated risks to security and development for centuries to millennia to come. To maintain the possibility of staying below 1.5°C, CO_2 emissions must be at least halved by 2030, and reduced to zero by mid-century. Otherwise, world leaders are *de facto* making a decision to erase many coastlines, displacing hundreds of millions of people – perhaps much sooner than we think.

Decisions made by policymakers today on future emissions of greenhouse gases will determine the rate of future sea-level rise.

SCIENTIFIC REVIEWERS

Richard B. Alley, Pennsylvania State University, IPCC AR2, AR3, AR4

Jonathan Bamber, University of Bristol, IPCC AR6 WG1, AR5 Review Editor, AR4 Review Editor

Julie Brigham-Grette, University of Massachusetts-Amherst

Robert DeConto, University of Massachusetts-Amherst, IPCC SROCC

Andrea Dutton, University of Wisconsin-Madison, IPCC SROCC

Carlota Escutia, Spanish High Council for Scientific Research and University of Granada

Carl-Friedrich Schleussner, Climate Analytics

Martin Siegert, University of Exeter

Michael Schaeffer, IPCC AR5 LA, Global Center on Adaptation, IPCC AR5

Chris Stokes, Durham University

[Roderik van de Wal, Utrecht University, IPCC AR3, AR4, AR5 Review Editor, SROCC]

LITERATURE AND ADDITIONAL READING

1. Alley, R.B., et al. (2015). Oceanic Forcing of Ice-Sheet Retreat: West Antarctica and More. Annual Review of Earth and Planetary Sciences, v. 43, no, 1, 207–231, https://doi.org/10.1146/annurev-earth-060614-105344.
2. Applegate, P.J., et al. (2015). Increasing temperature forcing reduces the Greenland Ice Sheet's response time scale. Climate Dynamics, v. 45, no, 7, 2001–2011, https://doi.org/10.1007/s00382-014-2451-7.
3. Armstrong McKay, D.I., et al. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science, v. 377, no, 6611, eabn7950, https://doi.org/doi:10.1126/science.abn7950.
4. Aschwanden, A., et al. (2019). Contribution of the Greenland Ice Sheet to sea level over the next millennium. Science Advances, v. 5, no, 6, eaav9396, https://doi.org/10.1126/sciadv.aav9396.
5. Bamber, J.L., et al. (2019). Ice sheet contributions to future sea-level rise from structured expert judgment. Proceedings of the National Academy of Sciences, v. 116, no, 23, 11195–11200, https://doi.org/doi:10.1073/pnas.1817205116.
6. Banwell, A.F., et al. (2021). The 32-year record-high surface melt in 2019/2020 on the northern George VI Ice Shelf, Antarctic Peninsula. The Cryosphere, v. 15, no, 2, 909–925, https://doi.org/10.5194/tc-15-909-2021.
7. Beckmann, J. and R. Winkelmann (2023). Effects of extreme melt events on ice flow and sea level rise of the Greenland Ice Sheet. The Cryosphere, v. 17, no, 7, 3083–3099, https://doi.org/10.5194/tc-17-3083-2023.

8. Boers, N. and M. Rypdal (2021). Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point. Proceedings of the National Academy of Sciences, v. 118, no, 21, e2024192118, https://doi.org/doi:10.1073/pnas.2024192118.
9. Box, J.E., et al. (2023). Greenland ice sheet rainfall climatology, extremes and atmospheric river rapids. Meteorological Applications, v. 30, no, 4, e2134, https://doi.org/https://doi.org/10.1002/met.2134.
10. Breyer, C., et al. (2023). Proposing a 1.0° C climate target for a safer future. PLOS Climate, v. 2, no, 6, e0000234.
11. Briner, J.P., et al. (2020). Rate of mass loss from the Greenland Ice Sheet will exceed Holocene values this century. Nature, v. 586, no, 7827, 70–74, https://doi.org/10.1038/s41586-020-2742-6.
12. Chandler, D.M. and A. Hubbard (2023). Widespread partial-depth hydrofractures in ice sheets driven by supraglacial streams. Nature Geoscience, v. 16, no, 7, 605–611, https://doi.org/10.1038/s41561-023-01208-0.
13. Christ, A.J., et al. (2023). Deglaciation of northwestern Greenland during Marine Isotope Stage 11. Science, v. 381, no, 6655, 330–335, https://doi.org/doi:10.1126/science.ade4248.
14. Clark, R.W., et al. (In Press). Synchronous retreat of Thwaites and Pine Island glaciers in response to external forcings in the presatellite era. Proceedings of the National Academy of Sciences.
15. Crawford, A.J., et al. (2021). Marine ice-cliff instability modeling shows mixed-mode ice-cliff failure and yields calving rate parameterization. Nature Communications, v. 12, no, 1, https://doi.org/10.1038/s41467-021-23070-7.
16. Davis, P.E.D., et al. (2023). Suppressed basal melting in the eastern Thwaites Glacier grounding zone. Nature, v. 614, no, 7948, 479–485, https://doi.org/10.1038/s41586-022-05586-0.
17. DeConto, R.M. and D. Pollard (2016). Contribution of Antarctica to past and future sea-level rise. Nature, v. 531, no, 7596, 591–597, https://doi.org/10.1038/nature17145.
18. DeConto, R.M., et al. (2021). The Paris Climate Agreement and future sea-level rise from Antarctica. Nature, v. 593, no, 7857, 83–89, https://doi.org/10.1038/s41586-021-03427-0.
19. Dumitru, O.A., et al. (2019). Constraints on global mean sea level during Pliocene warmth. Nature, v. 574, no, 7777, 233–236, https://doi.org/10.1038/s41586-019-1543-2.
20. Dutton, A., et al. (2015). Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science, v. 349, no, 6244, aaa4019, https://doi.org/doi:10.1126/science.aaa4019.
21. Fairbanks, R.G. (1989). A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature, v. 342, no, 6250, 637–642, https://doi.org/10.1038/342637a0.
22. Feldmann, J. and A. Levermann (2015). Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin. Proceedings of the National Academy of Sciences, v. 112, no, 46, 14191–14196, https://doi.org/10.1073/pnas.1512482112.
23. Garbe, J., et al. (2020). The hysteresis of the Antarctic Ice Sheet. Nature, v. 585, no, 7826, 538–544, https://doi.org/10.1038/s41586-020-2727-5.
24. Goelzer, H., et al. (2020). The future sea-level contribution of the Greenland ice sheet: a multi-model ensemble study of ISMIP6. The Cryosphere, v. 14, no, 9, 3071–3096, https://doi.org/10.5194/tc-14-3071-2020.
25. Graham, A.G.C., et al. (2022). Rapid retreat of Thwaites Glacier in the pre-satellite era. Nature Geoscience, https://doi.org/10.1038/s41561-022-01019-9.
26. Grant, G.R., et al. (2019). The amplitude and origin of sea-level variability during the Pliocene epoch. Nature, v. 574, no, 7777, 237–241, https://doi.org/10.1038/s41586-019-1619-z.
27. Greene, C.A., et al. (2022). Antarctic calving loss rivals ice-shelf thinning. Nature, v. 609, no, 7929, 948–953, https://doi.org/10.1038/s41586-022-05037-w.
28. Gregoire, L.J., A.J. Payne, and P.J. Valdes (2012). Deglacial rapid sea level rises caused by ice-sheet saddle collapses. Nature, v. 487, no, 7406, 219–222, https://doi.org/10.1038/nature11257.
29. Gudmundsson, G.H., et al. (2019). Instantaneous Antarctic ice sheet mass loss driven by thinning ice shelves. Geophysical Research Letters, v. 46, no, 23, 13903–13909, https://doi.org/https://doi.org/10.1029/2019GL085027.
30. Herraiz-Borreguero, L. and A.C. Naveira Garabato (2022). Poleward shift of Circumpolar Deep Water threatens the East Antarctic Ice Sheet. Nature Climate Change, v. 12, no, 8, 728–734, https://doi.org/10.1038/s41558-022-01424-3.
31. Hill, E.A., et al. (2023). The stability of present-day Antarctic grounding lines – Part 1: No indication of marine ice sheet instability in the current geometry. The Cryosphere, v. 17, no, 9, 3739–3759, https://doi.org/10.5194/tc-17-3739-2023.
32. Hofer, S., et al. (2020). Greater Greenland Ice Sheet contribution to global sea level rise in CMIP6. Nature Communications, v. 11, no, 1, 6289, https://doi.org/10.1038/s41467-020-20011-8.
33. Iizuka, M., et al. (2023). Multiple episodes of ice loss from the Wilkes Subglacial Basin during the Last Interglacial. Nature Communications, v. 14, no, 1, 2129, https://doi.org/10.1038/s41467-023-37325-y.
34. Joughin, I., B.E. Smith, and B. Medley (2014). Marine ice sheet collapse potentially under way for the Thwaites Glacier basin, West Antarctica. Science, v. 344, no, 6185, 735–738, https://doi.org/10.1126/science.1249055.
35. Khan, S.A., et al. (2020). Centennial response of Greenland's three largest outlet glaciers. Nature Communications, v. 11, no, 1, 5718, https://doi.org/10.1038/s41467-020-19580-5.
36. Li, Q., et al. (2023). Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. Nature, v. 615, no, 7954, 841–847, https://doi.org/10.1038/s41586-023-05762-w.
37. Lin, Y., et al. (2021). A reconciled solution of Meltwater Pulse 1A sources using sea-level fingerprinting. Nature Communications, v. 12, no, 1, 2015, https://doi.org/10.1038/s41467-021-21990-y.
38. Morlighem, M., et al. (2019). Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet. Nature Geoscience, v. 13, no, 2, 132–137, https://doi.org/10.1038/s41561-019-0510-8.
39. Mouginot, J., et al. (2015). Fast retreat of Zachariæ Isstrøm, northeast Greenland. Science, v. 350, no, 6266, 1357–1361, https://doi.org/doi:10.1126/science.aac7111.
40. Naish, T., et al. (2009). Obliquity-paced Pliocene West Antarctic ice sheet oscillations. Nature, v. 458, no, 7236, 322–328, https://doi.org/10.1038/nature07867.
41. Naughten, K.A., P.R. Holland, and J. De Rydt (2023). Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century. Nature Climate Change, https://doi.org/10.1038/s41558-023-01818-x.
42. Naughten, K.A., et al. (2022). Simulated Twentieth-Century Ocean Warming in the Amundsen Sea, West Antarctica. Geophysical Research Letters, v. 49, no, 5, e2021GL094566, https://doi.org/https://doi.org/10.1029/2021GL094566.
43. Noël, B., et al. (2021). A 21st Century Warming Threshold for Sustained Greenland Ice Sheet Mass Loss. Geophysical Research Letters, v. 48, no, 5, e2020GL090471, https://doi.org/https://doi.org/10.1029/2020GL090471.
44. Otosaka, I.N., et al. (2023). Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. Earth Syst. Sci. Data, v. 15, no, 4, 1597–1616, https://doi.org/10.5194/essd-15-1597-2023.

45. Paolo, F.S., H.A. Fricker, and L. Padman (2015). Volume loss from Antarctic ice shelves is accelerating. Science, v. 348, no, 6232, 327–331, https://doi.org/doi:10.1126/science.aaa0940.
46. Park, J.-Y., et al. (2023). Future sea-level projections with a coupled atmosphere-ocean-ice-sheet model. Nature Communications, v. 14, no, 1, 636, https://doi.org/10.1038/s41467-023-36051-9.
47. Pattyn, F., et al. (2018). The Greenland and Antarctic ice sheets under 1.5°C global warming. Nature Climate Change, v. 8, no, 12, 1053–1061, https://doi.org/10.1038/s41558-018-0305-8.
48. Picton, H.J., et al. (2022). Extensive and anomalous grounding line retreat at Vanderford Glacier, Vincennes Bay, Wilkes Land, East Antarctica. The Cryosphere Discuss., v. 2022, 1–40, https://doi.org/10.5194/tc-2022-217.
49. Pritchard, H.D., et al. (2012). Antarctic ice-sheet loss driven by basal melting of ice shelves. Nature, v. 484, no, 7395, 502–505, https://doi.org/10.1038/nature10968.
50. Reese, R., et al. (2023). The stability of present-day Antarctic grounding lines – Part 2: Onset of irreversible retreat of Amundsen Sea glaciers under current climate on centennial timescales cannot be excluded. The Cryosphere, v. 17, no, 9, 3761–3783, https://doi.org/10.5194/tc-17-3761-2023.
51. Reese, R., et al. (2018). The far reach of ice-shelf thinning in Antarctica. Nature Climate Change, v. 8, no, 1, 53–57, https://doi.org/10.1038/s41558-017-0020-x.
52. Rignot, E., et al. (2014). Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. Geophysical Research Letters, v. 41, no, 10, 3502–3509, https://doi.org/10.1002/2014gl060140.
53. Rignot, E., et al. (2019). Four decades of Antarctic Ice Sheet mass balance from 1979–2017. Proceedings of the National Academy of Sciences of the United States of America, v. 116, no, 4, 1095–1103, https://doi.org/10.1073/pnas.1812883116.
54. Rosier, S.H.R., et al. (2021). The tipping points and early warning indicators for Pine Island Glacier, West Antarctica. The Cryosphere, v. 15, no, 3, 1501–1516, https://doi.org/10.5194/tc-15-1501-2021.
55. Schmidt, B.E., et al. (2023). Heterogeneous melting near the Thwaites Glacier grounding line. Nature, v. 614, no, 7948, 471–478, https://doi.org/10.1038/s41586-022-05691-0.
56. Selley, H.L., et al. (2021). Widespread increase in dynamic imbalance in the Getz region of Antarctica from 1994 to 2018. Nature Communications, v. 12, no, 1, 1133, https://doi.org/10.1038/s41467-021-21321-1.
57. Siegert, M., et al. (2020). Twenty-first century sea-level rise could exceed IPCC projections for strong-warming futures. One Earth, v. 3, no, 6, 691–703.
58. Siegert, M.J., et al. (2023). Antarctic extreme events. Frontiers in Environmental Science, v. 11, https://doi.org/10.3389/fenvs.2023.1229283.
59. Slater, T., A.E. Hogg, and R. Mottram (2020). Ice-sheet losses track high-end sea-level rise projections. Nature Climate Change, v. 10, no, 10, 879–881, https://doi.org/10.1038/s41558-020-0893-y.
60. Smith, J.A., et al. (2017). Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier. Nature, v. 541, no, 7635, 77–80, https://doi.org/10.1038/nature20136.
61. Stokes, C.R., et al. (2022). Response of the East Antarctic Ice Sheet to past and future climate change. Nature, v. 608, no, 7922, 275–286, https://doi.org/10.1038/s41586-022-04946-0.
62. Wang, L., J.L. Davis, and I.M. Howat (2021). Complex Patterns of Antarctic Ice Sheet Mass Change Resolved by Time-Dependent Rate Modeling of GRACE and GRACE Follow-On Observations. Geophysical Research Letters, v. 48, no, 1, e2020GL090961, https://doi.org/https://doi.org/10.1029/2020GL090961.
63. Winkelmann, R., et al. (2015). Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet. Science Advances, v. 1, no, 8, e1500589, https://doi.org/doi:10.1126/sciadv.1500589.
64. Dumitru, O.A, Austermann, J., Polyak, V.J., Fornos, J.J., Asmerom,Y., Gines, J. Constraints on global mean sea level during Pliocene warmth. Nature, 574:233–236, 2019.
65. Dutton, A., Carlson, A., Long, A., Milne, G., Clark, P., DeConto, R., … Raymon, M. Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science, 2015.
66. Dvorak, M.T., Armour, K.C., Frierson, D.M.W. et al. Estimating the timing of geophysical commitment to 1.5 and 2.0°C of global warming. Nat. Clim. Chang, 12:547–552, 2022.
67. Edwards, T. L., Nowicki, S., Marzeion, B., Hock, R., Goelzer, H., Seroussi, H., et al. Projected land ice contributions to twenty-first-century sea level rise. Nature, 593(7857):74–82, 2021.
68. Etourneau, J., Sgubin, G., Crosta, X., Swingedouw, D., Willmott, V., Barbara, L., … Kim, J.-H. Ocean temperature impact on ice shelf extent in the eastern Antarctic Peninsula. Nature Communications, 2019.
69. Feldmann, J., Levermann, A. Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin. Proceedings of the National Academy of Sciences of the United States of America, pages 14191–14196, 2015.
70. Gilbert, E., Kittel, C. Surface Melt and Runoff on Antarctic Ice Shelves at 1.5°C, 2°C, and 4°C of Future Warming. Geophysical Research Letters., 2021.
71. Goelzer, H., Nowicki, S., Payne, A., Larour, E., Seroussi, H., Lipscomb, W., … van den Broeke, M. The future sea-level contribution of the Greenland ice sheet: a multi-model ensemble study of ISMIP6. The Cryosphere, pages 3071–3096, 2020.
72. Golledge, N., Lowry, D. Is the marine ice cliff hypothesis collapsing? Science, pages 1266–1267, 2021.
73. Golledge, N. R., Clark, P. U., He, F., Dutton, A., Turney, C. S. M., Fogwill, C. J. …. Retreat of the Antarctic Ice Sheet during the Last Interglaciation and implications for future change. Geophysical Research Letters, 48 (e2021GL094513), 2021.
74. Gonzalez-Herrero, S., Barriopedro, D., Trigo, R.M. et al. Climate warming amplified the 2020 record-breaking heatwave in the Antarctic Peninsula. Commun Earth Environ, 3(122), 2022.
75. Grant, G.R., Naish, T. R., Dunbar, G.D., Stocchi, P., … Patterson, M.O. The Amplitude and origin of sea level variability during the Pliocene Epoch. Nature, 574:237–241, 2019.
76. Greenbaum, J., Blankenship, D., Young, D., Richter, T., Roberts, J., Aitken, A., … Siegert, M. Ocean access to a cavity beneath Totten Glacier in East Antarctica. Nature Geoscience, pages 294–298, 2015.
77. Greene, Chad A. and Gardner, Alex S. and Schlegel, Nicole-Jeanne and Fraser, Alexander D. Antarctic calving loss rivals ice-shelf thinning. Nature, 609(7929):948–953, 2022.
78. Grinsted, A., Hesselbjerg Christensen, J. The transient sensitivity of sea level rise. Ocean Science Letters, pages 181–186, 2021.
79. Gudmundsson, G.H. and Paolo, F.S. and Adusumilli, S. and Fricker, H.A. Instantaneous Antarctic ice sheet mass loss driven by thinning ice shelves. Geophysical Research Letters, 46(23):13903–13909, 2019.
80. Herraiz-Borreguero, L., Naveira Garabato, A.C. Poleward shift of Circumpolar Deep Water threatens the East Antarctic Ice Sheet. Nat. Clim. Chang, 2022.

81. Hofer, S., Lang, C., Amory, C., Kittel, C., Delhasse, A., Tedstone, A., Fettweis, X. Greater Greenland Ice Sheet contribution to global sea level rise in CMIP6. Nature Communications., 2020.
82. Hogan, K., Larter, R., Graham, A., Arthern, R., Kirkham, J., Totten Minzoni, R., … Wellner, J. Revealing the former bed of Thwaites Glacier using sea-floor bathymetry: implications for warm-water routing and bed controls on ice flow and buttressing. The Cryosphere, pages 2883–2908, 2020.
83. IPCC. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global green- house gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. 2018.
84. IPCC. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. 2019.
85. IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press., 2021.
86. Jordan, T., Porter, D., Tinto, K., Millan, R., Muto, A., Hogan, K., … Paden, J. New gravity-derived bathymetry for the Thwaites, Crosson, and Dotson ice shelves revealing two ice shelf populations. The Cryosphere, pages 2869–2882, 2020.
87. Joughin, I., Smith, B., Medley, B. Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica. Science, pages 735–738, 2014.
88. Karlsson, N., Solgaard, A., Mankoff, K., Gillet-Chaulet, F., MacGregor, J., Box, J., … Fausto, R. A first constraint on basal melt-water production of the Greenland ice sheet. Nature Communications., 2021.
89. Khan, S., Bjørk, A., Bamber, J., Morlighem, M., Bevis, M., Kjaer, K., … Schenk, T. Centennial response of Greenland's three largest outlet glaciers. Nature Communications, 2020.
90. Kondo, K., Sugiyama, S., Sakakibara, D., Fukumoto, S. Flood events caused by discharge from Qaanaaq Glacier, northwestern Greenland. Journal of Glaciology, 2021.
91. Marzeion, B., Levermann, A. Loss of cultural world heritage and currently inhabited places to sea-level rise. Environmental Research Letters, 9(3), 2014.
92. Mengel, M., Levermann, A. Ice plug prevents irreversible discharge from East Antarctica. Nature Climate Change, pages 451–455, 2014.
93. Milillo, P., Rignot, E., Rizzoli, P. et al. Rapid glacier retreat rates observed in West Antarctica. Nat. Geosci., 15:48–53, 2022.
94. Mouginot, J., Rignot, E., Fenty, I., Khazendar, A., Morlighem, M., Buzzi, A., Paden, J. Fast retreat of Zachariæ Isstrøm, northeast Greenland. Science, pages 1357–1361, 2015.
95. Naish, T., Powell, P., Levy, R., Wilson, G., Scherer, R., Talarico, F., … Williams, T. Obliquity-paced Pliocene West Antarctic ice sheet oscillations. Nature, pages 322–328, 2009.
96. Naughten, K. A., Holland, P. R., Dutrieux, P., Kimura, S., Bett, D. T., Jenkins, A. Simulated twentieth-century ocean warming in the Amundsen Sea, West Antarctica. Geophysical Research Letters, 49(e2021GL094566), 2022.
97. Naughten, K., Rydt, J., Rosier, S., Jenkins, A., Holland, P., Ridley, J. Two-timescale response of a large Antarctic ice shelf to climate change. Nature Communications, 2021.
98. Nöel, B., Kampenhout, L. van, Lenaerts, J. T. M., Berg, W. J. van de, Broeke, M. R. van den. A 21st Century Warming Threshold for Sustained Greenland Ice Sheet Mass Loss. Geophysical Research Letters, 48(5), 2021.
99. Paolo, F.S. and Fricker, H.A. and Padman, L. Volume loss from antarctic ice shelves is accelerating. Science, 348(6232):327–331, 2015.
100. Pattyn, F., Ritz, C., Hanna, E., Asay-Davis, X., DeConto, R., Durand, G., … van den Broeke, M. The Greenland and Antarctic ice sheets under 1.5°C global warming. Nature Climate Change, pages 1053–1061, 2018.
101. Rantanen, M., Karpechko, A.Y., Lipponen, A. et al. The Arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ, 3(168), 2022.
102. Reese, R. and Gudmundsson, G. H. and Levermann, A. and Winkelmann, R. The far reach of ice-shelf thinning in Antarctica. Nature Climate Change, 8(1):53–57, 2018.
103. Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., Scheuchl, B. Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. Geophysical Research Letters, 2014.
104. Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M., Morlighem, M. Four decades of Antarctic Ice Sheet mass balance from 1979–2017. Proceedings of the National Academy of Sciences of the United States of America, pages 1095–1103, 2018.
105. Robinson, A., Calov, R., Ganopolski, A. Multistability and critical thresholds of the Greenland ice sheet. Nature Climate Change, pages 429–432, 2012.
106. Rosier, S., Reese, R., Donges, J., De Rydt, J., Gudmundsson, G., Winkel- mann, R. The tipping points and early warning indicators for Pine Island Glacier, West Antarctica. The Cryosphere, pages 1501–1516, 2021.
107. Selley, H., Hogg, A., Cornford, S., Dutrieux, P., Shepherd, A., Wuite, J., … Kim, T.-W. Widespread increase in dynamic imbalance in the Getz region of Antarctica from 1994 to 2018. Nature Communications, 2021.
108. Siegert, M., Alley, R., Rignot, E., Englander, J., Corell, R. Twenty-first century sea-level rise could exceed IPCC projections for strong-warming futures. One Earth, pages 691–703, 2020.
109. Slater, T., Hogg, A., Mottram, R. Ice-sheet losses track high-end sea-level rise projections. Nature Climate Change, pages 879–881, 2020.
110. Stokes, C.R., Abram, N.J., Bentley, M.J. Response of the East Antarctic Ice Sheet to past and future climate change. Nature, 608:275–286, 2022.
111. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, Global and Regional Sea Level Rise Scenarios for the United States: Up- dated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, 2022.
112. Vousdoukas, M.I., Clarke, J., Ranasinghe, R. African heritage sites threatened as sea-level rise accelerates. Nat. Clim. Chang., 12,:256–262, 2022.
113. Wille, J.D., Favier, V., Jourdain, N.C. et al. Intense atmospheric rivers can weaken ice shelf stability at the Antarctic Peninsula. Commun Earth Environ, 3(90), 2022.
114. Winkelmann, R., Levermann, A., Ridgwell, A., Caldeira, K. Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet. Science Advances, 1(8):e1500589, 2015.
115. Wood, M., Rignot, E., Fenty, I., An, L., Bjørk, A., Van Den Broeke, M., … Zhang, H. Ocean forcing drives glacier retreat in Greenland. Science Advances., 2021.
116. Wunderling, N., Donges, J., Kurths, J., Winkelmann, R. Interacting tip- ping elements increase risk of climate domino effects under global warming. Earth System Dynamics, pages 601–619, 2021.

Mountain Glaciers and Snow

Even 1.5°C Is Too High for Some Mountain Glaciers, But with Visible Benefits This Century to Preserve Ice

Why 2°C is Too High for Glaciers and Snow: Recent and more sophisticated measurements now confirm that essentially all mountain glaciers worldwide are losing ice: some, such as those in the Alps, at distressingly rapid rates over the past two summers alone. If 2°C warming is reached, projections show that nearly all tropical glaciers (north Andes, Africa) and most mid-latitude glaciers outside the Himalayas* and polar regions will disappear, some as early as 2050. Others are large enough to delay complete loss until the next century, but have already passed a point of no return. Even the Himalayas are projected to lose around 50% of today's ice at 2°C. Reestablishment of lost glaciers would require temperatures well below those of today, and take centuries to millennia. As glaciers melt, risks of catastrophic events – landslides, sudden ice shears, and in some cases glacial lake outburst floods – will rise, affecting entire communities. Winter snowpack at 2°C generally will decrease on average, but will also become more volatile; with some years of hardly any snow, as shown in the southern Andes just this past winter season, and others with record-breaking amounts that threaten infrastructure and lives. Losses in both snowpack and glacier ice will have dramatic impacts on downstream dry season water availability for agriculture, power generation, and drinking. Impacts may be extreme in especially vulnerable river basins, such as the Tarim in northwest China and the Indus.

Preserved at 1.5°C: Today's climate is already too warm to preserve some mountain glaciers, which will be lost even with no additional warming than that of today's 1.2°C. Continued warming, even through the brief 1.6°C peak of very low emissions (SSP1-1.9) still means that today's very fast ice loss in glaciers globally will continue through at least the 2050s. However, latest projections show that with very low emissions, this loss will begin to slow in at least some regions around 2060, and stabilize towards the end of this century. Some may even show slow glacier re-growth starting in the 2100s, though this would occur extremely slowly (many decades to centuries). Annual snowpack would stabilize at 1.5°C levels, e.g. still a lower average amount than today, but respond quite quickly to decreases in CO_2 in the atmosphere and resulting lower temperatures. This visible snow and ice preservation, and its benefits for freshwater resources, may be one of the earliest and visible signs to humanity that steps towards low emissions have meaningful results.

Today's Emissions Heading Towards 3°C+: If CO_2 continues to accumulate in the atmosphere at today's pace, which has not paused despite current pledges, global temperatures will reach at least 3°C by end of century. Once 3°C is passed, even most large polar glaciers, and the very high-altitude glaciers in the Himalayas and southern Andes, are unlikely to survive. Complete loss may not occur for one or two centuries, but will become inevitable should mitigation remain inadequate in the next few decades.

The 2°C Takeaway: 2°C will result in extensive, long-term, essentially irreversible ice loss from many of the world's glaciers in many major river basins, with some disappearing entirely. Snow cover also will greatly diminish. A rise of 3°C will spread and greatly speed up this loss. If global leaders cause temperatures to reach this point through continued fossil emissions, they are committing the planet to extensive loss and damage of water resources and ecosystems well beyond limits of feasible adaptation.

---

* As used in this chapter for ease of reference, "Himalayas" refers to the massive mountain and high plateau region running across Central, South and East Asia, from Afghanistan in the west, to Myanmar in the east; sometimes also referred to as "High Mountain Asia."

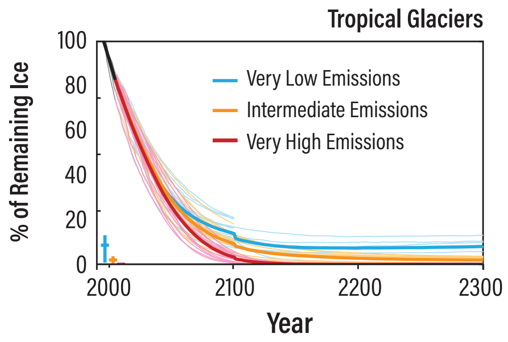
2023 Updates

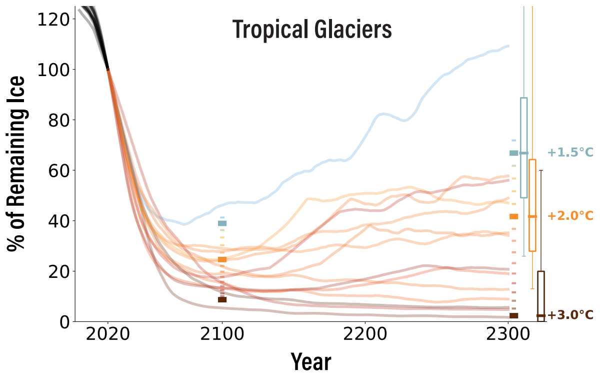
- Improved projections forecast greater glacier loss by 2100, including total or near-total glacier loss in mid and low latitudes by 2100 under a high emission scenario,[25] as well as up to 80% glacier loss in the Hindu Kush Himalaya.[2,13]
- New research suggests that glaciers can now produce floods even at the highest elevations, which were previously stabilized by snowfall and cooler temperatures.[33]
- One study found that an estimated fifteen million people worldwide are now at risk from glacier lake outburst floods, with most residing in High Mountain Asia and Peru.[30]
- New research highlights growing threats to hydropower in High Mountain Asia due to declining mountain glaciers and thawing mountain permafrost.[17]
- Numerous new studies have identified increasing decline of mountain snowpack,[3,10] with significant impacts on hazard risk, water supplies,[35] and food security, including via global trade.[24]
- Snowpack across the Arctic and near-Arctic, especially in northern Canada and Alaska, melted far earlier than normal, leaving ground bare for longer. Meteorologists attribute some of the record North American summer 2023 heatwaves to this record melt.
- Glaciers in the Swiss Alps lost 10% of their ice in the two years 2022–23, reported the Swiss glacier monitoring agency GLAMOS. These losses were attributed especially to heat waves, which are expected to intensify as time goes on.[6]
- What may have been the most extreme heatwave on the planet in 2023 occurred in the Andes during the southern hemisphere winter, with temperatures up to 20°C above normal for several weeks, leading to concerns for water shortages due to decreased snowpack, especially in Chile, Argentina and Paraguay.[22]
- New research underscores that threats to ecosystems are dramatically growing with loss of the mountain cryosphere, with decline and extinction already observed today.[2,13,36]
- The IPCC AR6 Synthesis Report reiterates the urgency of keeping global average temperature rise below 1.5°C to avoid the most serious consequences and hard adaptation limits for many generations in high mountain and downstream areas.[15]

Background

Many glaciers of the northern Andes, East Africa and Indonesia, especially those close to the Equator, are disappearing too rapidly to be saved even in the present 1.2°C climate.[19] These glaciers have mostly been shrinking since the end of the Little Ice Age, but global warming greatly accelerated their melting. Some of these,

FIGURE 3-1. **New Work on Glacier Projections**





Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–3.0°C

Glacier graphs in this chapter represent innovative new work from Schuster et al. (2023), using projections from the glacier models described in Rounce et al. (2023), Huss and Hock (2015), and Maussion et al. (2019), updating previous projections used in past SoC Reports (Marzeion et al., 2012) with much greater detail for individual glaciers. The most striking and positive difference is for tropical glaciers, showing that these need not be totally lost at even 1.5°C as projected in Marzeion (2012).

However, the reality is that as of 2023, these tiny glaciers near the equator (in Africa, South America and Indonesia) have already lost most of their ice. Those glaciers that remain are already quite small, and at very high altitudes that help protect them from warming. According to the new projections, at least some of these small patches of remaining ice likely will be preserved at 1.5°C, of high symbolic importance to local communities.

TOP: BASED ON MARZEION ET AL. (2012), BOTTOM: SCHUSTER ET AL. (2023)

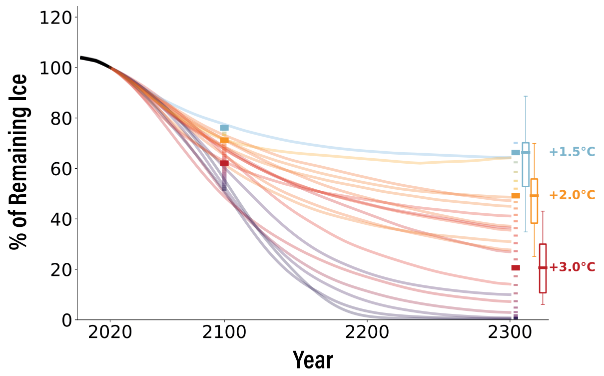
especially in parts of the northern Andes, would have provided a reliable seasonal source of water for hundreds or thousands of years without human-induced warming. Their loss – which for some glaciers may occur by mid-century – would impact rural populations in northern Peru especially, as well as in Bolivia and northern Chile, while also impacting major cities such as La Paz.[16]

Severe losses also are occurring today from mid-latitude glaciers and others outside the polar regions: these include glaciers in the European Alps, southern Andes and Patagonia, Iceland, Scandinavia, the North American Rockies and much of Alaska, and New Zealand. These losses will continue at a steep rate over the next several decades just from current warming, with smaller glaciers continuing to disappear completely and others decreasing to only 10–20% of their 2010 size. With very low emissions however, up to 40% of glacier ice in these regions could be preserved.[25] Projections in a few glacier regions even show slow re-growth beginning between 2100 and 2300, but only with very low emissions and essentially carbon neutrality by 2050.[20]

Any other emissions path will eventually result in almost complete loss of all land glaciers on Earth outside High Mountain Asia and high-latitude polar regions, which include northern Canada / Alaska and southern Patagonia. With high emissions, and global mean temperature rise exceeding 4°C by 2100, any substantial seasonal snowpack also will become rare outside the polar regions and very high mountains.[19]

Losses in both snowpack and glacier ice will have dramatic impacts on downstream dry season water availability.

FIGURE 3-2. **Glaciers Globally**

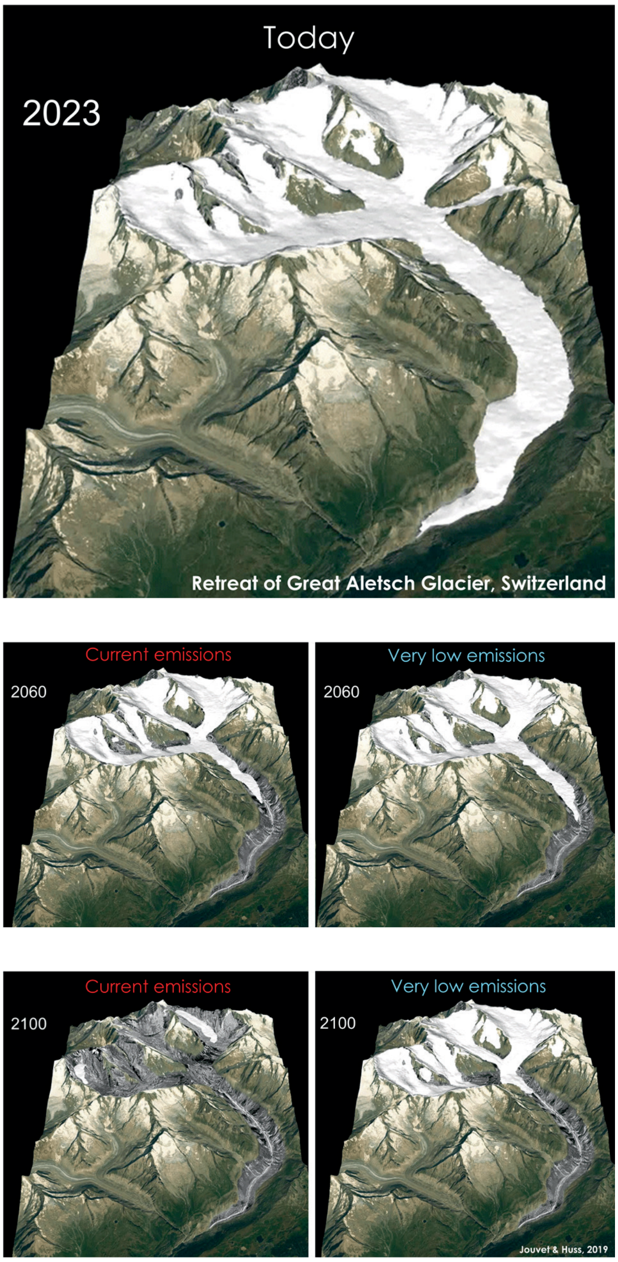


Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–4.5°C

Glaciers worldwide are losing ice at today's 1.2°C. Should current emissions continue, meaning global temperatures reach 4.5°C by 2100, this loss will become quite rapid even for the largest glaciers near the poles that make up most of this all-glacier graph; reaching 50% worldwide glacier loss by 2100 and no glaciers globally by 2200.

CREDIT: SCHUSTER ET AL. (2023)

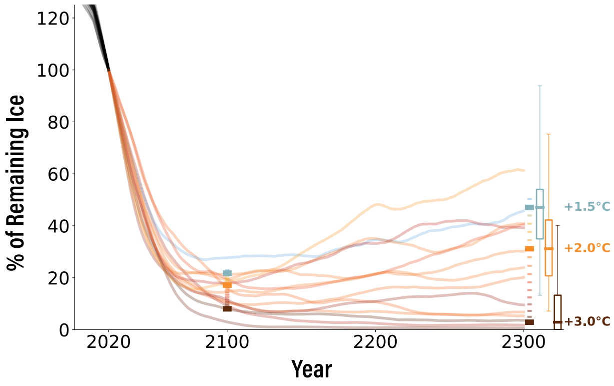
FIGURE 3-3. **The Future of Great Aletsch Glacier**



Great Aletsch today (top); and in 2060 (middle) and 2100 (bottom) with low and high emissions. With a great deal of ice loss already in-train with today's warming, the glacier will continue to lose ice through about 2060 even with low emissions; but by 2100, the difference is clear.

COURTESY OF MATTHIAS HUSS

FIGURE 3-4. **Glaciers of the Alps**



Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–3.0°C

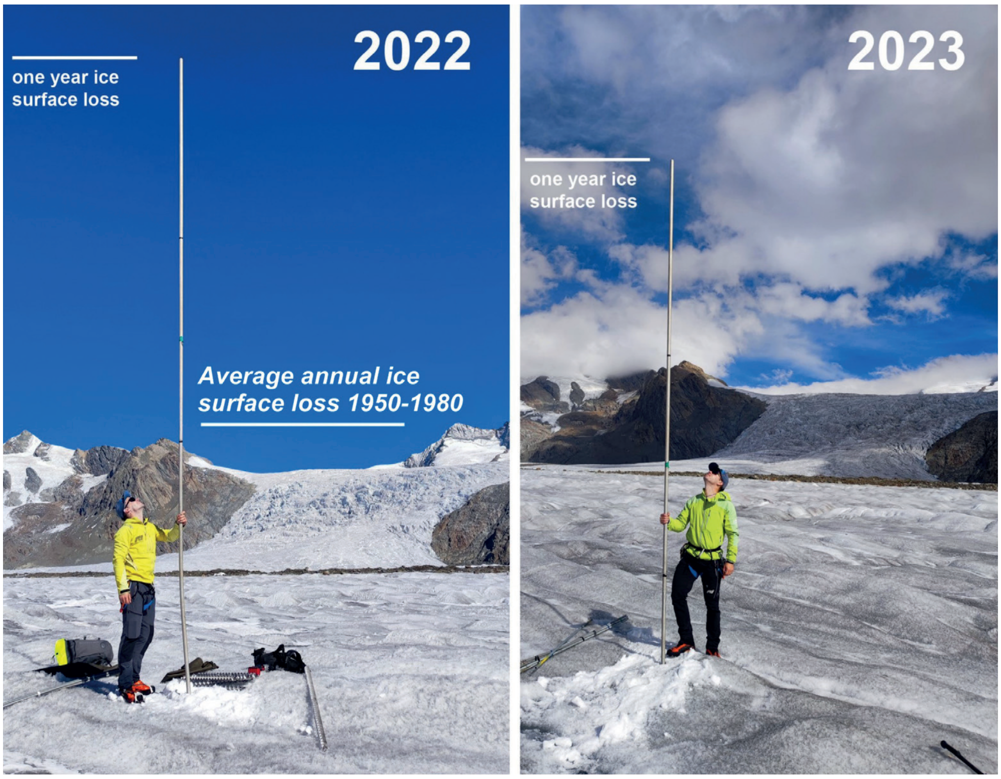
At 1.5°C, not only do models show the Alps preserving more ice, but even showing slow re-growth by 2300.

CREDIT: SCHUSTER ET AL. (2023)

In those "high altitude and high latitude" regions, only 35–75% of glacier volume will remain by the end of this century under high emissions scenarios.[19] However, if we follow a very low emissions pathway, the glaciers and snowpack of High Mountain Asia – important for seasonal water resources – will stabilize and eventually begin to return. Glaciers in Central Asia and the southern Andes also would preserve twice as much ice with rapid emissions reductions consistent with the 1.5°C limit.[25] At higher emissions levels resulting in peak temperatures above 2°C, losses in high altitude and high latitude regions will continue. With very high emissions, similar to today's year-on-year rise in CO_2 concentrations, this loss would be ever more rapid.[19] In the Hindu Kush Himalaya, 70–80% of current glacier volume will disappear by 2100 under such a high emission scenario; whereas a low emissions scenario could limit glacier loss to 30%.[13]

Glaciers generally gain mass via snow deposition in winter, and lose mass as meltwater in summer over the course of a year. Global warming means that a given glacier will experience a net loss of ice every year at higher and higher elevations, because the annual gain by snowfall turning to ice decreases, and an increasing loss from

FIGURE 3-5. **Two Record Years of Ice Loss**



Height of glacier ice loss at Konkordiaplatz, Switzerland, during record melt years 2022 and 2023 compared to the average yearly ice loss between 1950–1980. The Swiss Alps as a whole lost 10% of their remaining ice in just two summers.

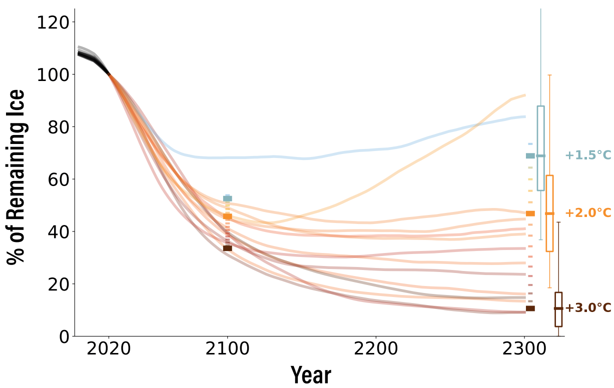
PHOTO: MATTHIAS HUSS.

Image by Praful Rao of Save the Hills

Flood damage in Rangpo caused by the Sikkim flood, when the Teesta III dam was swept away by a GLOF in October 2023.

A low emissions scenario could limit glacier loss to 30% in the Hindu Kush Himalaya.

FIGURE 3-6. **Glaciers of High Mountain Asia**



Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–3.0°C

High Mountain Asia includes the highest mountains of the world, in the Hindu Kush Himalaya. Even these extremely high altitude glaciers, which provide seasonal water to at least 2 billion people, will lose most of their ice by 3°C; 1.5°C preserves much more.

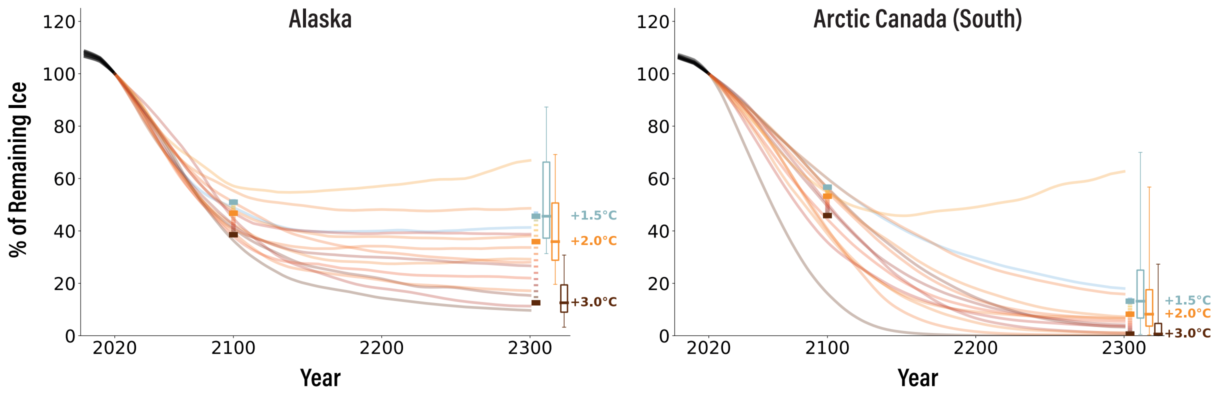
CREDIT: SCHUSTER ET AL. (2023)

melting especially at low elevation significantly outpaces the gain each year. A threshold is crossed when the entire glacier, from bottom to top, is losing ice each year: at that point, the glacier is doomed. The majority of glaciers in the European Alps experienced this during the summer of 2022,[34] with an overall loss of 6% of the total volume of Swiss glaciers alone in one single melt season.[29]

Glaciers can shrink and even disappear completely over the space of just decades or a century. When Glacier National Park in the U.S. was created in 1910, it had around 150 glaciers; today, fewer than 30 remain, and those have shrunk by about two-thirds. Half of the glaciers in World Heritage sites globally will likely disappear by 2100 if emissions continue under a "business-as-usual" scenario.[32] From 1901 to 2018, glaciers outside Antarctica contributed nearly 7 cm to global sea-level rise.[8] While such melt has been rapid, large glaciers grow back only slowly, especially at temperatures above pre-industrial. Limited modeling seems to indicate that "re-growth" of large mountain glaciers, to scales present in the mid-1900's or even today, would take many centuries; and perhaps even millennia in some regions (see glacier graphs figures).

Therefore, on human timescales, the disappearance of today's glaciers is an essentially permanent change to the mountain landscape. Very low emissions are key to ensuring as little ice as possible is lost during this current period of rapid decline. A very low emissions pathway is essential to preserving the ecosystem services glaciers

FIGURE 3-7. **Large Arctic Glaciers of North America**



Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–3.0°C

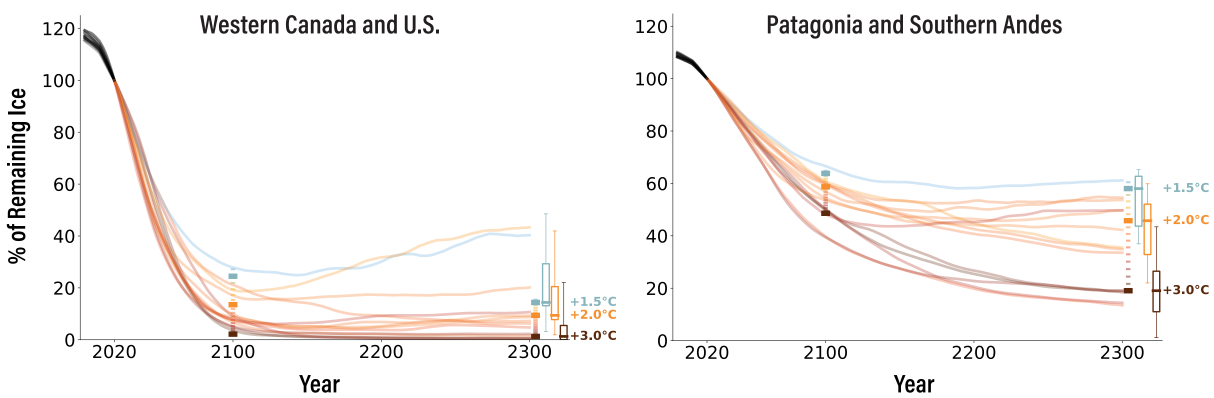
Very large glaciers, such as those in Alaska and Arctic Canada behave somewhat like ice sheets: slow to melt in the beginning, but then accelerating and continuing for centuries. So unlike smaller glaciers, their melt continues to accelerate through 2300, depending on global temperature in 2100.

CREDIT: SCHUSTER ET AL. (2023)

provide, and to minimizing the risk of severe hazards such as glacial lake outburst floods that accompany loss of mountain glaciers.[27,28,30,37]

Glaciers and snowpack have varying importance to nearby communities and those further downstream as a source of water for drinking and/or irrigation, with some contributing only a few percent over the course of a year, but of greater importance during dry seasons, heat waves and droughts.[4,23,31] Glaciers in some regions, such as the tropical Andes, or the Indus and Tarim basins in High Mountain Asia, contribute a high percentage of seasonal water supplies; in the dry Tarim and Aral Sea basins, close to 100% during the summer months.[13] While the rapid melting of glaciers temporarily increases water availability, as the glaciers continue shrinking that seasonal availability will begin to decrease (referred to as passing "peak water"). This may make certain economic activities – and even continued human habitation – impossible. Indeed, most glacier-covered regions outside high latitude polar regions and the Himalaya have already passed this period of "peak water".[11,12] Extensive adaptation therefore needs to begin immediately to prepare for this future, even as mitigation to preserve glaciers as much as possible is also prioritized.

FIGURE 3-8. **Glaciers of the Americas**

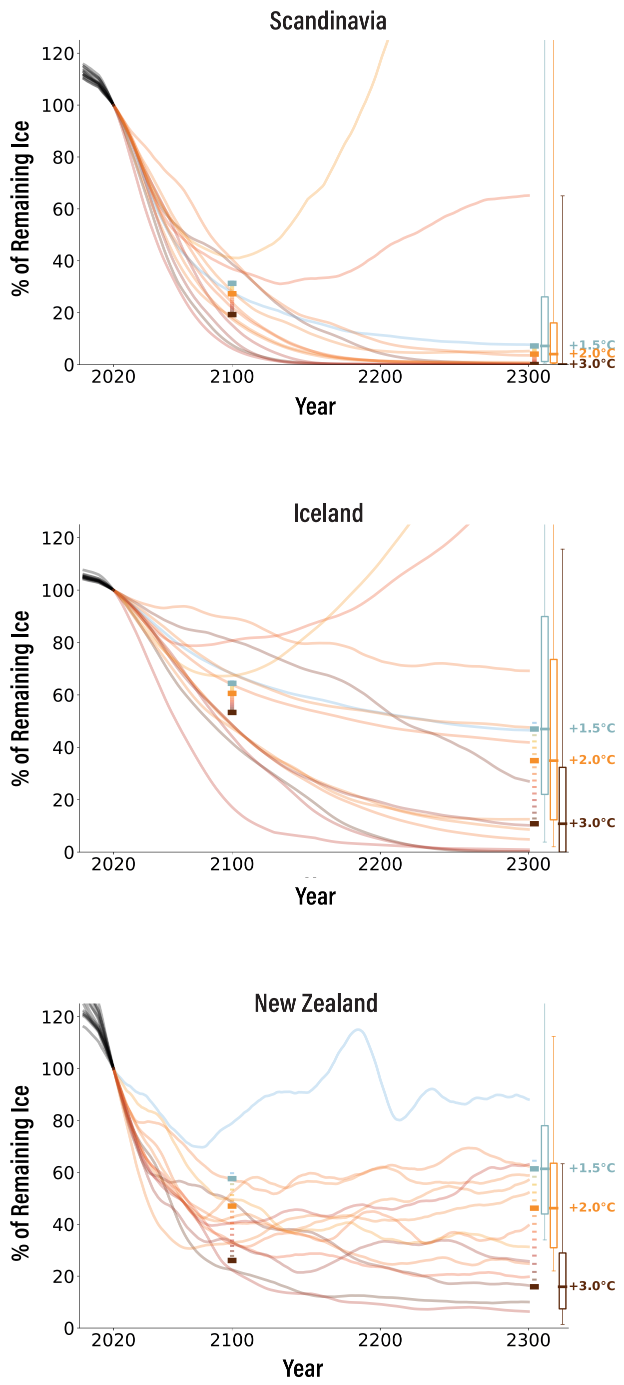


Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–3.0°C

The glaciers of western Canada and the U.S. are steeply losing ice today; but remaining within 1.5°C can preserve 50% more ice in 2100. The glaciers of Patagonia are among the fastest receding in the world; but these models show that loss slowing and preserving about 50% of their current ice by 2300; with much greater losses at 3°C.

CREDIT: SCHUSTER ET AL. (2023)

FIGURE 3-9. **Mid-Latitude Glaciers**



Colors Show Global Temperature Change in 2100, Without Overshoot, by Tenths of a Degree 1.4°–3.0°C

Smaller mid-latitude glaciers show surprising uncertainties in these new projections, especially Iceland and Scandinavia, where some models assume shutdown of the AMOC, causing that region to cool and glaciers actually to grow. However, most models show these glaciers preserving much more ice at 1.5°C. In the case of Scandinavia, only low emissions preserve amounts reliably above zero.

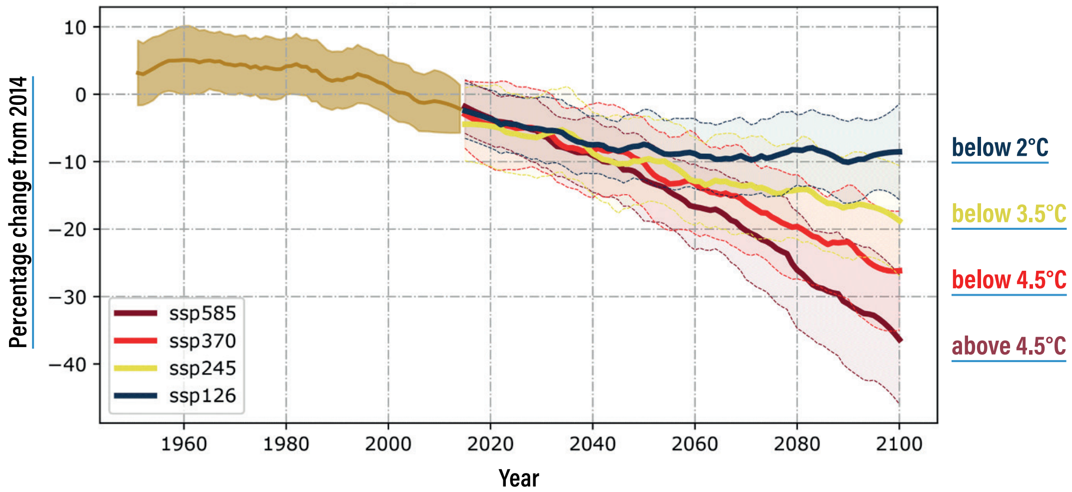
CREDIT: SCHUSTER ET AL. (2023)

Reestablishment of lost glaciers would require temperatures well below those of today, and take centuries to millennia.

In addition to glaciers, mountains also store water in the form of snow. In fact, seasonal freshwater in many mountain and lowland regions is dependent on annual snowfall, and meltwater from snow is of greater important than meltwater from glaciers in many areas. However, snowfall has become less consistent in many mountain watersheds, with extremes of "snow drought" alternating with high amounts of snow, or wet snow, that increase the risks of avalanche and flood,[14] such as in California, USA in winter 2023. In many mountains, it now appears that snow generally is following the same downward trajectory as glaciers: snowfall is reducing as temperatures rise above freezing at higher and higher altitudes, with precipitation that would have fallen as snow in past decades, increasingly coming down as rain,[8] and often in the form of hazardous extreme rainfall.[21] At lower elevations and latitudes, snow will fall less often or not at all, and the winter season will shorten.[26] Seasonal snowpack will not form, resulting in loss of stored water in the snow itself and in underground aquifers. A decreasing extent and duration of snowpack has already been observed in many mountain areas.[3,10] Continued declines in annual snowpack will result in negative economic impacts for many sectors, especially agriculture, hydropower, and tourism,[9] with global ramifications; and threatens the availability of sufficient water supplies for downstream populations.[18]

Mountain snow sustains water supplies for ecosystems and people far beyond mountain regions, as meltwater travels great distances across grasslands and deserts to densely populated and cultivated coastal regions. For example, people in cities as diverse as Los Angeles, Delhi, and Marrakech are to some degree dependent on meltwater from snow. In the western U.S., rising temperatures have caused a general decrease in annual snowpack, leading to ever more severe water shortages.[7] In both the Arctic and mountain regions, the well-being of people and many species depend on seasonal snow cover. For reindeer-based Arctic Indigenous cultures, increasing numbers of animals are lost to starvation when more unseasonal rains falls on snow, forming thick layers of ice that makes it impossible for reindeer to access grazing through the ice cover. Decreases in snow cover negatively impact snow-dependent tourism, especially in the United States, Japan, and Europe.[9,11] Lack of mountain snow cover also increases the risk of wildfires, as well as natural hazards that can materialize as disasters

FIGURE 3-10. **Decline in Northern Hemisphere Snowpack**



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

MUDRYK ET AL. 2020

such as mudslides in the wake of such wildfires. In some areas, the impacts of glacier melt and snowmelt on freshwater availability have already contributed to increasing tensions and/or conflicts related to water resources.[1]

A strengthening of climate pledges will have especially significant benefits for those communities in the Andes and Central Asia that are most dependent on glacier runoff as a seasonal source of water for drinking and irrigation. Stronger pledges also will significantly benefit economies dependent on meltwater from glaciers and seasonal snowpack for power generation, agriculture and revenue from snow tourism, such as in the European Alps and North American West. Low emissions also allow local communities more time to adapt, even in those equatorial and mid-latitude regions where smaller glaciers are doomed to disappear completely even at 1.5°C.

Every fraction of a degree of global temperature rise substantially impacts the loss of the mountain cryosphere.[5,25] To preserve as much glacier ice and ecosystem services as possible, a sharp strengthening of climate action is needed towards the 1.5°C limit. This requires a general 50% reduction in human-induced GHG emissions by 2030, and stronger commitments and implementation of actions in the near-term 2030–2040 timeframe. These low emissions pathways, minimizing overshoot, could make the difference between rapid and disruptive loss of regionally important glaciers and snowpack, and significant steps towards their preservation.

Every fraction of a degree of global temperature rise substantially impacts the loss of the mountain cryosphere.

SCIENTIFIC REVIEWERS

Carolina Adler, Mountain Research Initiative, Lead Author IPCC AR6 WGII and SROCC

Guðfinna Aðalgeirsdóttir, University of Iceland, IPCC AR6

Daniel Farinotti, ETH-Zurich, WSL

Matthias Huss, ETH-Zurich, WSL

Regine Hock, University of Oslo, Norway, University of Alaska Fairbanks, IPCC AR4, SROCC coordinating Lead Author, AR6

Miriam Jackson, ICIMOD, IPCC AR6

Georg Kaser, University of Innsbruck, IPCC AR4, AR5, SROCC and AR6 Review Editor

Michael Lehning, EPFL, IPCC SROCC

Ben Marzeion, University of Bremen, IPCC AR5, SROCC, AR5 and AR6 WG1

Fabien Maussion, University of Bristol

Ben Orlove, Columbia University, IPCC SROCC, AR6 WG2

David Rounce, Carnegie Mellon University

Heidi Sevestre, University of Svalbard

Heidi Steltzer, Fort Lewis College, IPCC SROCC

Philippus Wester, IPCC AR6 WG2

LITERATURE AND ADDITIONAL READING

1. Adler, C., et al. (2022). Mountains. In: Climate Change 2022: Impacts, Adaptation Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp., 2273–2318, https://doi.org/10.1017/9781009325844.022.
2. Bosson, J.B., et al. (2023). Future emergence of new ecosystems caused by glacial retreat. Nature, v. 620, no, 7974, 562–569, https://doi.org/10.1038/s41586-023-06302-2.
3. Carrer, M., et al. (2023). Recent waning snowpack in the Alps is unprecedented in the last six centuries. Nature Climate Change, v. 13, no, 2, 155–160, https://doi.org/10.1038/s41558-022-01575-3.
4. Chandel, V.S. and S. Ghosh (2021). Components of Himalayan River Flows in a Changing Climate. Water Resources Research, v. 57, no, 2, e2020WR027589, https://doi.org/https://doi.org/10.1029/2020WR027589.
5. Compagno, L., et al. (2022). Future growth and decline of high mountain Asia's ice-dammed lakes and associated risk. Communications Earth & Environment, v. 3, no, 1, 191, https://doi.org/10.1038/s43247-022-00520-8.
6. Cremona, A., et al. (2023). European heat waves 2022: contribution to extreme glacier melt in Switzerland inferred from automated ablation readings. The Cryosphere, v. 17, no, 5, 1895–1912, https://doi.org/10.5194/tc-17-1895-2023.
7. Douville, H., et al. (2021). Water Cycle Changes. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1055–1210, https://doi.org/10.1017/9781009157896.010.
8. Fox-Kemper, B., et al., *Ocean, Cryosphere and Sea Level Change, in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte, et al., Editors. 2021, Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA. p. 1211–1362. https://doi.org/10.1017/9781009157896.011.
9. François, H., et al. (2023). Climate change exacerbates snow-water-energy challenges for European ski tourism. Nature Climate Change, v. 13, no, 9, 935–942, https://doi.org/10.1038/s41558-023-01759-5.
10. Hale, K.E., et al. (2023). Recent decreases in snow water storage in western North America. Communications Earth & Environment, v. 4, no, 1, 170, https://doi.org/10.1038/s43247-023-00751-3.
11. Hock, R., et al. (2019). GlacierMIP – A model intercomparison of global-scale glacier mass-balance models and projections. Journal of Glaciology, v. 65, no, 251, 453–467, https://doi.org/10.1017/jog.2019.22.
12. Huss, M. and R. Hock (2018). Global-scale hydrological response to future glacier mass loss. Nature Climate Change, v. 8, no, 2, 135–140, https://doi.org/10.1038/s41558-017-0049-x.
13. ICIMOD (2023). Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook. (P. Wester, S. Chaudhary, N. Chettri, M. Jackson, A. Maharjan, S. Nepal, & J. F. Steiner [Eds.]). ICIMOD, https://doi.org/10.53055/ICIMOD.1028.
14. Intergovernmental Panel on Climate, C., *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* 2018.
15. IPCC (2023). Summary for Policymakers. In: Climate Change 2023: Synthesis Report.Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 1-34, https://doi.org/10.59327/IPCC/AR6-9789291691647.001.
16. Kinouchi, T., et al. (2019). Water security in high mountain cities of the Andes under a growing population and climate change: A case study of La Paz and El Alto, Bolivia. Water Security, v. 6, 100025, https://doi.org/https://doi.org/10.1016/j.wasec.2019.100025.
17. Li, D., et al. (2022). High Mountain Asia hydropower systems threatened by climate-driven landscape instability. Nature Geoscience, v. 15, no, 7, 520–530, https://doi.org/10.1038/s41561-022-00953-y.
18. Marty, C., et al. (2017). How much can we save? Impact of different emission scenarios on future snow cover in the Alps. The Cryosphere, v. 11, no, 1, 517–529, https://doi.org/10.5194/tc-11-517-2017.
19. Marzeion, B., et al. (2020). Partitioning the Uncertainty of Ensemble Projections of Global Glacier Mass Change. Earth's Future, v. 8, no, 7, e2019EF001470, https://doi.org/https://doi.org/10.1029/2019EF001470.
20. Marzeion, B., A.H. Jarosch, and M. Hofer (2012). Past and future sea-level change from the surface mass balance of glaciers. The Cryosphere, v. 6, no, 6, 1295–1322, https://doi.org/10.5194/tc-6-1295-2012.
21. Ombadi, M., et al. (2023). A warming-induced reduction in snow fraction amplifies rainfall extremes. Nature, v. 619, no, 7969, 305–310, https://doi.org/10.1038/s41586-023-06092-7.
22. Patterson, M. (2023). One of 2023's most extreme heatwaves is happening in the middle of winter. The Conversation, https://doi.org/theconversation.com/one-of-2023s-most-extreme-heatwaves-is-happening-in-the-middle-of-winter-211062.
23. Pritchard, H.D. (2019). Asia's shrinking glaciers protect large populations from drought stress. Nature, v. 569, no, 7758, 649–654, https://doi.org/10.1038/s41586-019-1240-1.
24. Qin, Y., et al. (2022). Snowmelt risk telecouplings for irrigated agriculture. Nature Climate Change, v. 12, no, 11, 1007–1015, https://doi.org/10.1038/s41558-022-01509-z.
25. Rounce, D.R., et al. (2023). Global glacier change in the 21st century: Every increase in temperature matters. Science, v. 379, no, 6627, 78–83, https://doi.org/doi:10.1126/science.abo1324.
26. Schmucki, E., et al. (2015). Simulations of 21st century snow response to climate change in Switzerland from a set of RCMs. International Journal of Climatology, v. 35, no, 11, 3262–3273, https://doi.org/https://doi.org/10.1002/joc.4205.
27. Shugar, D.H., et al. (2021). A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. Science, v. 373, no, 6552, 300–306, https://doi.org/doi:10.1126/science.abh4455.
28. Stuart-Smith, R.F., et al. (2021). Increased outburst flood hazard from Lake Palcacocha due to human-induced glacier retreat. Nature Geoscience, v. 14, no, 2, 85–90, https://doi.org/10.1038/s41561-021-00686-4.

29. Swiss Academy of Sciences (2023). Two catastrophic years obliterate 10% of Swiss glacier volume. https://doi.org/scnat.ch/en/uuid/i/b8d5798e-a75e-5a7d-a858-f7a6613524ed-Two_catastrophic_years_obliterate_10_of_Swiss_glacier_volume.
30. Taylor, C., et al. (2023). Glacial lake outburst floods threaten millions globally. Nature Communications, v. 14, no, 1, 487, https://doi.org/10.1038/s41467-023-36033-x.
31. Ultee, L., S. Coats, and J. Mackay (2022). Glacial runoff buffers droughts through the 21st century. Earth Syst. Dynam., v. 13, no, 2, 935–959, https://doi.org/10.5194/esd-13-935-2022.
32. UNESCO (2022). World Heritage Glaciers: Sentinels of climate change. https://doi.org/doi.org/10.3929/ethz-b-000578916.
33. Veh, G., et al. (2023). Less extreme and earlier outbursts of ice-dammed lakes since 1900. Nature, v. 614, no, 7949, 701–707, https://doi.org/10.1038/s41586-022-05642-9.
34. Voordendag, A., et al. (2023). Brief communication: The Glacier Loss Day as an indicator of a record-breaking negative glacier mass balance in 2022. The Cryosphere, v. 17, no, 8, 3661–3665, https://doi.org/10.5194/tc-17-3661-2023.
35. Wieder, W.R., et al. (2022). Pervasive alterations to snow-dominated ecosystem functions under climate change. Proceedings of the National Academy of Sciences, v. 119, no, 30, e2202393119, https://doi.org/doi:10.1073/pnas.2202393119.
36. Wilkes, M.A., et al. (2023). Glacier retreat reorganizes river habitats leaving refugia for Alpine invertebrate biodiversity poorly protected. Nature Ecology & Evolution, v. 7, no, 6, 841–851, https://doi.org/10.1038/s41559-023-02061-5.
37. Zheng, G., et al. (2021). Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. Nature Climate Change, v. 11, no, 5, 411–417, https://doi.org/10.1038/s41558-021-01028-3.

■

38. Huss, M., & Hock, R. (2015). A new model for global glacier change and sea-level rise. Frontiers in Earth Science, 3(September), 1–22. https://doi.org/10.3389/feart.2015.00054
39. Maussion, F., Butenko, A., Champollion, N., Dusch, M., Eis, J., Fourteau, K., Gregor, P., Jarosch, A. H., Landmann, J., Oesterle, F., Recinos, B., Rothenpieler, T., Vlug, A., Wild, C. T., & Marzeion, B. (2019). The Open Global Glacier Model (OGGM) v1.1. Geoscientific Model Development, 12(3), 909–931. https://doi.org/10.5194/gmd-12-909-2019
40. Schuster, L., Huss, M., Maussion, F., Rounce, D. R., & Tober, B. S. (2023). lilianschuster/glacier-model-projections-until2300: v1.0 (v1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10059778
41. Rounce, D. R., Hock, R., McNabb, R. W., Millan, R., Sommer, C., Braun, M. H., Malz, P., Maussion, F., Mouginot, J., Seehaus, T. C., & Shean, D. E. (2021). Distributed global debris thickness estimates reveal debris significantly impacts glacier mass balance. Geophysical Research Letters. https://doi.org/10.1029/2020GL091311

CHAPTER 4

Permafrost

Exceeding 1.5°C Means Higher Permafrost Emissions for Centuries

Why 2°C is Too High for Permafrost: 2°C global mean temperature means 4–6°C in the Arctic where most permafrost is located, since recent observations show parts of the Arctic warming 2–3 times faster than the rest of the planet. In addition, up to half of recent permafrost thaw has occurred during extreme heat events of up to 12°C above average, as a result of "abrupt thaw" processes where coastlines or hillsides collapse, or lakes form; exposing much deeper and greater amounts of permafrost to thaw. Once thawed, permafrost begins emitting CO_2 or methane, even if temperatures later drop below freezing. These emissions are irreversibly set in motion and will not slow for 1–2 centuries, meaning that future generations must offset them (draw down carbon) at scales the size of a major emitter. At 2°C, annual total permafrost emissions (both CO_2 and methane)* would probably total the size of the entire European Union's emissions from 2019 (≈200Gt total by 2100 and about twice that by 2300).[57] Permafrost thaw at 2°C might also be accelerated further by loss of Arctic sea ice in summer for several months, as the open water absorbs more heat; and by increased wildfires in Siberia and North America.

Preserved at 1.5°C: Even at 1.5°C, studies indicate significant permafrost thaw and related emissions due to the dynamics outlined above, but these will be less in scale since temperatures will "only" average 3–4°C higher than today in the Arctic. "Very low" emissions (SSP1-1.9 also result in temperatures declining to below 1.4°C by the end of this century, preventing most additional new thaw. Summer Arctic sea ice also is mostly restored by this "very low" emissions level, helping to stabilize or decrease summer Arctic temperatures and extreme heat. Annual permafrost emissions will still need to be offset by future generations, but should be 30–50% less, more on the scale of India in 2019 (150Gt by 2100).[57]

Today's Emissions Aiming Towards 3°C+: If CO_2 continues to grow in the atmosphere at today's pace, which has not paused despite current pledges, global temperatures will reach 3°C or more by the end of this century. At such high temperatures, much of the Arctic, and nearly all mountain, permafrost will reach the thawed state, producing annual carbon emissions on the scale of the U.S. plus EU in 2019 for centuries,[57] greatly accelerating global heating.

The 2°C Takeaway: 2°C – and even 1.5°C – is too high to prevent extensive permafrost thaw and resulting CO_2 and methane emissions that will cause temperatures to continue to rise, even once human emissions reach zero, unless offset by extensive negative emissions/carbon drawdown; but 1.5°C will decrease the size of such emissions significantly.

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

2023 Updates

- Over the past several decades, the Tibetan Plateau has warmed two times faster than the global average, increasing the vulnerability of its permafrost to thawing, sinking, and collapse. Limiting warming below 1.5°C instead of 2°C could reduce the costs of infrastructure damage from permafrost thaw in the Tibetan Plateau by $1.32 billion before the end of the century.[20]
- Under even "moderate" emissions, nearly two-thirds of the permafrost area in the Tibetan Plateau will become a "high-hazard" zone by 2100.[41]
- Global impacts of permafrost thaw will have cascading effects on health, infrastructure, and a wide range of socioeconomic variables.[4,24]
- In the Arctic, climate warming decreases the duration of winter snow cover while increasing the amount of snowfall. Deeper snow can rapidly thaw permafrost; over several decades, it can lead to a four-fold increase in the amount of thawed permafrost and related carbon emissions.[40]
- During a warm period roughly three million years ago, more than 90% of the permafrost then existing (which was nearly as large as today's permafrost extent) disappeared under climate conditions similar to those projected under high emissions. Near-surface permafrost remained only in a few pockets of the eastern Siberian uplands, Canadian high Arctic archipelago and northernmost Greenland.[16]
- Methane released from sub-Arctic North American wetlands could triple by the end of the century if temperatures exceed 3–4°C, but these emissions could be nearly halved by following a low emissions pathway. As temperatures increase across the sub-Arctic, frozen soils thaw earlier, allowing microbes to release more methane gas for longer periods, in a positive feedback loop between global temperature rise and carbon emissions from wetlands, along with those from permafrost and peatlands.[3]
- Ponds formed by rapidly retreating glaciers on Svalbard are releasing high levels of methane; similar conditions may exist in the path of glacier loss in Alaska and on Greenland, where glaciers are far larger.[28]
- Nineteen years of radiocarbon dating of emissions from permafrost indicate more "old" carbon is being emitted, confirming that emissions from permafrost soils are indeed "old" carbon sequestered in the soil for centuries to millennia, and that these emissions are growing.[54]

Background

Permafrost is ground that remains frozen through at least two years. The permafrost region covers 22% of the Northern Hemisphere land area and holds vast amounts of ancient organic carbon.[57] Observations confirm that permafrost is rapidly warming and releasing part of that thawed carbon into the atmosphere as both carbon dioxide (CO_2) and methane. Permafrost thaw is projected to add as much greenhouse gas forcing as a large country, depending on just how much the planet warms. Today, at 1.2°C of warming above pre-industrial, annual permafrost emissions are about the same as Japan's, currently about the seventh largest global contributor of human emissions.[56]

Permafrost stretches across Arctic tundra and taiga forest, especially in Siberia, and also occurs in high mountain regions globally. Of greatest concern to climate is near-surface permafrost (i.e. the first few meters below the surface), but permafrost sometimes extends to depths of over a thousand meters[22,32,43]. Permafrost is a frozen mixture of soil, rock, ice and organic material, holding about three times as much carbon as currently exists in the Earth's atmosphere with Tibetan Plateau and near-coastal subsea permafrost included.[19,55,57] Cold temperatures in stable permafrost have protected this organic matter from decomposing for many thousands of years.

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

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

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

Global impacts of permafrost thaw will have cascading effects on health, infrastructure, and a wide range of socioeconomic variables.

Permafrost also occurs in shallow near-coastal seabeds especially off Eastern Siberia, in areas not covered by sea water at the end of the last Ice Age, but flooded as temperatures rose to today's. This subsea permafrost is rapidly thawing, as it has been "prewarmed" by overlying seawater throughout the past 10–15,000 years, with elevated methane concentrations measured in these shallow coastal waters.[45]

The Arctic however is now warming at 2–4 times the global average,[42] making these ancient permafrost stores of carbon highly vulnerable to thaw; followed by subsequent release of that stored carbon as both CO_2 and methane through the action of soil microbes over many years after that initial thaw.

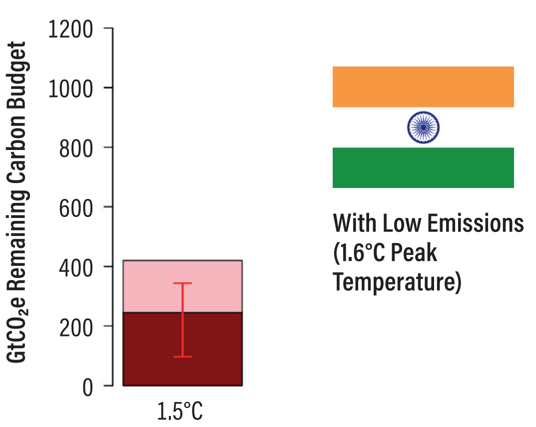
Models project that the land area covered by surface permafrost (in the first few meters of soils) will decline across large regions as temperatures rise.[55] Model estimations show that there has already been about a 7% decrease in near-surface permafrost extent over the past five decades,[33] and at the global average temperature increase of 1.2°C, we are already committed to losing about 25% of surface permafrost. Scientists anticipate that 40% of near-surface permafrost area will be lost by 2100, even if we hold temperatures close to 1.5°C globally. Over 70% of pre-industrial surface permafrost will thaw by 2100 should temperatures exceed 4°C.[6]

As temperatures have risen, permafrost has not only declined in area, but thawed to greater depth and is beginning to release its stored carbon, potentially at levels equal to that of Japan today (0.3–0.6 Pg carbon).[56] Most of this released carbon comes as CO_2. However, if permafrost thaws under wet conditions, such as under wetlands, lakes or coastal waters; some of that carbon enters the atmosphere as methane. While not lasting as long in the atmosphere as CO_2, methane warms the climate far more potently during its lifetime: about 30 times more than carbon dioxide over a 100-year period, and nearly 100 times more over 20 years, leading to faster and more intense warming globally.[14]

Permafrost thaw occurs gradually over its entire region but is also vulnerable to abrupt thaw events that can result in collapse and erosion, which can further accelerate thaw by exposing additional permafrost to warmer air temperatures and rain.[52] Such rapid collapse can also result in the formation of new lakes or wetlands, where additional and deeper thaw may occur. In northwestern Alaska, lake drainage rates are now ten times higher than their historical average in the 1980s, with 100–250 lakes rapidly lost each year.[31]

Coastal permafrost is especially vulnerable to these factors, with the additional erosion from wind and waves by warmer and more storm-prone Arctic seas. As coastal permafrost thaws, it can contribute to increased erosion of thousands of kilometers along the coasts of Alaska,

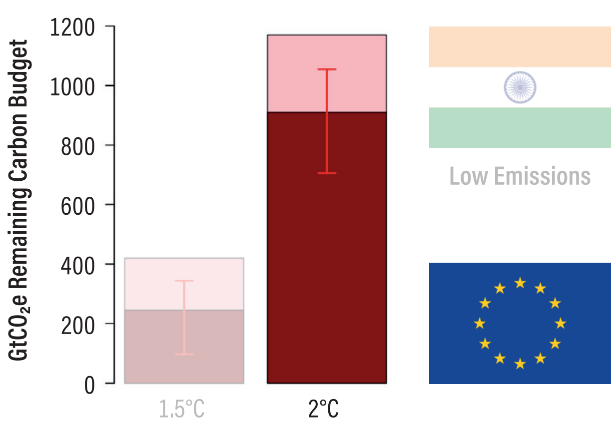
FIGURE 4-2. **Permafrost Emissions Decrease Our Carbon Budget at 1.5°C...**



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

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

FIGURE 4-3. **...But Decrease It More at 2°C**



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

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

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

Canada and Russia, and across the Arctic.[25,50,60,61] Rising global temperatures have even accelerated permafrost thaw in Greenland, increasing the vulnerability of coastal mountain regions to unpredictable landslides and collapse.[58]

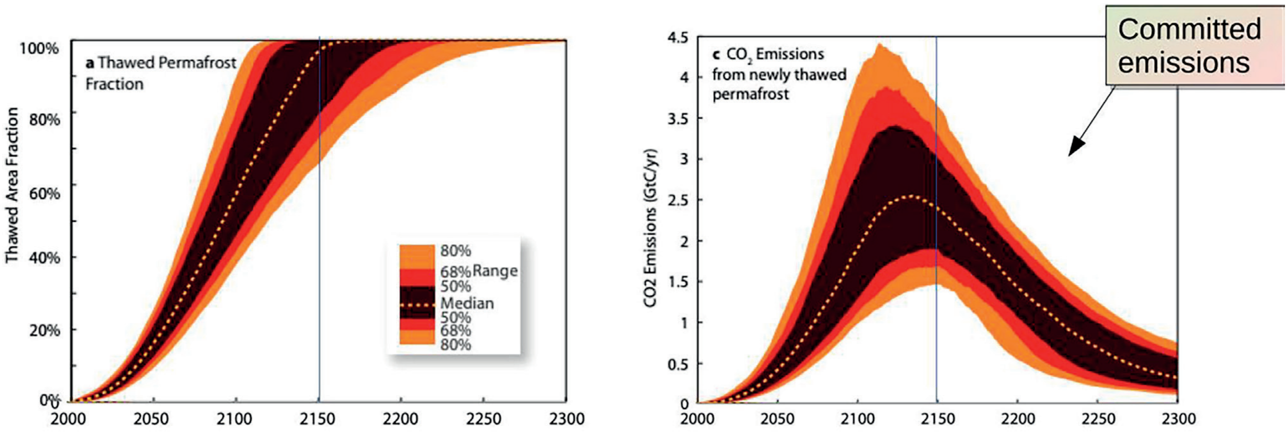
More incidents of extreme summer rainfall may increase the depth of permafrost thaw by more than 30%. Under a high emissions scenario, precipitation in the Arctic is projected to increase by 60% by 2100 and increasingly shift from snow to rain due to rising air temperatures.[35]

Current global climate models have not included such abrupt thaw processes, which expose deeper frozen carbon previously considered immune from thawing for many more centuries.[50,60] 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.[61] Increasing wildfires in the Arctic due to warmer and drier conditions also cause deeper and more rapid post-fire permafrost thawing.[36] At high latitudes, where much of the permafrost domain is located, most emissions from wildfire originate from below-ground combustion – rather than the combustion of above-ground biomass. Like emissions from other abrupt thaw events, these fire-related emissions – either from direct combustion, or from the effects of fire on permafrost – are typically excluded from global-scale models.[38,59]

Once triggered, emissions from permafrost thaw processes are most often permanent on human timescales, because re-building of new permafrost soils takes centuries to thousands of years.[10] While new vegetation growing on thawed permafrost soils might take up some portion of these emissions, the sheer scale of permafrost emissions at warmer temperatures would dwarf such uptake. New research actually shows that Arctic greening stimulated by higher temperatures and rising CO_2 may cause even larger losses of permafrost carbon, because the roots of these new plants stimulate emissions from microbes in the soil.

Subsea permafrost beneath the shallow coastal waters of the Arctic Ocean may also release greenhouse gases. These are permafrost soils that were flooded as sea levels rose at the end of the last ice age. Their current and future contribution to carbon emissions remains uncertain but could be significant. Estimates of total amounts, which are highly uncertain range from 170–740 Gt carbon, with 14–110 Gt carbon potentially released under high emissions by 2100, and up to 45–590 vulnerable to release by 2300 as the Arctic Ocean continues to warm on a multi-century level once atmospheric temperatures pass 4°C.[45]

FIGURE 4-4. **Committed Permafrost Emissions**



Permafrost thaw (left) is followed by centuries of emissions (right), meaning future generations must offset these.

CREDIT: S. CHADBURN, ADAPTED FROM SCHENIDER VON DIEMLING ET AL (2015) ADAPATED FROM GASSER, ET AL. (2018)

Once thaw occurs, permafrost emissions are irreversibly set in motion...for 1-2 centuries, meaning that future generations must offset them.

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

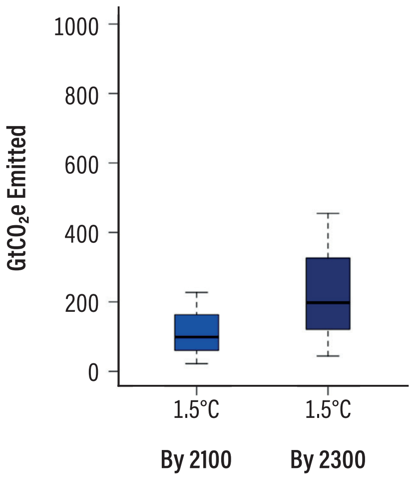
Permafrost emissions today and in the future are on the same scale as large industrial countries[44,54] but can be minimized if the planet remains at lower temperatures. If we limit warming to 1.5°C, emissions through 2100 will be about as large as those of India today, 2.5Gt/year, totaling around 150Gt CO2 by 2100. Should we instead reach 2°C, permafrost emissions will about equal those of the almost the entire European Union** today on an annual basis, 3-4Gt/year, for about 200 Gt CO2-eq by 2100. Even higher temperatures, exceeding 3-4°C by 2100, will however likely result in up to 400Gt CO2-eq additional carbon release from permafrost, adding the equivalent of adding another United States or China (currently 5-10Gt/year) annually to the global carbon budget through 2100.[6,15,18,27,38,60]

Calculations of the remaining planetary carbon budget must take these indirect human-caused emissions from permafrost thaw into account to accurately determine when and how emissions reach "carbon neutrality"; and not just through 2100, but well into the future.[1,9,15] This is because the thawing of permafrost is a slow process and because once thawed, permafrost soils continue to emit carbon for at least 100 years, and possibly several centuries. The actions of decision makers today to delay actions to decrease CO2 emissions will thereby commit future generations to offset permafrost carbon emissions through negative emissions (carbon dioxide removal), even after all human emissions cease and temperatures stabilize.[10]

In addition to the impacts of permafrost thaw on global climate, the direct physical effects of permafrost thaw (i.e., ground slumping, lake drainage, increased erosion and flooding) have been having severe impacts on Arctic people, lands, and economies for decades. Thawing permafrost is causing the loss of Arctic lands, threatening cultural and subsistence resources, and damaging infrastructure, like roads, pipelines and houses, as the ground sinks unevenly beneath them.[51] According to AMAP's latest *Climate Update*, more than 66% of Arctic settlements are located on permafrost. In Alaska, for example, permafrost thaw will increase cumulative

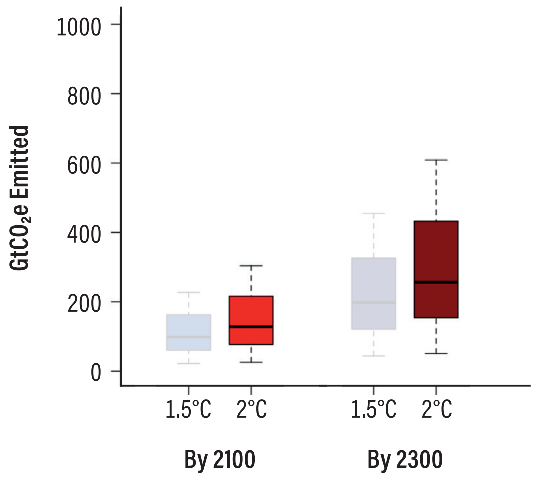
** technically "OECD Europe"

FIGURE 4-5. **Emissions Continue for Centuries after Initial Thaw: at 1.5°C**



ADAPATED FROM GASSER, ET AL. (2018)

FIGURE 4-6. **Multi-generational Permafrost Emissions at 2°C**



ADAPATED FROM GASSER, ET AL. (2018)

maintenance costs of public infrastructure by an estimated US$5.5 billion by 2100.[2] Some Alaskan permafrost is now in a thawed state year-round. With high emissions, three-quarters of Alaska's permafrost zone may reach this permanently unfrozen state within the next decade, with the thawed layer reaching depths of 10 m or more by 2100.[12]

Coastal and riverine permafrost erosion has already required some communities in Alaska to relocate homes and entire communities. Russia (with 60% of its total land area on permafrost) faces the most extensive risk, with recent studies estimating infrastructure loss and damage of tens of billions of dollars by 2050 if current warming continues.[17]

If global mean temperature rises above 2°C, more than 75% of permafrost peatland regions in northern Europe and western Siberia will become too warm and wet to maintain permafrost by the 2060s. Even with low emissions however, models do not project a return to conditions suitable to maintain peatland permafrost in Norway, Sweden, Finland, and parts of Russia – suggesting that these permafrost peatlands are close or have already passed a tipping point.[13]

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.[9,15] Warming in the Arctic already is occurring three to four times faster than the rest of the planet, due in part to the loss of snowpack, glaciers and sea ice.[42] The darker exposed bare ground and seawater absorb far more heat, further accelerating Arctic warming and additional thaw and loss of permafrost. A 2°C higher annual temperature globally translates into 4–6°C higher annual temperatures in the Arctic, including longer and more intense fire seasons and increasing heat waves where temperatures exceed 20°C sometimes for weeks on end, leading to much greater permafrost loss in a continuing feedback loop.

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

SCIENTIFIC REVIEWERS

Benjamin W. Abbott, Brigham Young University

Julia Boike, Alfred Wegener Institute (AWI)

Sarah Chadburn, University of Exeter

Gustaf Hugelius, Bolin Centre for Climate Research, Stockholm University

Hugues Lantuit, AWI

Susan Natali, Woodwell Climate Research Center

Paul Overduin, AWI

Vladimir Romanovsky, University of Alaska-Fairbanks

Christina Schädel, Woodwell Climate Research Center

Ted Schuur, IPCC LA SROCC, Northern Arizona University

Merritt Turetsky, INSTAAR / University of Guelph

Lawrence Hislop / GRID-Arendal resources library, www.grida.no/resources/1139

The people of Shishmaref, Alaska voted to move their entire village because of coastal permafrost erosion caused by global warming.

LITERATURE AND ADDITIONAL READING:

1. Abbott, B., Brown, M., Carey, J., Ernakovich, J., Frederick, J., Guo, L., Hugelius, G., . . . Zolkos, S. (2022). We Must Stop Fossil Fuel Emissions to Protect Permafrost Ecosystems. Frontiers in Environmental Science. https://www.doi.org/10.3389/fenvs.2022.889428
2. AMAP, 2021. Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy-makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. 16 pp. https://www.amap.no/documents/download/6759/inline
3. Bansal, S., van der Burg, M.P., Fern, R.R., Jones, J.W., Lo, R., McKenna, O.P., . . . Gleason, R.A. (2023). Large increases in methane emissions expected from North America's largest wetland complex. Science Advances Vol 9, Issue 9. https://doi.org/10.1126/sciadv.ade1112
4. Bauer, N., Keller, D.P., Garbe, J., Karstens, K., Piontek, F., von Bloh, W., . . . Winkelmann, R. (2023). Exploring risks and benefits of overshooting a 1.5 °C carbon budget over space and time. Environmental Research Letters, 18 054015. https://doi.org/10.1088/1748-9326/accd83
5. Biller-Celander, N., Shakun, J., Mcgee, D., Wong, C., Reyes, A., Hardt, B., . . . Lauriol, B. (2021). Increasing Pleistocene permafrost persistence and carbon cycle conundrums inferred from Canadian speleothems. Science Advances. http://doi.org/10.1126/sciadv.abe5799
6. Chadburn, S., Burke, E., Cox, P., Friedlingstein, G., & Westermann, S. (2017). An observation-based constraint on permafrost loss as a function of global warming. Nature Climate Change, 340–344. https://doi.org/10.1038/nclimate3262
7. Chen, Y., Lara, M., Jones, B., Frost, G., & Hu, F. (2021). Thermokarst acceleration in Arctic tundra driven by climate change and fire disturbance. One Earth. https://doi.org/10.1016/j.oneear.2021.11.011
8. Cheng, F., Garzione, C., Li, X., Salzmann, U., Schwarz, F., Haywood, A., . . . Tripati, A. (2022) Alpine permafrost could account for a quarter of thawed carbon based on Plio-Pleistocene paleoclimate analogue. Nature Communications. https://doi.org/10.1038/s41467-022-29011-2
9. Comyn-Platt, E., Hayman, G., Huntingford, C., Chardburn, S., Burke, E., Harper, A., . . . Sitch, S. (2018). Carbon budgets for 1.5 and 2°C targets lowered by natural wetland and permafrost feedbacks. Nature Geoscience, 11, pages 568–573. https://doi.org/10.1038/s41561-018-0174-9
10. de Vrese, P., & Brovkin, V. (2021). Timescales of the permafrost carbon cycle and legacy effects of temperature overshoot scenarios. Nature Communications. https://doi.org/10.1038/s41467-021-23010-5
11. Douglas, T., Hiemstra, C., Anderson, J., Barbato, R., Bjella, K., Deeb, E., & . . . Wagner, A. (2021). Recent degradation of interior Alaska permafrost mapped with ground surveys, geophysics, deep drilling, and repeat airborne lidar. The Cryosphere. https://doi.org/10.5194/tc-15-3555-2021
12. Farquharson, L., Romanovsky, V., Kholodov, A., & Nicolsky, D. (2022). Sub-aerial talik formation observed across the discontinuous permafrost zone of Alaska. Nature Geoscience, 475-481. https://doi.org/10.1038/s41561-022-00952-z
13. Fewster, R., Morris, P., Ivanovic, R., Swindles, G., Peregon, A., & Smith, C. (2022). Imminent loss of climate space for permafrost peatlands in Europe and Western Siberia. Nature Climate Change, 373-379. https://doi.org/10.1038/s41558-022-01296-7

14. Froitzheim, N., Majka, J., & Zastrozhnov, D. (2021). Methane release from carbonate rock formations in the Siberian permafrost area during and after the 2020 heat wave. Proceedings of the National Academy of Sciences of the United States of America, 118, 32, e2107632118. https://doi.org/10.1073/pnas.2107632118
15. Gasser, T., Kechiar, M., Ciais, P., Burke, E., Kleinen, T., Zhu, D., . . . Obersteiner , M. (2018). Path-dependent reductions in CO2 emission budgets caused by permafrost carbon release. Nature Geoscience, 830-835. https://doi.org/10.1038/s41561-018-0227-0
16. Guo, D., Wang, H., Romanovsky, V.E., Haywood, A.M., Pepin, N., Salzmann, U., . . . Kamae, Y. (2023). Highly restricted near-surface permafrost extent during the mid-Pliocene warm period. Proceedings of the National Academy of Sciences of the United States of America, 120, 36, e2301954120. https://doi.org/10.1073/pnas.2301954120
17. Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella K., & Luoto, M. (2022). Impacts of permafrost degradation on infrastructure. Nat Rev Earth Environ 3, 24–38. https://doi.org/10.1038/s43017-021-00247-8
18. Hugelius, G., Loisel, J., Chadburn, S., Jackson, R., Jones, M., MacDonald, G., . . . Yu, Z. (2020). Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. Proceedings of the National Academy of Sciences of the United States of America, 117, 34, 20438-20446. https://doi.org/10.1073/pnas.1916387117
19. Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J., Schuur, E., Ping, C.-L., . . . Kuhry, P. (2014). Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. Biogeosciences, 6573–6593. https://doi.org/10.5194/bg-11-6573-2014
20. ICIMOD (2023). Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook. (P. Wester, S. Chaudhary, N. Chettri, M. Jackson, A. Maharjan, S. Nepal, & J. F. Steiner [Eds.]). ICIMOD. https://doi.org/10.53055/ICIMOD.1028
21. IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty[V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R.Shukla,A. Pirani, W. Moufouma-Okia, C.Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield(eds.)]. https://www.ipcc.ch/sr15/
22. IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press. https://www.ipcc.ch/srocc/
23. IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press. https://doi:10.1017/9781009157896
24. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, https://doi.org/10.59327/IPCC/AR6-9789291691647
25. Irrgang, A.M., Bendixen, M., Farquharson, L.M., Baranskaya, A.V., Erikson, L.H., Gibbs, A.E., . . . & Jones, B.M. (2022). Drivers, dynamics and impacts of changing Arctic coasts. Nat Rev Earth Environ 3, 39–54. https://doi.org/10.1038/s43017-021-00232-1
26. Juhls, B., Antonova, S., Angelopoulos, M., Bobrov, N., Grigoriev, M., Langer, M., . . . Overduin, P. (2021). Serpentine (Floating) Ice Channels and their Interaction with Riverbed Permafrost in the Lena River Delta, Russia. Frontiers in Earth Science. https://doi.org/10.3389/feart.2021.689941
27. Keuper, F., Wild, B., Kummu, M., Beer, C., Blume-Werry, G., Fontaine, S., Gavazov, K., Gentsch, N., Guggenberger, G., Hugelius, G. and Jalava, M. (2020) Carbon loss from northern circumpolar permafrost soils amplified by rhizosphere priming. Nature Geoscience, pp.1-6. https://doi.org/10.1038/s41561-020-0607-0
28. Kleber, G.E., Hodson, A.J., Magerl, L., Mannerfelt, E.S., Bradbury, H.J., Zhu, Y., . . . Turchyn, A.V. (2023). Groundwater springs formed during glacial retreat are a large source of methane in the high Arctic. Nature Geoscience, 16, 597–604. https://doi.org/10.1038/s41561-023-01210-6
29. Koven, C., Lawrence, D., & Riley, W. (2015). Permafrost carbon−climate feedback is sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics. Proceedings of the National Academy of Sciences of the United States of America, 112, 12, 3752-3757. https://doi.org/10.1073/pnas.1415123112
30. Lapham, L., Dallimore, S., Magen, C., Henderson, L., Leanne C., P., Gonsior, M., . . . Orcutt, B. (2020). Microbial Greenhouse Gas Dynamics Associated With Warming Coastal Permafrost, Western Canadian Arctic. Frontiers in Earth Science. https://doi.org/10.3389/feart.2020.582103
31. Lara, M., Chen, Y., & Jones, B. (2021). Recent warming reverses forty-year decline in catastrophic lake drainage and hastens gradual lake drainage across northern Alaska. Environmental Research Letters. https://doi.org/10.18739/A2BV79W8S
32. Lawrence, D., Slater, A., & Swenson, S. (2012). Simulation of Present-Day and Future Permafrost and Seasonally Frozen Ground Conditions in CCSM4. Journal of Climate, 2207–2225. https://doi.org/10.1175/JCLI-D-11-00334.1
33. Li, H., Väliranta, M., Mäki, M., Kohl, L., Sannel, A., Pumpanen, J., . . . Bianchi, F. (2020). Overlooked organic vapor emissions from thawing Arctic permafrost. Environmental Research Letters. https://doi.org/10.1088/1748-9326/abb62d
34. MacDougall, A., Avis, C., & Weaver, A. (2012). Significant contribution to climate warming from the permafrost carbon feedback. Nature Geoscience, 719–721. https://doi.org/10.1038/ngeo1573
35. Magnússon, R., Hamm, A., Karsanaev, S., Limpens, J., Kleijn, D., Frampton, A., . . . Heijmans, M. (2022). Extremely wet summer events enhance permafrost thaw for multiple years in Siberian tundra. Nature Communications. https://doi.org/10.1038/s41467-022-29248-x
36. McCarty, J., Smith, T., & Turetsky, M. (2020). Arctic fires re-emerging. Nature Geoscience. https://doi.org/10.1038/s41561-020-00645-5
37. McGuire, A., Lawrence, D., Koven, C., Clein, J., Burke, E., Chen, G., . . . Zhuang, Q. (2018). Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. Proceedings of the National Academy of Sciences of the United States of America, 115, 15 3882-3887. https://doi.org/10.1073/pnas.1719903115
38. Natali, S., Holdren, J., Rogers, B., Treharne, R., Duffy, P., Pomerance, R., & MacDonald, E. (2021). Permafrost carbon feedbacks threaten global climate goals. Proceedings of the National Academy of Sciences of the United States of America, 118, 21, e2100163118. https://doi.org/10.1073/pnas.2100163118

39. Obu, J. (2021). How Much of the Earth's Surface is Underlain by Permafrost? Journal of Geophysical Research Earth Surface. https://doi.org/10.1029/2021JF006123
40. Pedron, S.A., Jespersen, R.G., Xu, X., Khazindar, Y., Welker, J.M., & Czimczik, C.I. (2023). More Snow Accelerates Legacy Carbon Emissions From Arctic Permafrost. AGU Advances 4, 4. https://doi.org/10.1029/2023AV000942
41. Ran, Y., Cheng, G., Dong, Y. Hjort, J., Lovecraft, A.L., Kang, S., . . . Li, X. (2022). Permafrost degradation increases risk and large future costs of infrastructure on the Third Pole. Commun Earth Environ 3, 238. https://doi.org/10.1038/s43247-022-00568-6
42. Rantanen, M., Karpechko, A.Y., Lipponen, A. Nordling, K., Hyvärinen, O., Ruosteenoja, K., . . . Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ 3, 168. https://doi.org/10.1038/s43247-022-00498-3
43. Romanovsky, V., Isaksen, K., Anisimov, O., & Drozdov, D. (2017). Changing permafrost and its impacts. Snow, Water, Ice and Permafrost in the Arctic (SWIPA), Arctic Monitoring and Assessment Programme (AMAP). 65-102. https://www.amap.no/documents/download/2987/inline
44. Rößger, N., Sachs, T., Wille, C., Boike, J., & Kutzbach, L. (2022) Seasonal increase of methane emissions linked to warming in Siberian tundra. Nature Climate Change, 12, 1031–1036. https://doi.org/10.1038/s41558-022-01512-4
45. Sayedi, S., Abbott, B., Thornton, B., Frederick, J., Vonk, J., Overduin, P., . . . Demidov, N. (2020). Subsea permafrost carbon stocks and climate change sensitivity estimated by expert assessment. Environmental Research Letters. https://doi.org/10.1088/1748-9326/abcc29
46. Schädel, C., Bader, M.-F., Schuur, E., Biasi, C., Bracho, R., Čapek, P., . . . Wickland, K. (2016). Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. Nature Climate Change, 950–953. https://doi.org/10.1038/nclimate3054
47. Schaefer, K., Elshorbany, Y., Jafarov, E., Schuster, P., Striegl, R., Wickland, K., & Sunderland , E. (2020). Potential impacts of mercury released from thawing permafrost. Nature Communications. https://doi.org/10.1038/s41467-020-18398-5
48. Schaefer, K., Lantuit, H., Romanovsky, V., Schuur, E., & Witt, R. (2014). The impact of the permafrost carbon feedback on global climate. Environmental Research Letters. https://doi.org/10.1088/1748-9326/9/8/085003
49. Schaefer, K., Lantuit, H., Romanovsky, V. E., and Schuur, E.A.G. (2012). Policy Implementations of Warming Permafrost, United Nations Environment Programme (UNEP), Nairobi, Kenya, pp. 30. https://www.unep.org/resources/report/policy-implications-warming-permafrost
50. Schneider von Deimling, T., Grosse, G., Strauss, J., Schirrmeister, L., Morgenstern, A., Schaphoff, S., . . . Boike, J. (2015). Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. Biogeosciences, 3469-3488. https://doi.org/10.5194/bg-12-3469-2015
51. Schneider von Deimling, T., Lee, H., Ingeman-Nielsen, T., Westermann, S., Romanovsky, V., Lamoureux, S., . . . Langer, M. (2021). Consequences of permafrost degradation for Arctic infrastructure – bridging the model gap between regional and engineering scales. The Cryosphere, 2451–2471. https://doi.org/10.5194/tc-15-2451-2021
52. Schuur, E., Abbott, B., Bowden, W., Brovkin, V,, Camill, P., Canadell, J., . . . Zimov, S. (2013). Expert assessment of vulnerability of permafrost carbon to climate change. Climate Change, 359–74. https://doi.org/10.1007/s10584-013-0730-7
53. Schuur, E., Abbott, B., Commane, R., Ernakovich, J., Euskirchen, E., Hugelius, G., . . . Turetsky, M. (2022). Permafrost and Climate Change: Carbon Cycle Feedbacks From the Warming Arctic. Annual Review of Environment and Resources 47, 343-371. https://doi.org/10.1146/annurev-environ-012220-011847
54. Schuur, E., Hicks Pries, C., Mauritz, M., Pegoraro, E., Rodenhizer, H., See, C., & Ebert, C. (2023). Ecosystem and Soil Respiration Radiocarbon Detects Old Carbon Release as a Fingerprint of Warming and Permafrost Destabilization with Climate Change. Philosophical Transactions of the Royal Society A, Vol 38, Issue 2261. https://doi.org/10.1098/rsta.2022.0201
55. Schuur, E., McGuire, A., Schädel, C., Grosse, G., Harden, J., Hayes, D., . . . Vonk, J. (2015). Climate change and the permafrost carbon feedback. Nature, 171–179. https://doi.org/10.1038/nature14338
56. Schuur, T. Permafrost and the Global Carbon Cycle. Arctic Report Card 2019. J. Richter-Menge, M. L. Druckenmiller, and M. Jeffries, Eds. https://arctic.noaa.gov/report-card/report-card-2019/
57. Strauss, J., Abbott, B., Hugelius, G., Schuur, E., Treat, C., Fuchs, M., . . . & Biasi, C. (2021) Permafrost: Importance of permafrost as major carbon stock. In: FAO and ITPS. Recarbonizing global soils – A technical manual of recommended management practices. Volume 2 – Hot spots and bright spots of soil organic carbon. Rome, FAO. https://doi.org/10.4060/cb6378en
58. Svennevig, K., Hermanns, R., Keiding, M., Binder, D., Citterio, M., Dahl-Jensen, T., . . . Voss, P. (2022). A large frozen debris avalanche entraining warming permafrost ground—the June 2021 Assapaat landslide, West Greenland. Landslides. https://doi.org/10.1007/s10346-022-01922-7
59. Treharne, R., Rogers, B.M., Gasser, T., MacDonald, E., & Natali, S. (2022). Identifying Barriers to Estimating Carbon Release From Interacting Feedbacks in a Warming Arctic. Front. Clim. 3:716464. https://doi.org/10.3389/fclim.2021.716464
60. Turetsky, M., Abbot, B., Jones, M., Anthony, K., Olefeldt, D., Schuur, E., . . . McGuire, A. (2020). Carbon release through abrupt permafrost thaw. Nature Geoscience, 138–143. https://doi.org/10.1038/s41561-019-0526-0
61. Turetsky, M., Abbott, B., Jones, M., Anthony, K., Olefeldt, D., Schuur, E., . . . Sannel, A. (2019). Permafrost collapse is accelerating carbon release. Nature. https://doi.org/10.1038/d41586-019-01313-4
62. Wu, M.-H., Chen, S.-Y, Chen, J.-W., & Wang, Y.-F. (2021). Reduced microbial stability in the active layer is associated with carbon loss under alpine permafrost degradation. Proceedings of the National Academy of Sciences of the United States of America, 118, 25, e2025321118. https://doi.org/10.1073/pnas.2025321118
63. Wu, M.-H., Chen, S.-Y., Chen, J.-W., Xue, K., Chen, S.-L., Wang, X.-M., . . . Wang, Y.-F. (2021). Reduced microbial stability in the active layer is associated with carbon loss under alpine permafrost degradation. Proceedings of the National Academy of Sciences of the United States of America, 118, 25, e20253211. https://doi.org/10.1073/pnas.2025321118
64. Zhuang, Q., Melillo, J., Sarofim, M., Kicklighter, D., McGuire, A., Felzer, B., . . . Hu, S. (2006). CO2 and CH4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century. Geophysical Research Letters. https://doi.org/10.1029/2006GL026972

CHAPTER 5

Sea Ice*

At Both Poles, 2°C Is Too High

Why 2°C is Too High for Sea Ice: By 2°C, the Arctic Ocean will be sea ice-free in summer not occasionally, but almost every year; and for periods of up to four months (July-October). The most recent projections show frequent ice-free conditions by 2050 even with "low emissions" (SSP1-2.6), a carbon pathway that peaks at 1.8°C (graph b, Figure 1, below). Open water in the Arctic for several months will absorb more heat from polar 24-hour sunlight conditions. A warmer Arctic will increase coastal permafrost thaw – adding more carbon to the atmosphere – and speed Greenland Ice Sheet melt and resulting sea-level rise. It also means that any Arctic sea ice recovery may take many decades, even with a subsequent return to lower atmospheric temperatures, because the water will hold that heat far longer. More open water, for longer periods may also absorb more carbon dioxide (CO_2), increasing Arctic Ocean acidification rates (see Polar Oceans chapter). In the Antarctic, complete loss of sea ice every summer seems plausible at 2°C if current trends continue, and would almost certainly speed up loss from the Antarctic ice sheet and resulting sea-level rise.

Preserved at 1.5°C: Studies consistently indicate that Arctic sea ice will still melt almost completely some summers even at 1.5°C, but not each year and only for a brief period (days to a few weeks) when it does. Only "very low" emissions (SSP1-1.9, which peaks at 1.6°C) can maintain Arctic sea ice in this state, and lead to some recovery by 2100, when temperatures begin to decline below 1.4°C (graph a, Figure 1). Negative impacts on sea ice-dependent Indigenous communities and ecosystems will still be significant, however, since at least one ice-free summer is now inevitable before 2050 even with "very low" emissions, according to the IPCC. Projections of sea ice in the Southern Ocean around Antarctica are considerably less certain, but record-low conditions in 2023 around much of Antarctica indicate that its threshold for complete summer sea ice loss might be even lower than for the Arctic.

Today's Emissions Aiming Towards 3°C+: If CO_2 concentrations continue to grow in the atmosphere at today's pace, which has not paused despite current pledges, global temperatures will reach at least 3°C by the end of this century. At such high temperatures, the Arctic Ocean may be ice-free not only in summer, but also well into the fall and melting much earlier in spring (graphs c,d; Figure 1). Based on recent developments, the ring of sea ice protecting Antarctic ice shelves and the ice sheet may also disappear for greater periods each summer. Feedbacks to further warming, Greenland and Antarctic ice sheet loss, and weather extremes would be intense and volatile.

The 2°C Takeaway: Perhaps more so than for any other part of the cryosphere, 2°C is far too high to prevent extensive sea ice loss at both poles, with severe feedbacks to global weather and climate.

---

* In previous *State of the Cryosphere* reports, this chapter was actually titled "Arctic sea ice" and touched only briefly on Antarctic sea ice, because there was little to report: Antarctic sea ice extent had not fluctuated much despite global warming. However, the past two-three years – and 2023 in particular – has shown a striking shift also in the Antarctic sea ice response to warming; so this chapter is now re-titled "Sea Ice" and covers both.

2023 Updates

- Arctic sea ice is more sensitive to greenhouse gas emissions than predicted by the IPCC AR6 report; and 90% of Arctic sea ice loss can be directly attributed to anthropogenic emissions. A threshold has now been crossed in which ice-free conditions in the month of September will occur at times even with very low emissions, and with much slower and later surface freeze-up. This study showed that anything above "very low" emissions (SSP1-1.9) results in complete loss of summer sea ice each year, with longer periods of ice-free conditions as emissions rise. Under current policies, the Arctic will experience ice-free summers in the 2030s, and the length of time that the Arctic is ice-free will expand into August and October by 2080.[10,23]
- Changes to Arctic sea ice go beyond its reduced coverage. Decades of measurements from the Fram Strait (where most multi-year ice is expelled into the North Atlantic, where it quickly breaks apart) show that Arctic sea ice crossed a threshold in 2005–2007, when half of the Arctic's thick multi-year ice disappeared; it has never recovered. Today, less than 10% of Arctic sea ice passing through the Fram Strait is over 4 meters thick. This more mobile, thinner, weaker ice is more prone to being pushed by strong Arctic winds towards the Atlantic, where warmer waters cause faster rates of melting. A typical sea ice floe now spends one-third less time in the Arctic Ocean compared to two decades ago.[40]
- Global warming has slowed the re-growth of Arctic sea ice in fall and winter following the melt season. The frequency of atmospheric rivers – narrow corridors of warmer, moist air – has increased over the central Arctic, causing slower refreezing of the fragile ice attempting to recover after the summer melt season.[47]
- Studies of plankton micro-fossils in sediment cores gathered from beneath the Arctic Ocean indicate that it was at least seasonally completely ice-free during the Last Inter-Glacial (LIG) period, or Eemian, 125,000 years ago, when global temperatures were between 1.5°–2°C above pre-industrial.[45]
- Continued Arctic warming has particularly reduced the number of days in which sea ice is produced in the Kara and Laptev seas — regions often called the "ice factories of the Arctic" due to their essential role in forming winter sea ice. The amount of new sea ice produced is expected to decrease dramatically if emissions are not reduced rapidly, accelerating the pace of Arctic sea ice loss.[9]
- Antarctic sea ice in 2023 experienced its greatest loss since records began; with each month setting a new record low. A record summer minimum of 1.79 million km^2 was set on February 21, 2023. During the Southern Hemisphere winter, its extent remained far below average; and a new record-low maximum (when the sea ice reaches its greatest area) was set on September 10, 2023, at 1 million km^2 less than the previous record. In July 2023, 2.77 million square km^2 of ice were 'missing' compared to average — a reduction equivalent to an area the size of Argentina.
- The unprecedented reduction in Antarctic sea ice extent since 2016 represents a regime shift to a new state of inevitable decline caused by ocean warming, and attribution techniques show that the primary cause is anthropogenic fossil fuel emissions.[33,35]
- One example of how the recent reductions in Antarctic sea ice have had catastrophic impacts is the effect on Emperor penguins, which rely on stable sea ice platforms between April and December to successfully breed. If sea ice breaks up early, the chicks fall into the water and drown. The low spring sea ice extent in 2022 led to the highest rates of breeding failure ever recorded. In some regions, 80% of penguin colonies suffered total breeding failure.[17]

The unprecedented reduction in Antarctic sea ice extent since 2016 represents a regime shift to a new state of inevitable decline caused by ocean warming.

Background

ARCTIC SEA ICE

Arctic sea ice serves as a "global refrigerator" and is an important regulator of the Earth's temperature. This large area of ice-covered ocean — 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 sea ice and snow, the darker open ocean water absorbs heat, amplifying Arctic and overall global warming. Sea ice has served this cooling role in the climate system almost continuously for at least the past 125,000 years.

The area of Arctic sea ice that survives the summer, however, has declined by at least 40% since 1979, when reliable satellite measurements first became available.[12,30] Estimates based on eyewitness accounts from ships and polar explorers place the decline since 1900 at around 60%.[46] In addition, the Arctic ocean has become dominated by a thinner, faster moving covering of seasonal ice which typically doesn't survive the summer.[38] This is in contrast to the coverage of thick, rough "multiyear ice" which stands to go extinct entirely with the advent of ice-free summers.[13,27,38,40] The total volume of Arctic sea ice since the 1970s has therefore declined by nearly two-thirds: a much faster and greater decline than its area.

This rapid loss of summer sea ice is a significant cause of "Arctic amplification," which refers to the greater rise in temperature observed in the high latitudes of the northern hemisphere compared to the rest of the globe.[20,34,38] It also carries wide-ranging weather, ecological, and economic consequences. These include the loss of traditional livelihoods for Arctic Indigenous people dependent on stable sea ice platforms for hunting, fishing and travel.

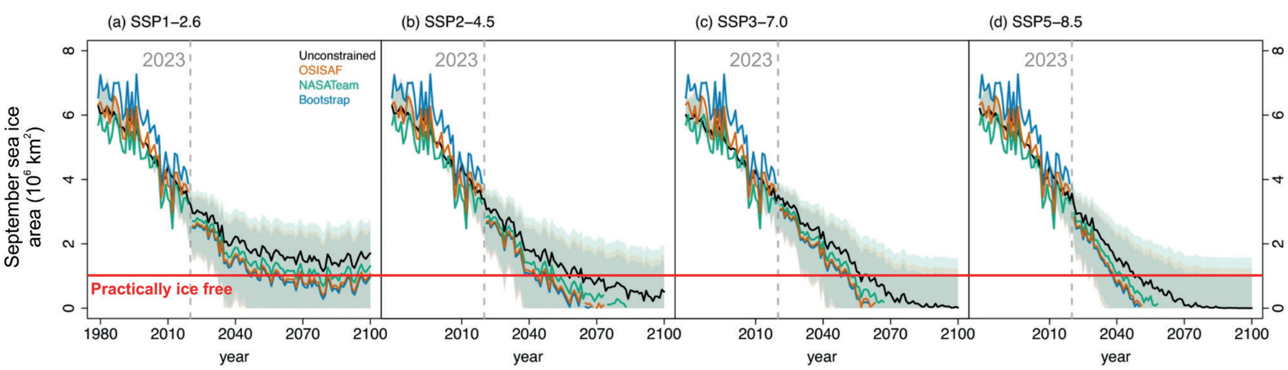
Sea ice has served a cooling role in the climate system almost continuously for at least the past 125,000 years.

Less summer sea ice also influences mid-latitude weather systems, as exemplified by the persistent and abnormal cold, warm, wet, and dry conditions in recent years that can be related to a more "wobbly" jet stream.[2,7,11,16,41,42]

Continued sea ice loss will cause significant harm to Arctic Ocean ecosystems. Many marine species there evolved with an ice "ceiling" for much of the year, and populations of these keystone species are expected to crash, except in small pockets with persistent ice during the first ice-free summer event.[36,38] Even with low emissions, ice-free summer conditions are projected to occur at least once before 2050.[13,23,27,29,30] This will have a lasting effect on the entire Arctic food chain, and perhaps beyond.

Summer Arctic sea ice extent has often been considered a bellwether of climate change, with great attention paid to the September minimum extent each year. In reality, however, sea ice thickness and extent have declined in all months since the 1980s; and the consensus of sea ice scientists is that the ice cover has already fundamentally changed, crossing a threshold to a new state.[1,31,38,40] Amplified Arctic warming has reduced how effectively sea ice can recover in winter.[9,49] As a result, thinner and younger ice has replaced much of the multi-year ice that used to circulate around the North Pole before being discharged into the North Atlantic Ocean.[22,24,38] This thinner, weaker ice is more prone to being pushed towards the Atlantic by winds where warmer waters

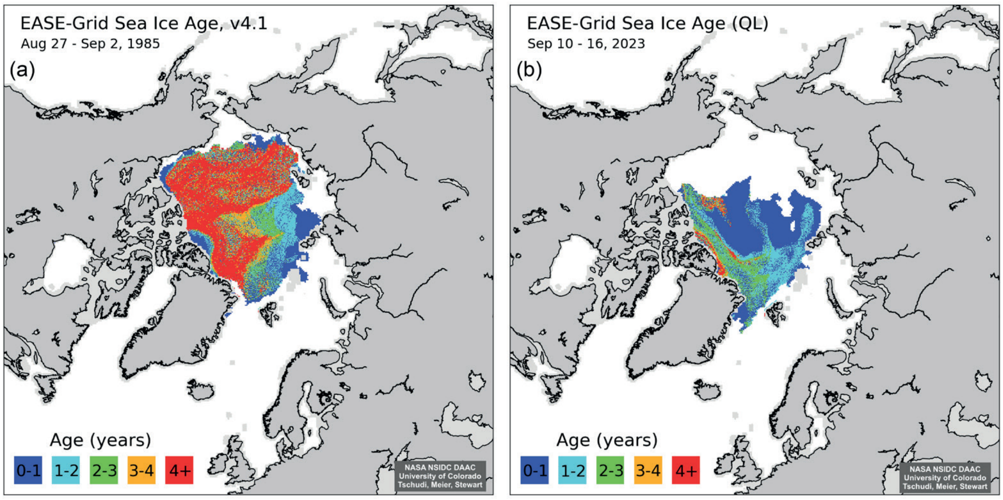
FIGURE 5-1. **Latest Modeling: "Very Low" Emissions Path Preserves Arctic Summer Ice**



Updated projections of September Arctic sea ice area for different emissions scenarios using state-of-the-art modeling. Only very low emissions (SSP1-1.9) results in sea ice recovery above ice-free conditions.

SOURCE: KIM ET AL. (2023)

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



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

SOURCE: NSIDC

result in faster rates of melting; consequently, sea ice now spends one-third less time in the Arctic Ocean compared to two decades ago.[40]

This former "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 for only 1-3 years on average.[38]

Despite this fundamental change already observed at today's heightened temperatures, the first ice-free summer will be an event that the Arctic likely has not experienced since at least the spike in warming that occurred at the end of the last ice age 8,000 years ago, and possibly not since the warm Eemian period 125,000 years ago.[45] Today's temperatures now almost equal those of the Eemian, when much of Greenland may have been ice-free in part due to feedbacks from this seasonally open and warmer Arctic Ocean, with sea levels 5-10 meters (16-32 feet) higher than today.[3,14] This is the current trajectory of the Earth's climate; CO_2 levels from human emissions today are higher than at any point in the last 3 million years.

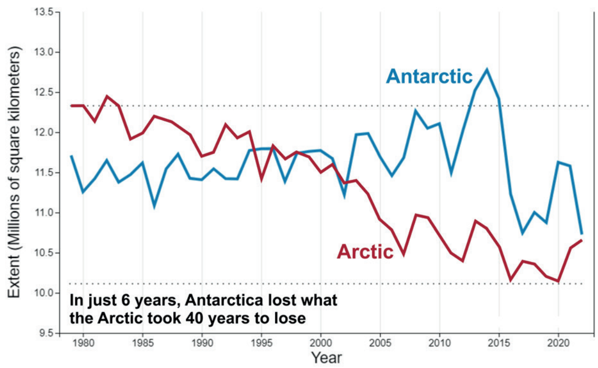
Like many impacts of climate change, Arctic sea ice loss over the past three decades has not occurred gradually, but rather in abrupt loss events when combinations of wind and warmer temperatures drove lower ice extents.[4,5,12,25,26] It is likely that a near-complete loss of summer sea ice (defined as dipping below 15% of the Arctic Ocean's area, or 1 million km^2) will occur with one of these sudden events, but perhaps not occur again for several years. Eventually total-loss summers will become more frequent, and if temperatures continue to rise past a threshold of about 1.7°C, they will become the norm for some portion of each summer, with ice-free conditions ultimately extending into spring and autumn.[10,23,27,28]

The former "ecosystem of ice" no longer exists.

The occurrence of the first sea ice-free Arctic summer is therefore unpredictable, but scientists now believe it is inevitable, and likely to occur at least once before 2050 even under a "very low" emissions scenario.[13,27,28,30] However, under both very low and low emissions scenarios, summer sea ice extent would likely stabilize, with occasional ice-free years, but remain generally above the threshold for ice-free conditions. Greater amounts of sea ice may then form, slowly increasing as atmospheric temperatures decline below 1.5°C, but with multi-year ice nevertheless taking many decades to re-form due to a warmer Arctic Ocean.[4]

In contrast, continuing on the current emissions trajectory may lead to the Arctic becoming ice free in the summer as soon as the 2030s.[23] Even moderate emissions will lead to ice-free conditions most summers once global mean temperature rise reaches about 1.7°C. The length of this ice-free state would increase in lock-step with emissions and temperature,[10,28,29,39] eventually stretching from July-October at 2°C.[21,29] 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.[10,38]

FIGURE 5-3. **Arctic v. Antarctic Sea Ice Loss**



With the rapid decline in Antarctic sea ice over the past six years – especially in 2023 – Antarctica sea ice loss now nearly equals that in the Arctic.

SOURCE DATA: NSIDC.

The global impact of complete Arctic summer sea ice loss will therefore include accelerated global warming and its cascading impacts. Given the greater absorption of solar heat into open water, it will lead to higher autumn and winter temperatures in the Arctic that are expected to affect weather patterns around the Northern Hemisphere.[2,8,11,16,41,42,44,48,50] Unusual weather patterns likely will involve persistent conditions (drought, heatwaves, cold spells, or stormy periods), such as the extreme current multi-year drought in the U.S. Southwest; extreme heatwaves in northwestern North America in June 2021 and much of Europe in 2022 and 2023;[41] the summer 2018 drought in Scandinavia that contributed to extensive wildfires and agricultural losses, and the severe freeze in the central U.S. during February 2021.[7] Accelerating permafrost thaw and melting of land ice on Greenland and Arctic glaciers would lead to greater emissions of greenhouse gases and faster sea-level rise.

Finally, while some Arctic governments declare that an ice-free summer Arctic will bring near-term economic opportunity, it is important to balance such statements with the global impacts elsewhere. The 2°C of global warming above pre-industrial levels that will cause summer ice-free conditions and allow exploitation of Arctic resources will also amplify the risks and societal disruptions noted elsewhere in this report, such as 6–20 meters committed long-term sea-level rise, fisheries loss from acidification, and extensive coastal damage from more intense storms and coastal permafrost thaw, including in the coastal Russian High North.[2,7,10,37,42] Such profound adverse impacts almost certainly will eclipse any temporary economic benefits brought by an ice-free summer Arctic.

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

ANTARCTIC SEA ICE

Although the extent of sea ice around Antarctica had been stable or even increased slightly over the last several decades, recent observations document a very sharp decline beginning in 2016, equal to or exceeding those in the Arctic but occurring over the space of only a few years, rather than decades.[32] This sharp decline was highlighted in the summers of 2022 and 2023, when Antarctic sea ice extent fell below 2 million square kilometers for the first time,[43] reaching a record-breaking minimum extent of 1.79 million km² on February 21, 2023. This trend of unusually low sea ice extent has continued into the Southern Hemisphere winter of 2023 when sea ice is normally expected to recover; by July 2023, 2.77 million km² of ice were 'missing' compared to average conditions between 1981-2010 — a reduction equivalent to losing an area of ice the size of Argentina. The final maximum, reached on September 10, 2023, was fully 1 million km² below the previous record.

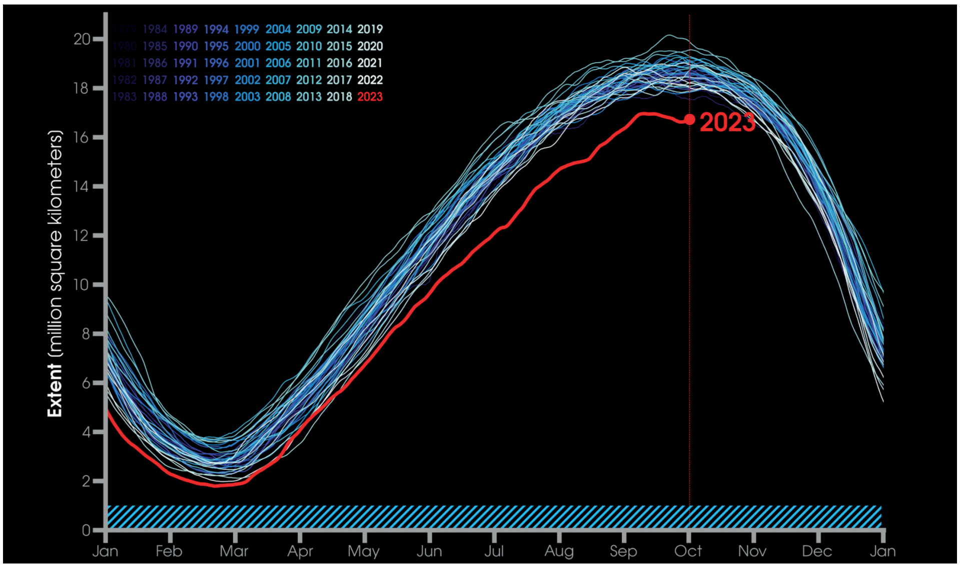
The recent behavior of Antarctic sea ice is unprecedented since records began. It signals that Antarctic sea ice may have shifted into a new regime of decline because of ocean warming caused by anthropogenic fossil fuel emissions.[33,35]

These reductions in Antarctic sea ice extent in recent years have negatively impacted ice sheet stability, ocean circulation, and ecosystems in a similar manner to ongoing changes in the Arctic. The continued loss of Antarctic sea ice will expose ice shelves to greater ocean swell which may trigger their rapid disintegration.[6] Ice shelves that weaken or even collapse can 'open the floodgates' to significant sea level rise, due to their role in restraining the flow of land-based ice into the ocean.[18] Sea ice losses around some regions of Antarctica are also predicted to modify ocean circulation patterns to bring warmer water masses closer to the main ice sheet, accelerating the melting of Antarctic glaciers.[19]

Antarctic sea ice also plays an essential role in producing Antarctic Bottom Water — the densest water mass on the planet — which drives the entire global ocean

The recent behavior of Antarctic sea ice is unprecedented since records began.

FIGURE 5-4. **Antarctic Sea Ice Since 1979**



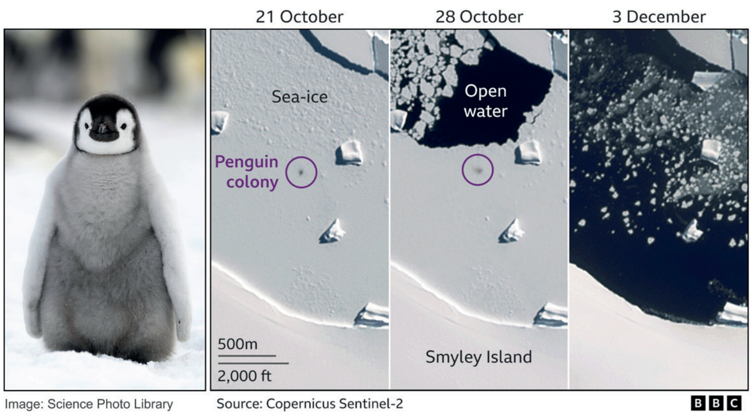
A record low summer sea ice extent was reached in February 2023; and then the 2023 "maximum" in September was a record-blowing 1 million km^2 below the previous record.

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

"conveyor belt," transporting carbon and heat deep into the ocean, where it is stored for centuries to millennia. A 40% decline in sea ice in the Weddell Sea has reduced the production of Antarctic Bottom Water in this region by almost a third in the last three decades.[49] A slowdown in Antarctic sea ice production could therefore harm the Southern Ocean's ability to take CO_2 out of the atmosphere, accelerating the pace of global temperature rise. Dramatic reductions in Antarctic sea ice extent have also had a catastrophic impact on Emperor penguins, which rely on stable sea ice platforms between April and December to successfully breed.[17]

For decades, Antarctic sea ice seemed almost immune to global warming, showing changes of at most 1-2% while Arctic sea ice declined precipitously by 40–60% during the same period. This apparent immunity to global warming may no longer hold. Given the long-term impacts on Antarctic ice sheet stability and global sea-level rise, the human consequences of Antarctic sea ice loss may ultimately prove far greater than that of its Arctic cousin.

FIGURE 5-5. **Loss of Penguin Colonies**



Loss of the Smyley Island emperor penguin colony in 2022 due to early Antarctic sea ice breakup

CREDIT: J. AMOS.

The human consequences of Antarctic sea ice loss may ultimately prove far greater than those of its Arctic cousin.

SCIENTIFIC REVIEWERS

Jennifer Francis, Woodwell Climate Research Center

Ronald Kwok, Polar Science Center, Applied Physics Laboratory, University of Washington

Robbie Mallett, University of Manitoba

Walt Meier, National Snow and Ice Data Center

Dirk Notz, University of Hamburg, Germany

Martin Sommerkorn, IPCC SROCC CLA, WWF-Arctic

Julienne Stroeve, University College London/University of Manitoba/NSIDC

Paul Wassmann, UiT - The Arctic University of Norway (emeritus)

LITERATURE AND ADDITIONAL READING

1. Årthun, M., et al. (2021). The Seasonal and Regional Transition to an Ice-Free Arctic. Geophysical Research Letters, v. 48, no, 1, e2020GL090825, https://doi.org/https://doi.org/10.1029/2020GL090825.
2. Bailey, H., et al. (2021). Arctic sea-ice loss fuels extreme European snowfall. Nature Geoscience, v. 14, no, 5, 283–288, https://doi.org/10.1038/s41561-021-00719-y.
3. Barnett, R.L., et al. (2023). Constraining the contribution of the Antarctic Ice Sheet to Last Interglacial sea level. Science Advances, v. 9, no, 27, eadf0198, https://doi.org/doi:10.1126/sciadv.adf0198.
4. Bathiany, S., et al. (2016). On the Potential for Abrupt Arctic Winter Sea Ice Loss. Journal of Climate, v. 29, no, 7, 2703–2719, https://doi.org/https://doi.org/10.1175/JCLI-D-15-0466.1.
5. Burgard, C. and D. Notz (2017). Drivers of Arctic Ocean warming in CMIP5 models. Geophysical Research Letters, v. 44, no, 9, 4263–4271, https://doi.org/https://doi.org/10.1002/2016GL072342.
6. Christie, F.D.W., et al. (2022). Antarctic ice-shelf advance driven by anomalous atmospheric and sea-ice circulation. Nature Geoscience, v. 15, no, 5, 356–362, https://doi.org/10.1038/s41561-022-00938-x.
7. Cohen, J., et al. (2021). Linking Arctic variability and change with extreme winter weather in the United States. Science, v. 373, no, 6559, 1116–1121, https://doi.org/doi:10.1126/science.abi9167.
8. Cohen, J., et al. (2014). Recent Arctic amplification and extreme mid-latitude weather. Nature Geoscience, v. 7, no, 9, 627–637, https://doi.org/10.1038/ngeo2234.
9. Cornish, S.B., et al. (2022). Rise and fall of sea ice production in the Arctic Ocean's ice factories. Nature Communications, v. 13, no, 1, 7800, https://doi.org/10.1038/s41467-022-34785-6.
10. Crawford, A., et al. (2021). Arctic open-water periods are projected to lengthen dramatically by 2100. Communications Earth & Environment, v. 2, no, 1, 109, https://doi.org/10.1038/s43247-021-00183-x.
11. Cvijanovic, I., et al. (2017). Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall. Nature Communications, v. 8, no, 1, 1947, https://doi.org/10.1038/s41467-017-01907-4.
12. Ding, Q., et al. (2017). Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. Nature Climate Change, v. 7, no, 4, 289–295, https://doi.org/10.1038/nclimate3241.
13. Docquier, D. and T. Koenigk (2021). Observation-based selection of climate models projects Arctic ice-free summers around 2035. Communications Earth & Environment, v. 2, no, 1, 144, https://doi.org/10.1038/s43247-021-00214-7.
14. Dutton, A., et al. (2015). Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science, v. 349, no, 6244, aaa4019, https://doi.org/doi:10.1126/science.aaa4019.
15. Fox-Kemper, B., et al., *Ocean, Cryosphere and Sea Level Change*, in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte, et al., Editors. 2021, Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA. p. 1211–1362. https://doi.org/10.1017/9781009157896.011.
16. Francis, J.A. and S.J. Vavrus (2012). Evidence linking Arctic amplification to extreme weather in mid-latitudes. Geophysical Research Letters, v. 39, no, 6, https://doi.org/https://doi.org/10.1029/2012GL051000.
17. Fretwell, P.T., A. Boutet, and N. Ratcliffe (2023). Record low 2022 Antarctic sea ice led to catastrophic breeding failure of emperor penguins. Communications Earth & Environment, v. 4, no, 1, 273, https://doi.org/10.1038/s43247-023-00927-x.
18. Füerst, J.J., et al. (2016). The safety band of Antarctic ice shelves. Nature Climate Change, v. 6, 479–482, https://doi.org/10.1038/nclimate2912.
19. Gómez-Valdivia, F., et al. (2023). Projected West Antarctic Ocean Warming Caused by an Expansion of the Ross Gyre. Geophysical Research Letters, v. 50, no, 6, e2023GL102978, https://doi.org/https://doi.org/10.1029/2023GL102978.
20. Haine, T.W.N. and T. Martin (2017). The Arctic-Subarctic sea ice system is entering a seasonal regime: Implications for future Arctic amplification. Scientific Reports, v. 7, no, 1, 4618, https://doi.org/10.1038/s41598-017-04573-0.
21. Jahn, A. (2018). Reduced probability of ice-free summers for 1.5°C compared to 2°C warming. Nature Climate Change, v. 8, no, 5, 409–413, https://doi.org/10.1038/s41558-018-0127-8.
22. Kacimi, S. and R. Kwok (2022). Arctic Snow Depth, Ice Thickness, and Volume From ICESat-2 and CryoSat-2: 2018–2021. Geophysical Research Letters, v. 49, no, 5, e2021GL097448, https://doi.org/https://doi.org/10.1029/2021GL097448.
23. Kim, Y.-H., et al. (2023). Observationally-constrained projections of an ice-free Arctic even under a low emission scenario. Nature Communications, v. 14, no, 1, 3139, https://doi.org/10.1038/s41467-023-38511-8.
24. Kwok, R. (2018). Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018). Environmental Research Letters, v. 13, no, 10, 105005.
25. Liu, Z., et al. (2021). Acceleration of western Arctic sea ice loss linked to the Pacific North American pattern. Nature Communications, v. 12, no, 1, 1519, https://doi.org/10.1038/s41467-021-21830-z.
26. Mallett, R.D.C., et al. (2021). Record winter winds in 2020/21 drove exceptional Arctic sea ice transport. Communications Earth & Environment, v. 2, no, 1, 149, https://doi.org/10.1038/s43247-021-00221-8.

27. Niederdrenk, A.L. and D. Notz (2018). Arctic Sea Ice in a 1.5°C Warmer World. Geophysical Research Letters, v. 45, no, 4, 1963–1971, https://doi.org/https://doi.org/10.1002/2017GL076159.
28. Notz, D. and J. Stroeve (2016). Observed Arctic sea-ice loss directly follows anthropogenic CO2 emission. Science, v. 354, no, 6313, 747–750, https://doi.org/doi:10.1126/science.aag2345.
29. Notz, D. and J. Stroeve (2018). The Trajectory Towards a Seasonally Ice-Free Arctic Ocean. Current Climate Change Reports, v. 4, no, 4, 407–416, https://doi.org/10.1007/s40641-018-0113-2.
30. Overland, J.E. and M. Wang (2013). When will the summer Arctic be nearly sea ice free? Geophysical Research Letters, v. 40, no, 10, 2097–2101, https://doi.org/https://doi.org/10.1002/grl.50316.
31. Overpeck, J.T., et al. (2005). Arctic system on trajectory to new, seasonally ice-free state. Eos, Transactions American Geophysical Union, v. 86, no, 34, 309–313, https://doi.org/https://doi.org/10.1029/2005EO340001.
32. Parkinson, C.L. (2019). A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. Proceedings of the National Academy of Sciences, v. 116, no, 29, 14414–14423, https://doi.org/doi:10.1073/pnas.1906556116.
33. Purich, A. and E.W. Doddridge (2023). Record low Antarctic sea ice coverage indicates a new sea ice state. Communications Earth & Environment, v. 4, no, 1, 314, https://doi.org/10.1038/s43247-023-00961-9.
34. Rantanen, M., et al. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment, v. 3, no, 1, 168, https://doi.org/10.1038/s43247-022-00498-3.
35. Raphael, M.N. and M.S. Handcock (2022). A new record minimum for Antarctic sea ice. Nature Reviews Earth & Environment, v. 3, no, 4, 215–216, https://doi.org/10.1038/s43017-022-00281-0.
36. Schweiger, A.J., et al. (2021). Accelerated sea ice loss in the Wandel Sea points to a change in the Arctic's Last Ice Area. Communications Earth & Environment, v. 2, no, 1, 122, https://doi.org/10.1038/s43247-021-00197-5.
37. Stranne, C., et al. (2021). The climate sensitivity of northern Greenland fjords is amplified through sea-ice damming. Communications Earth & Environment, v. 2, no, 1, 70, https://doi.org/10.1038/s43247-021-00140-8.
38. Stroeve, J. and D. Notz (2018). Changing state of Arctic sea ice across all seasons. Environmental Research Letters, v. 13, no, 10, 103001.
39. Stroeve, J.C., et al. (2012). Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. Geophysical Research Letters, v. 39, no, 16, https://doi.org/https://doi.org/10.1029/2012GL052676.
40. Sumata, H., et al. (2023). Regime shift in Arctic Ocean sea ice thickness. Nature, v. 615, no, 7952, 443–449, https://doi.org/10.1038/s41586-022-05686-x.
41. Sun, J., et al. (2022). Influence and prediction value of Arctic sea ice for spring Eurasian extreme heat events. Communications Earth & Environment, v. 3, no, 1, 172, https://doi.org/10.1038/s43247-022-00503-9.
42. Tang, Q., X. Zhang, and J.A. Francis (2014). Extreme summer weather in northern mid-latitudes linked to a vanishing cryosphere. Nature Climate Change, v. 4, no, 1, 45–50, https://doi.org/10.1038/nclimate2065.
43. Turner, J., et al. (2022). Record Low Antarctic Sea Ice Cover in February 2022. Geophysical Research Letters, v. 49, no, 12, e2022GL098904, https://doi.org/https://doi.org/10.1029/2022GL098904.
44. Vavrus, S.J. (2018). The Influence of Arctic Amplification on Mid-latitude Weather and Climate. Current Climate Change Reports, v. 4, no, 3, 238–249, https://doi.org/10.1007/s40641-018-0105-2.
45. Vermassen, F., et al. (2023). A seasonally ice-free Arctic Ocean during the Last Interglacial. Nature Geoscience, v. 16, no, 8, 723–729, https://doi.org/10.1038/s41561-023-01227-x.
46. Walsh, J.E., et al. (2017). A database for depicting Arctic sea ice variations back to 1850. Geographical Review, v. 107, no, 1, 89–107, https://doi.org/10.1111/j.1931-0846.2016.12195.x.
47. Zhang, P., et al. (2023). More frequent atmospheric rivers slow the seasonal recovery of Arctic sea ice. Nature Climate Change, v. 13, no, 3, 266–273, https://doi.org/10.1038/s41558-023-01599-3.
48. Zhang, R. and J.A. Screen (2021). Diverse Eurasian Winter Temperature Responses to Barents-Kara Sea Ice Anomalies of Different Magnitudes and Seasonality. Geophysical Research Letters, v. 48, no, 13, e2021GL092726, https://doi.org/https://doi.org/10.1029/2021GL092726.
49. Zhou, S., et al. (2023). Slowdown of Antarctic Bottom Water export driven by climatic wind and sea-ice changes. Nature Climate Change, v. 13, no, 7, 701–709, https://doi.org/10.1038/s41558-023-01695-4.
50. Zou, Y., et al. (2021). Increasing large wildfires over the western United States linked to diminishing sea ice in the Arctic. Nature Communications, v. 12, no, 1, 6048, https://doi.org/10.1038/s41467-021-26232-9.

Polar Ocean Acidification, Warming and Freshening

Very Low Emissions – The Only Means to Save Many Polar Species and Fisheries

Why 2°C is Too High for Polar Oceans: All 2°C emissions pathways lead to CO_2 levels in the atmosphere well above 450 ppm, the critical level for polar oceans identified decades ago by marine scientists. The Arctic and Southern Oceans are bearing the brunt of acidification impacts because they absorb CO_2 faster. At these CO_2 levels, peaking near 500 ppm in the atmosphere, the near-polar oceans, especially the Barents, North and Baltic seas, also would have acidification levels rivaling that of the poles. Shell-building animals, and commercial fisheries that rely on them in the food chain – valuable species such as krill, cod, salmon, lobsters, king crab, to name just a few – may not survive in the wild or even in fish farms. Given warmer waters and lack of protective sea ice for several months each summer, marine heat waves and extreme acidification events will cause additional losses. These "overshoot" corrosive conditions, set by peak atmospheric CO_2 levels, are essentially irreversible, lasting tens of thousands of years.

Preserved at 1.5°C: The "very low" emissions pathways resulting in temperatures close to the 1.5°C Paris limit reliably maintain atmospheric CO_2 well below 450 ppm; the most ambitious (SSP1-1.9) sees CO_2 levels peak at 430 ppm. This will limit corrosive stressing conditions to mostly seasonal damage in smaller sections of the Arctic and Southern Oceans, spreading marginally from what is already seen as shell damage today. This 430 ppm threshold is very close however: the May 2023 monthly average CO_2 level at Mauna Loa Observatory was 424 ppm. Destructive compound events combining marine heatwaves and extreme acidification have already caused population crashes even at today's 1.2°C. Worse can be expected by 1.5°C, but very low emissions pathways would see temperatures dropping below 1.4° C by 2100, as CO_2 levels in the atmosphere trend downwards.

Today's Emissions Aim Towards 3°C+: If CO_2 continues to accumulate in the atmosphere at today's pace, which has not paused despite current pledges, CO_2 levels will reach at least 600 ppm by the end of this century, with global mean temperature exceeding 3°C and continuing to increase thereafter. Acidification will occur throughout the Arctic and Southern Oceans as well as many near-polar regions, and these corrosive conditions will persist for tens of thousands of years. In the polar oceans, this will almost certainly results in mass extinctions of species, given the 30–70,000 year persistence of ocean acidification, as well as the very long period these oceans will hold heat.

The 2°C Takeaway: 2°C will result in year-round, essentially permanent corrosive conditions in extensive regions of Earth's polar and some near-polar seas; with widespread negative impacts on key fisheries and species.

2023 Updates

- CO_2 levels topped 424 ppm several times in 2023, with 424.00 the monthly average at Mauna Loa Observatory. With that 424 measurement, levels of CO_2 in the atmosphere have now officially increased 50% over pre-industrial. (NOAA Mauna Loa, 2023).
- Marine heatwaves occurred worldwide in 2023. In polar and near-polar regions, perhaps the greatest high temperature anomaly took place in the North Atlantic and North Sea in May-July, when water temperatures reached record high levels. West of Ireland, temperatures peaked at 4–5°C above average, a "Category 5" occurrence classified "Beyond Extreme" with temperatures as high for nearly as high about average in several areas of the Arctic, including near Svalbard in July, and the Barents Sea in early August (NOAA Marine Heatwave Watch, 2023). Unusually warm winter water of 2°C above normal also was measured in July near ice-free conditions off Antarctica.
- The net oceanic uptake rate of CO_2 will likely decrease in the future owing to several converging trends: reduced storage capacity due to acidification to-date; increased outgassing of natural CO_2 due to ocean warming ; and changes in ocean circulation and biology.[24] While this may slow acidification, it means that CO_2 levels in the atmosphere will rise more quickly unless emissions are reduced.
- Parts of the Arctic Ocean seafloor will be exposed to corrosive waters by mid to late century, with 27% of the Atlantic Arctic exposed even with low emissions. Under high emissions, 45% of this seafloor will face such exposure.[42] Nearly 1.3 million km^2 of the Arctic continental shelf and slope is predicted to become submerged within a mid-depth, acidified water mass that will be corrosive to by the end of the 21st century.[25]
- With continued high emissions, weakening of the Atlantic Meridional Oceanic Circulation (AMOC) ranges from 29% to 61% by 2100.[2] Another method of modeling indicated that a high emissions scenario might lead to a complete halt of the AMOC, potentially as early as 2025.[12]
- The Southern Ocean has changed rapidly in the past three to six decades. Large and deep warming has overcome inter-annual variability in many regions, due to a combination of ice shelf melt, loss of sea ice and increasing precipitation. Stratification – stark differences in temperature and salinity at different water depths – is increasing much faster than previously thought. This may decrease the influx of cold water from the surface and warm the deep Southern Ocean; with great impacts on global ocean circulation and ocean CO_2 uptake, as well as nutrient availability for Southern Ocean species.[63]

Background

Increasing CO_2 concentration leads not only to climate change, but also to increasing rates of acidification of the world's oceans. Oceans provide a vital service to the global climate system by absorbing CO_2; limiting global warming, despite sharp increases in human carbon emissions. However, such ocean carbon absorption comes with a price: when dissolved into seawater, CO_2 forms carbonic acid, fundamentally changing the chemistry of the ocean. This phenomenon is known as ocean acidification; and rates of acidification today are faster than at any point in the past 300 million years.[27]

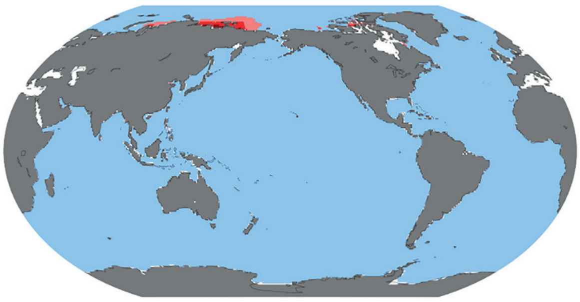
The Arctic and Southern Oceans have absorbed the lion's share of this dissolved CO_2, mostly because colder and fresher waters can hold more carbon, which gets transferred to deep waters allowing more CO_2 to be taken up at the surface. By some estimates, polar waters have absorbed up to 60% of the carbon taken up by the world's

The Arctic and Southern Oceans are bearing the brunt of acidification impacts because they absorb CO_2 faster.

oceans thus far.[6] This makes them an important carbon sink, helping to hold down global heating. However, this "sink" comes at a cost for polar marine environments, because it also results in higher rates of acidification than anywhere else on Earth.

Ocean acidification makes it more difficult for shell-building animals to reproduce, as well as to build and maintain their structures. In all water-dwelling organisms, ocean acidification also increases the energy costs to maintain pH in the cells and tissues.[54] In this way, ocean acidification harms key organisms such as marine gastropods and pteropods, sea urchins, clams,

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



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

IMAGE SOURCE: IPCC SROCC (2019).

and crabs.[18,35] Some polar organisms are adapted to stable pH conditions that have existed for several million years. When pre-exposed to stable conditions, organisms are sensitive to even small changes in seawater chemistry, and will be strongly and quickly impacted by the more rapid and greater ocean acidification of polar waters.[36,65]

Such impacts have already been observed.[4,5,19] These harmful impacts at the lower end of the marine food chain will cascade towards higher ends of the food chain, such as whales and humans.

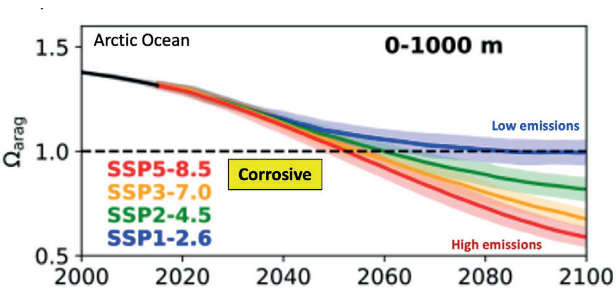
There is currently no practical way for humans to reverse ocean acidification. The only way to slow and eventually halt the acidification process is through rapid CO_2 emissions reductions and future carbon dioxide removal (CDR). If emissions continue to rise, these more acidic conditions will persist for tens of thousands of years. This is because processes that buffer (decrease) the acidity in the ocean occur very slowly, over nearly geologic time scales. Although CO_2 only" lasts for 800-1000 years in the atmosphere, ocean processes are much slower. It will take some 30-70,000 years to bring acidification and its impacts back to pre-industrial levels, following the weathering of rocks on land into the ocean.[27] This very long lifetime of acidification in the oceans is a crucial reason why mitigation efforts focused on "solar-radiation management," as opposed to decreasing atmospheric CO_2 represent a special threat to the health of the world's oceans, especially those at the poles.

Global temperatures peaking at 1.5°C will occur at atmospheric CO_2 levels of around 450 ppm, which scientists of the Inter-academy Panel (a consortium of national Academies of Sciences) identified in 2008 as an important threshold for serious global ocean acidification.[43] 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

"Very low" emissions pathways will limit corrosive stressing conditions to mostly seasonal damage.

FIGURE 6-2. **Arctic Ocean Acidification with Different Emissions Pathways**



Only the very low emissions pathway (blue line, SSP1-1.9) keeps Arctic Ocean waters above year-round corrosive levels.

SOURCE: AMENDED FROM TERHAAR ET AL (2021).

FIGURE 6-3. **Shell Damage from Acidification**

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

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

Harmful impacts at the lower end of the marine food chain will cascade towards higher ends of the food chain.

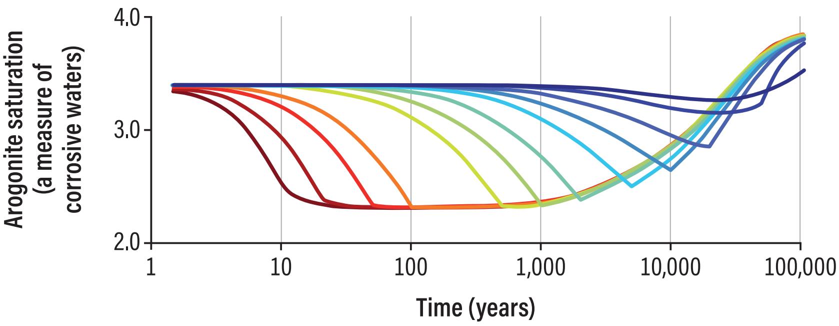
decade now in some regions of the polar oceans where acidification thresholds have been exceeded already, due to local conditions.[1] In the Southern Ocean, the ability of some vulnerable organisms to build shells declined by around 4% between 1998 and 2014.[19] Pteropods – tiny marine snails known as "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.[4] Pteropods are hugely important in the polar food web, serving as an important source of food for young salmon, Arctic cod, char and other economically important species.

Over the past several million years, global ocean acidity has been relatively stable. Today's rate of change is unprecedented however in at least the past 300 million years, when severe changes in ocean conditions, including high rates of acidification, resulted in the mass extinction of many organisms.[52] While polar and global oceans have undergone changes in Earth's past, these occurred more slowly. The speed of today's acidification is therefore a key part of its threat: it is occurring far too quickly to allow many species of today to adapt, evolve and survive.

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

The compounding effects of multiple stressors is especially the case in the Arctic, where in addition to rising acidification, warming has been unusually rapid. Summer surface water temperatures have increased by around 2°C since 1982, primarily due to sea ice loss (causing more heat to be absorbed from the sun's rays) and the inflow of warmer waters from lower latitudes. At today's global warming of 1.2°C above pre-industrial, Arctic sea ice cover and thickness has decreased throughout the year. Current warming also has caused the near-total

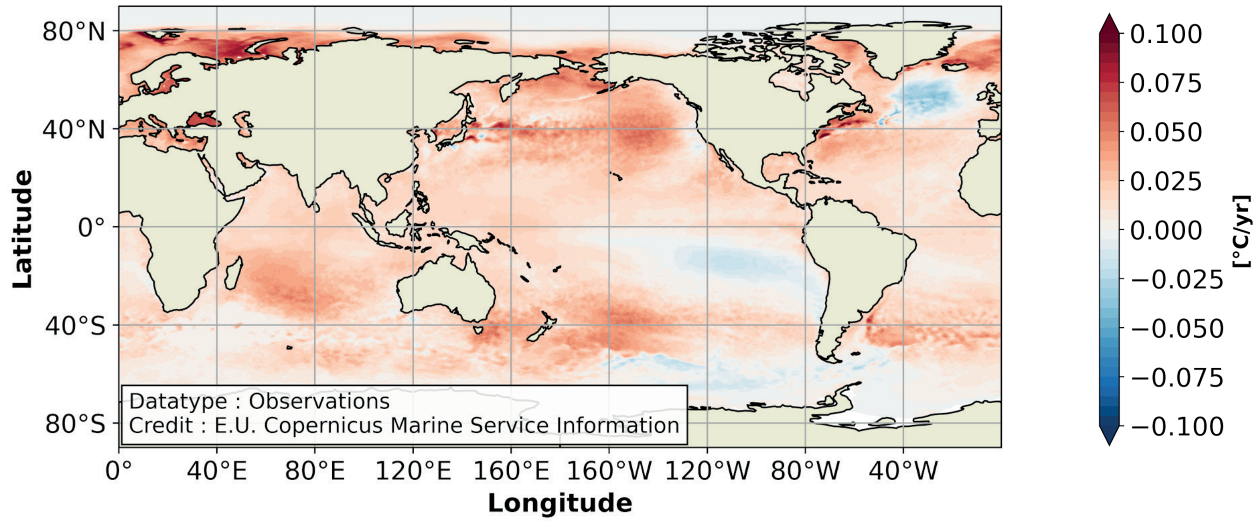
FIGURE 6-4. **Over Ten Thousand Years for Recovery from Ocean Acidification**



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

ADAPTED FROM HONISCH ET AL (2012)

FIGURE 6-5. **Sea Surface Temperature Trends (1993–2021)**



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

CREDIT: E.U. COPERNICUS MARINE SERVICE INFORMATION

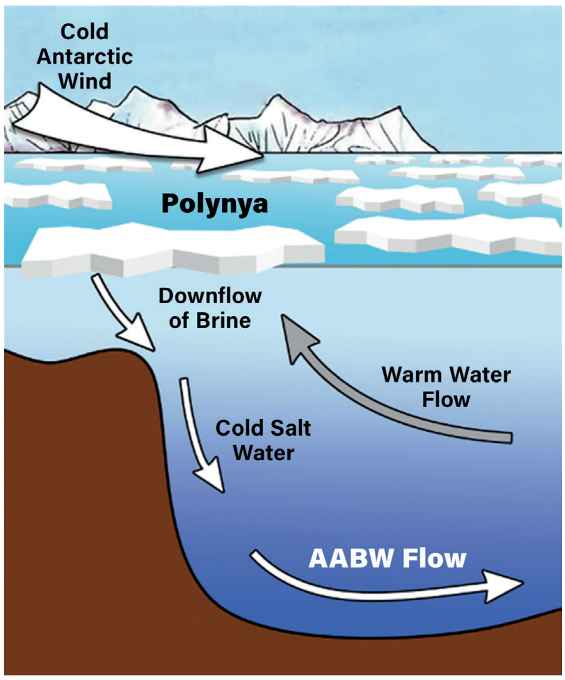
Compound events combining marine heatwaves and extreme acidification have already caused population crashes even at today's 1.2°C.

disappearance of the thick multi-year ice that previously covered much of the Arctic Ocean year-round.[47] Many meters thick and persisting for 7-10 years, this older and thicker ice can be thought of as the "coral reefs" of polar oceans, providing habitat and a food source for many polar species, including ice-associated algae. With all multi-year ice projected to disappear, even with very low emissions that will still result in 1.5-1.7°C of global warming, so too may disappear the species that rely on this thicker ice.

The Southern Ocean around Antarctica also has warmed more than other ocean regions, in particular along the western Antarctic Peninsula, where virtually all sea ice disappeared in the 2023 austral summer. Chilean scientists have found an increase in marine heatwaves each decade since 1981 in regions north of the Peninsula; and in the Amundsen-Bellingshausen, Ross and Davis Seas.[72] This Southern Ocean warming seems increasingly important in overall global ocean heat increase.

Warming of polar waters have resulted in more frequent extreme heat events, with temperatures that go beyond levels that polar species evolved to survive,

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



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

SOURCE: MOROZOV ET AL (2021)

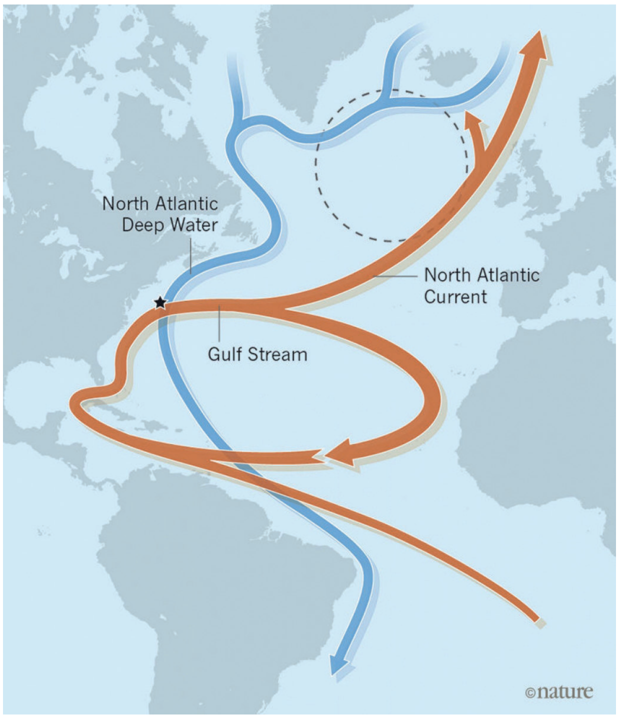
essentially trapping polar endemic species with nowhere else to migrate. Warming waters also cause the poleward movement of other species, increasing competition for food resources.[1,12] In some instances, especially where extreme heatwaves occur in the ocean, polar species have apparently even experienced lethal temperatures. Large die-offs of seabirds and gray whales in regions of the Bering Sea have occurred several times over the past decade, and seem to be associated with these marine heatwaves. Ice-associated algae and animals also are being lost as sea ice declines due to warming. Ocean pollution adds another layer of stress to polar species.[40] 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.[4,68]

Increased run-off from glaciers, ice sheets, and – in the case of the Arctic Ocean – rivers, is affecting global ocean circulation by freshening polar ocean surface waters. Colder, fresher water sits like a lid on top of the deeper, warmer and saltier water below, reducing vertical transport of water upwards. This can stall ocean currents, especially the AMOC – the system of ocean currents carrying warm water from the tropics to the North Atlantic. The AMOC acts as a motor for currents in the North Atlantic, and thereby drives ocean currents worldwide. The phenomenon of a "lid" isolating the surface and deep ocean also prevents nutrients from reaching the surface where most species live,[17,51] carbon sequestration in deeper waters , and heat transport. Freshening itself can have negative physiological impacts, or impair species movements.[16,11]

Another major driver of global ocean circulation, carbon sequestration, and nutrient distribution is the Antarctic Bottom Water (AABW) formed during annual sea ice formation along the margins of Antarctica.[63] Recently, the IPCC assessed that AABW formation will decline in a warming world due to increased freshwater input from the melting Antarctic Ice Sheet and a decline in sea ice. The Weddell Sea Bottom Water contributes nearly half of the AABW, and its volume has reduced by 30% since 1992. This reduction is probably associated with an over 40% decline in sea ice formation rates. Further reduction in AABW formation, and thus nutrient, heat, and carbon circulation, will likely depend on future carbon emissions.[71]

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

FIGURE 6-7. **Global Ocean Currents**



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

SOURCE: MAROTZKE (2012)

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

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

2°C will result in year-round, essentially permanent corrosive conditions in extensive regions of Earth's polar and some near-polar seas.

SCIENTIFIC REVIEWERS

Nina Bednaršek, National Institute of Biology, Slovenia

Richard Bellerby, East China Normal University/Norwegian Institute for Water Research

Elise S. Droste, Alfred Wegener Institute (AWI) Helmholtz Centre for Polar and Marine Research

Sam Dupont, University of Gothenburg

Helen S. Findlay, Plymouth Marine Laboratory

Humberto E. González, University Austral of Chile/Fondap IDEAL

Sian Henley, University of Edinburgh

Peter Thor, Swedish Meteorological and Hydrological Institute (SMHI)

Paul Wassmann, UiT – The Arctic University of Norway (Emeritus)

LITERATURE AND ADDITIONAL READING

1. AMAP, 2018. AMAP Assessment 2018: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. vi+187pp
2. Baker, J. A., Bell, M. J., Jackson, L. C., Renshaw, R., Vallis, G. K., Watson, A. J., & Wood, R. A. (2023). Overturning pathways control AMOC weakening in CMIP6 models. *Geophysical Research Letters*, 50, e2023GL103381. https://doi.org/10.1029/2023GL103381
3. Bednaršek, N., Feely, R., Reum, J., Peterson, B., Menkel, J., Alin, S., & Hales, B. (2014). Limacina helicina shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. Proc. R. Soc. B 281: 20140123. https://doi.org/10.1098/rspb.2014.0123
4. Bednaršek, N., Pelletier, G., Ahmed, A., A. Feely, R. (2020). Chemical Exposure Due to Anthropogenic Ocean Acidification Increases Risks for Estuarine Calcifiers in the Salish Sea: Biogeochemical Model Scenarios. https://doi.org/10.3389/fmars.2020.00580
5. Bednaršek, N., Kerry-Ann, N., Feely, R., Claudine, H., Katsunori, K., Albert, H., . . . & Darren, P. (2021). Integrated Assessment of Ocean Acidification Risks to Pteropods in the Northern High Latitudes: Regional Comparison of Exposure, Sensitivity and Adaptive Capacity. Frontiers in Marine Science. https://doi.org/10.3389/fmars.2021.671497
6. Caldeira, K., & Duffy, P. B. (2000). The role of the Southern Ocean in uptake and storage of anthropogenic carbon dioxide. Science, 287(5453), 620–622. doi: DOI 10.1126/science.287.5453.620
7. Cantoni, C., Hopwood, M., Clarke, J., Chiggiato, J., Achterberg, E., & Cozzi, S. (2020). Glacial Drivers of Marine Biogeochemistry Indicate a Future Shift to More Corrosive Conditions in an Arctic Fjord. Journal of Geophysical Research Biogeosciences. https://doi.org/10.1029/2020JG005633
8. Chambault, P., Kovacs, K., Lydersen, C., Shpak, O., Teilmann, J., Albertsen, C., & Heide-Jørgensen, M. (2022). Future seasonal changes in habitat for Arctic whales during predicted ocean warming. *Science Advances,* 8, 29. https://doi.org/10.1126/sciadv.abn2422
9. Cummings, V. et al. "Ocean Acidification at High Latitudes: Potential Effects on Functioning of the Antarctic Bivalve *Laternula Elliptica*." Ed. Jack Anthony Gilbert. *PLoS ONE* 6.1 (2011): e16069. *PMC*. Web. 22 Nov. 2015.
10. Cyronak, T., Schulz, K. G. and Jokiel, P. L. (2016) "The Omega myth: what really drives lower calcification rates in an acidifying ocean Tyler," *ICES Journal of Marine Science*, 73(3), pp. 558–562. doi: 10.1093/icesjms/fsv075.
11. Dickinson, G.H., Ivanina, A. V., Matoo, O. B., Pörtner, H. O., Lannig, G., Bock, C., Beniash, E., Sokolova, I. M. Interactive effects of salinity and elevated CO_2 levels on juvenile eastern oysters, *Crassostrea virginica*. *J Exp Biol* 1 January 2012; 215 (1): 29–43. doi: https://doi.org/10.1242/jeb.061481
12. Ditlevsen, P., Ditlevsen, S. Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nat Commun* 14, 4254 (2023). https://doi.org/10.1038/s41467-023-39810-w
13. Dunmall, K., McNicholl, D., Zimmerman, C., Gilk-Baumer, S., Burril, S., & von Biela, V. (2022). First juvenile chum salmon confirms successful reproduction for Pacific salmon in the North American Arctic. *Canadian Journal of Fisheries and Aquatic Sciences*. 79(5): 703–707. https://doi.org/10.1139/cjfas-2022-0006
14. Dupont, S. & Pörtner, H. (2013). Get ready for ocean acidification, *Nature,* 498, 429. https://doi.org/10.1038/498429a
15. Dupont, S., Havenhand, J., Thorndyke, W., Peck, L., & Thorndyke, M. (2008). Near-future level of CO2-driven acidification radically affects larval survival and development on the brittle star *Ophiothrix fragilis*. 373: 285–294, 2008 Marine Ecology Progress Series. https://doi.org/10.3354/meps07800.
16. Dvoretsky VG, Dvoretsky AG (2009) Spatial variations in reproductive characteristics of the small copepod *Oithona similis* in the Barents Sea. Mar Ecol Prog Ser 386:133–146. https://doi.org/10.3354/meps08085
17. Farmer, J., Sigman, D., Granger, J., Underwood, O., Fripiat, F., Cronin, T., . . . & Haug, G. (2021). Arctic Ocean stratification set by sea level and freshwater inputs since the last ice age. *Nat. Geosci.* 14, 684–689. https://doi.org/10.1038/s41561-021-00789-y
18. Figuerola B, Hancock AM, Bax N, Cummings VJ, Downey R, Griffiths HJ, Smith J and Stark JS (2021) A Review and Meta-Analysis of Potential Impacts of Ocean Acidification on Marine Calcifiers From the Southern Ocean. Front. Mar. Sci. 8:584445. doi: 10.3389/fmars.2021.584445
19. Freeman, N.M. & Lovenduski, N.S. (2015), Decreased calcification in the Southern Ocean over the satellite record, *Geophys. Res. Lett*., 42, 1834–1840. https://doi.org/10.1002/2014GL062769.
20. Frölicher, T. L., Sarmiento, J.L., Paynter, D.J., Dunne, J.P., Krasting, J.P., & Winton, M. (2015). Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. *J. Climate*. 28, 862–886, https://doi.org/10.1175/JCLI-D-14-00117.1
21. Gattuso, J.-P., Magnan, A., Billé, R., Cheung, W.W.L., Howes, E.L., Joos, F., . . . & Turley, C. (2015). Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science*, 349, https://doi.org/10.1126/science.aac4722.
22. Gattuso, J.-P., Magnan, A., Bopp, L., Cheung, W., Duarte., C., Hinkel, J., . . . & Rau, G. (2018). Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems. Front. Mar. Sci. 5:337. https://doi.org/10.3389/fmars.2018.00337
23. Green, H.L., Findlay, H.S., Shutler, J.D., Land, P.E. & Bellerby, R.G.J. (2021) Satellite Observations Are Needed to Understand Ocean Acidification and Multi-Stressor Impacts on Fish Stocks in a Changing Arctic Ocean. Front. Mar. Sci. 8:635797. https://doi.org/10.3389/fmars.2021.635797`
24. Gruber, N., Bakker, D.C.E., DeVries, T. Et al. Trends and variability in the ocean carbon sink. *Nat Rev Earth Environ* 4, 119–134 (2023). https://doi.org/10.1038/s43017-022-00381-x

25. Harris, P.T., Westerveld, L., Zhao, Q., Costello, M.J., 2023. Rising snow line: Ocean acidification and the submergence of seafloor geomorphic features beneath a rising carbonate compensation depth. Marine Geology, 463, 107121, https://doi.org/10.1016/j.margeo.2023.107121
26. Hauri, C., Pagès, R., McDonnell, A., Stuecker, M., Danielson, S., Hedstrom, K., . . . & Doney, S. (2021). Modulation of ocean acidification by decadal climate variability in the Gulf of Alaska. Commun Earth Environ 2, 191. https://doi.org/10.1038/s43247-021-00254-z
27. Hönisch, B., Ridgwell, A., Schmidt, D., Thomas, E., Gibbs, S., Sluijs, A., . . . & Williams, B. (2012). The Geological Record of Ocean Acidification, Science 335, 1058. https://doi.org/10.1126/science.1208277
28. IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.
29. IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp.
30. IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty[V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R.Shukla,A. Pirani, W. Moufouma-Okia, C.Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield(eds.)].
31. IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.
32. IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.
33. Jacobs, S. S. (2004) "Bottom water production and its links with the thermohaline circulation," *Antarctic Science*, 16(4), pp. 427–437. doi: 10.1017/S095410200400224X.
34. Kikuchi, T., Nishino, S., Fujiwara, A., Onodera, J., Yamamoto-Kawai, M., Mizobata., K., Fukamachi, Y., & Watanabe, E. (2021). Status and trends of Arctic Ocean environmental change and its impacts on marine biogeochemistry: Findings from the ArCS project. Polar Science, 27: 100639. https://doi.org/10.1016/j.polar.2021.100639
35. Kroeker, K., Kordas, R., Crim, R., Hendriks, I., Ramajo, L., Singh, G., . . . & Gattuso, J.-P. (2013). Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Global Change Biology, 19, 1884–1896, https://doi.org/10.1111/gcb.12179
36. Lewis, C.N., Brown, K.A., Edwards, L.A., Cooper G., Findlay, H.S., 2013. Sensitivity to ocean acidification parallels natural pCO2 gradients experienced by Arctic copepods under winter sea ice. PNAS, E4960–E4967, www.pnas.org/cgi/doi/10.1073/pnas.1315162110
37. Li, G., Cheng, L., Zhu, J. Trenberth, K., Mann, M., & Abraham, J. (2020). Increasing ocean stratification over the past half-century. *Nat. Clim. Chang.* 10, 1116–1123. https://doi.org/10.1038/s41558-020-00918-2
38. Lin, Y., Moreno, C., Marchetti, A. Ducklow, H., Schofield, O., Delage, E., . . . & Cassa, N. (2021). Decline in plankton diversity and carbon flux with reduced sea ice extent along the Western Antarctic Peninsula. Nat Commun 12, 4948. https://doi.org/10.1038/s41467-021-25235-w
39. Mann, P.J., Strauss, J., Palmtag, J. Dowdy, K., Ogneva, O., Fuchs, M., . . . & Juhls, B. (2022). Degrading permafrost river catchments and their impact on Arctic Ocean nearshore processes. *Ambio* 51, 439–455. https://doi.org/10.1007/s13280-021-01666-z
40. Manno, C., Peck, V.L., Corsi, I., & Bergami, E. (2022). Under pressure: Nanoplastics as a further stressor for sub-Antarctic pteropods already tackling ocean acidification. Marine Pollution Bulletin, 174. https://doi.org/10.1016/j.marpolbul.2021.113176
41. Mathis, J.T., Cross, J.N., Evans, W., & Doney, S.C. (2015). Ocean acidification in the surface waters of the Pacific-Arctic boundary regions. *Oceanography* 28(2):122–135, http://dx.doi.org/10.5670/oceanog.2015.36
42. McGovern, E., Schilder, J., Artioli, Y., Birchenough, S., Dupont, S., Findlay, H., Skjelvan, I., Skogen, M.D., Álvarez, M., Büsher, J.V., Chierici, M., Aagaard Christensen, J.P., Diaz, P.L., Grage, A., Gregor, L., Humphreys, M., Järnegren, J., Knockaert, M., Krakau, M., Nogueira, M., Ólafsdóttir, S.R., von Schuckmann, K., Carreiro-Silva, M., Stiasny, M., Walsham, P., Widdicombe, S., Gehlen, M., Chau, T.T.T., Chevallier, F., Savoye, N., Clark, J., Galli, G., Hordoir, R. and Moffat. C. 2022. Ocean Acidification. In: OSPAR, 2023: The 2023 Quality Status Report for the North-East Atlantic. OSPAR Commission, London. Available at: https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/other-assessments/ocean-acidification
43. McNeil, B.I. & Matear, R.J. (2008). Southern Ocean acidification: A tipping point at 450-ppm atmospheric CO2. *Proceedings of the National Academy of Sciences of the United States of America.* 2008; 105(48):18860–18864. https://doi.org/10.1073/pnas.0806318105
44. National Academies of Sciences, Engineering, and Medicine 2022. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278
45. Niemi, A. *et al.* (2021) "Biological Impact of ocean acidification in the Canadian Arctic: Widespread severe pteropod shell dissolution in Amundsen Gulf," *Frontiers in Marine Science*, 8(March), pp. 1–16. doi: 10.3389/fmars.2021.600184.
46. Nissen, C. *et al.* (2022) "Abruptly attenuated carbon sequestration with Weddell Sea dense waters by 2100," *Nature Communications*, 13(1). doi: 10.1038/s41467-022-30671-3.

47. Notz, D. & SIMIP Community (2020). Arctic sea ice in CMIP6. Geophysical Research Letters, 47, e2019GL086749. https://doi.org/10.1029/2019GL086749
48. Orr, J. C. *et al.* (2005) "Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms," *Nature*, 437(7059), pp. 681–686. doi: 10.1038/nature04095.
49. Orr, J.C., Kwiatkowski, L., & Pörtner, H.-O. (2022). Arctic Ocean annual high in pCO2 could shift from winter to summer. Nature, 610, 94–100. https://doi.org/10.1038/s41586-022-05205-y
50. Orsi, A. H., Johnson, G. C. and Bullister, J. L. (1999) "Circulation, mixing, and production of Antarctic Bottom Water," *Progress in Oceanography*, 43(1), pp. 55–109. doi: 10.1016/S0079-6611(99)00004-
51. Pan, X.L., Li, B.F. & Watanabe, Y.W. (2022). Intense ocean freshening from melting glacier around the Antarctica during early twenty-first century. *Sci Rep* 12, 383. https://doi.org/10.1038/s41598-021-04231-6
52. Pelejero, C., Calvo, E., Hoegh-Guldberg, O. (2010). Paleo-perspectives on ocean acidification. Doi: https://doi.org/10.1016/j.tree.2010.02.002
53. Penn, J. & Deutsch, C. (2022). Avoiding ocean mass extinction from climate warming. Science, 376, 6592, 524–526. https://doi.org/10.1126/science.abe9039
54. Pörtner, H.O., M. Langenbuch, B. Michaelidis, Synergistic effects of temperature extremes, hypoxia, and increases in CO2 on marine animals: from Earth history to global change, J. Geophys. Res. C Ocean 110 (2005) 1e15, https://doi.org/10.1029/2004JC002561.
55. Qi, D., Ouyang, Z., Chen, L., Wu, Y., Lei, R., Chen, B., . . . & Cai, W.-J. (2022). Climate change drives rapid decadal acidification in the Arctic Ocean from 1994 to 2020. Science, 377, 1544–1550. https://doi.org/10.1126/science.abo0383
56. Ridgwell, A. & Schmidt, D. (2010). Past constraints on the vulnerability of marine calcifiers to massive carbon dioxide release. Nature Geosci 3, 196–200. https://doi.org/10.1038/ngeo755
57. Riebesell, U. & Gattuso, J.P. (2015). Lessons learned from ocean acidification research. Nature Climate Change, 5, 12–14. https://doi.org/10.1038/nclimate2456
58. Sasse, T.P., McNeil, B.I., Matear, R.J., & Lenton, A. (2015) Quanitfying the influence of CO2 seasonality on future aragonite undersaturation onset. Biogeosciences, 12: 6017–6031. https://doi.org/10.5194/bg-12-6017-2015
59. Steiner, N., Bowman, J., Campbell, K., Chierici, M., Eronen-Rasimus, E., Falardeau, M., . . . & Wongpan, P. (2021). Climate change impacts on sea-ice ecosystems and associated ecosystem services. Elementa: Science of the Anthropocene; 9 (1): 00007. https://doi.org/10.1525/elementa.2021.00007
60. Stroeve, J. and Notz, D. (2018) "Changing state of Arctic sea ice across all seasons," *Environmental Research Letters*, 13(103001), pp. 1–23. doi: 10.1088/1748-9326/aade56.
61. Terhaar, J. *et al.* (2020) "Evaluation of data-based estimates of anthropogenic carbon in the Arctic Ocean," *Journal of Geophysical Research: Oceans*, 125(6). doi: 10.1029/2020JC016124.
62. Terhaar, J., Torres, O., Bourgeois, T., & Kwiatkowski, L. (2021). Arctic Ocean acidification over the 21st century co-driven by anthropogenic carbon increases and freshening in the CMIP6 model ensemble, Biogeosciences, 18, 2221–2240. https://doi.org/10.5194/bg-18-2221-2021
63. The SO-CHIC consortium *et al.* 2023 Southern ocean carbon and heat impact on climate. *Phil. Trans. R. Soc. A* 381: 20220056. https://doi.org/10.1098/rsta.2022.0056
64. Thyrring, J., MacLeod, C., Marshall, K., Kennedy, J., Tremblay, R., & Harley, C. (2022). Ocean acidification increases susceptibility to sub-zero air temperatures in ecosystem engineers (Mytilus sp.): a limit to poleward range shifts. BioRxiV. https://doi.org/10.1101/2022.06.30.498370
65. Vargas, C., Lagos, N., Lardies, M., Duarte, C., Manríquez, P., Aguilera, V., . . . & Dupont, S. (2017) Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. Nature Ecology and Evolution, 1:84. https://pubmed.ncbi.nlm.nih.gov/28812677
66. Vargas, C.A., Cuevas, L.A., Broitman, B.R. et al. Upper environmental pCO2 drives sensitivity to ocean acidification in marine invertebrates. Nat. Clim. Chang. 12, 200–207 (2022). https://doi.org/10.1038/s41558-021-01269-2
67. Vehmaa, A. & Reinikainen, M. (2018). Ocean Acidification in the Baltic Sea. Air Pollution and Climate Series 40 ISBN: 978-91-984717-2-4
68. Wilson, T., Cooley, S., Tai, T.C., Cheung, W., & Tyedmers, P. (2020) Potential socioeconomic impacts from ocean acidification and climate change effects on Atlantic Canadian fisheries. PLoS ONE 15(1): e0226544. https://doi.org/10.1371/journal.pone.0226544
69. Wittmann, A.C. & Pörtner, H.O. (2013). Sensitivities of extant animal taxa to ocean acidification. Nature Climate Change, 3, 995–1001. https://doi.org/10.1038/nclimate1982
70. Zachos, J. C., Röhl, U., Schellenberg, S. A., …,Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum.*Science* 308, 1611–1615 (2005). DOI:10.1126/science.1109004
71. Zhou, S., Meijers, A.J.S., Meredith, M.P. *et al.* Slowdown of Antarctic Bottom Water export driven by climatic wind and sea-ice changes. *Nat. Clim. Chang.* 13, 701–709 (2023). https://doi.org/10.1038/s41558-023-01695-4
72. https://drive.google.com/drive/folders/1mUCZQETTSRt8vFrmWcysub9cMpw5sGI2?usp=drive_link


International Cryosphere
Climate Initiative