Cryosphere1.5°

Where Urgency and Ambition Meet

WHY CRYOSPHERE DYNAMICS MUST MEAN 1.5° PATHWAYS FOR 2020 NDCS

DECEMBER 2019

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Cryosphere1.5°: Where Urgency and Ambition Meet –
Why Cryosphere Dynamics Must Mean 1.5° Pathways for 2020 NDCs

DEDICATION

Two days before this report was released at COP-25 in Madrid under the Chilean COP Presidency, a Chilean Air Force plane on its way to Escudero Station on the Antarctic Peninsula lost radio contact over the Drake Passage. It is presumed lost with all 38 onboard, consisting of crew, supply, and technical personnel as well as researchers from the University of Magallanes, including a 24-year-old graduate student. It is the largest research-oriented loss of life in Antarctic history, and a reminder that this climate and cryosphere research remains of great risk to those conducting and supporting it.

This report is dedicated to all those who have given their lives in service of research in these snow-and-ice covered regions of the world.

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Preface

Over the next year, governments face the most consequential decision collectively made in the history of humanity: whether to take concrete steps to keep the planet below 1.5°C warming, or make the decision – either explicitly, or de facto through inaction – to force the planet's temperatures higher.

These 2020 NDCs, or Nationally Determined Contributions will mostly cover the years up to 2030, following the Paris Agreement NDCs in 2015 that mostly covered 2020–2025. This decade is what the IPCC Special Report on 1.5 Degrees of Warming (SR1.5) determined as critical to stay below the 1.5° level. So far, not only do combined NDCs to-date risk our reaching 3°C or more in 80 years: present emission trends have us breaching 4°C within the lifetimes of many children born today. Emissions have in other words, continued unchecked on a "business as usual" scenario despite the signing of the Paris Agreement four years ago.

Since Paris, other political and economic forces have caused a growing number of decision makers to place their attention elsewhere, from populist domestic politics to destructive international conflicts. This Report, reviewed by over 30 IPCC and other leading scientists, is an attempt to bring attention back to what inevitably will result if attention remains so diverted, all because of the freezing point of water.

The cryosphere – snow and ice regions – is amazingly sensitive to small changes in temperature: at root, the slight temperature difference between solid frozen ice, and liquid water. This principle holds for an ice cube taken from the freezer, or a mountain glacier or great polar ice sheet: once temperature exceeds 0°C/32°F, it melts. And in Earth's past, the difference between the 1°C above pre-industrial temperatures where we are today, and 2°C has been very different planetary states, including the difference between a few meters of sea-level rise, to well above 20 meters.

Glaciers, snow, permafrost and sea ice all make up the cryosphere: slow to react to warmer temperatures, but even slower to return once temperatures fall again. A decision to allow temperatures to go above 1.5°C – let alone 2.0°C or above – inevitably will cause a change in cryosphere that will in turn, change the Earth to one which has never seen human existence.

The summaries in this Cryosphere1.5 Report, taken from the IPCC SR1.5 and Special Report on the Oceans and Cryosphere (SROCC) and other published research, confirm this physical reality that at some point in the gradient above 1.5°C, processes will be set in motion that cannot be halted or easily reversed, in some cases not even if temperatures return to pre-industrial. This is why policy decisions in the coming years will determine the future state of the Earth for centuries and generations to come. Never has a single generation held the future of so many coming generations, species and ecosystems in its hands. Cryosphere climate change is not like air or water pollution, where the impacts remain local and from which ecosystems largely can be restored. Cryosphere climate change, driven by the physical law of water's response to 0°C, is different. Slow to manifest itself, once triggered it inevitably forces the Earth's climate system into a new state, one that most scientists believe has not existed for 65 million years.

This future however is neither defined, nor hopeless. Instead, pathways to the needed lower emissions levels not only exist, but were very well-defined in the SR1.5 as physically, technologically, and economically feasible.

This is why decision makers in the span of the next year will make the most consequential decision in the history of humanity, let alone the planet. As they – as you – make these decisions, it is important that you know what they will mean. Will the Earth address the cryosphere crisis, or let it fail because other, more short-term issues took precedence?

The choice is ours. The cryosphere cares about nothing but the melting point of water.

Christiana Figueres
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Executive Summary

AVERTING A MUCH-CHANGED EARTH

Decisionmakers today face with a choice between unprecedented but necessary policies and actions that will hold the world below 1.5°C, or take a slower, seemingly more "prudent" and "realistic" path towards 2°C, 3°C or above. The IPCC Special Report on 1.5 Degrees of Warming (SR1.5) laid out those choices in stark and clear terms upon its release in October 2018. Nearly a year later, the Special Report on Oceans and Cryosphere (SROCC) summarized the current status and future of the water and ice parts of the world. In the cryosphere – portions of the globe seasonally or permanently in a frozen state – it detailed a world undergoing rapid and in some respects, irreversible changes, all tied to the freezing point of water; or rather, the melting point of ice.

This Report, authored and reviewed by over 40 IPCC and other cryosphere scientists, combines the findings of both the SR1.5, and SROCC, plus published studies since. Its inevitable, science-based conclusion: failure to choose policies keeping the world below 1.5° is neither measured nor economically prudent. Instead, it will result in a cascading series of disasters; not only for people living this century, but even more so for the generations that follow. Warming above 1.5° will have many impacts, but the physical realities of changes in cryosphere alone will drive much of what follows.

This is because the gradient between today's 1°C above pre-industrial temperatures, to 1.5° and 2°C and above, represents a drastic and on human timescales, essentially permanent shift in the state of our planet *because of the cryosphere response*. The Report's main findings:

Ice Sheets and Sea-Level Rise

We see far greater risk of massive irreversible sea-level rise (SLR) at 2°C, on a scale of 12–20 meters or more in the long term. The climate record of the earth over the past few million years is quite clear:

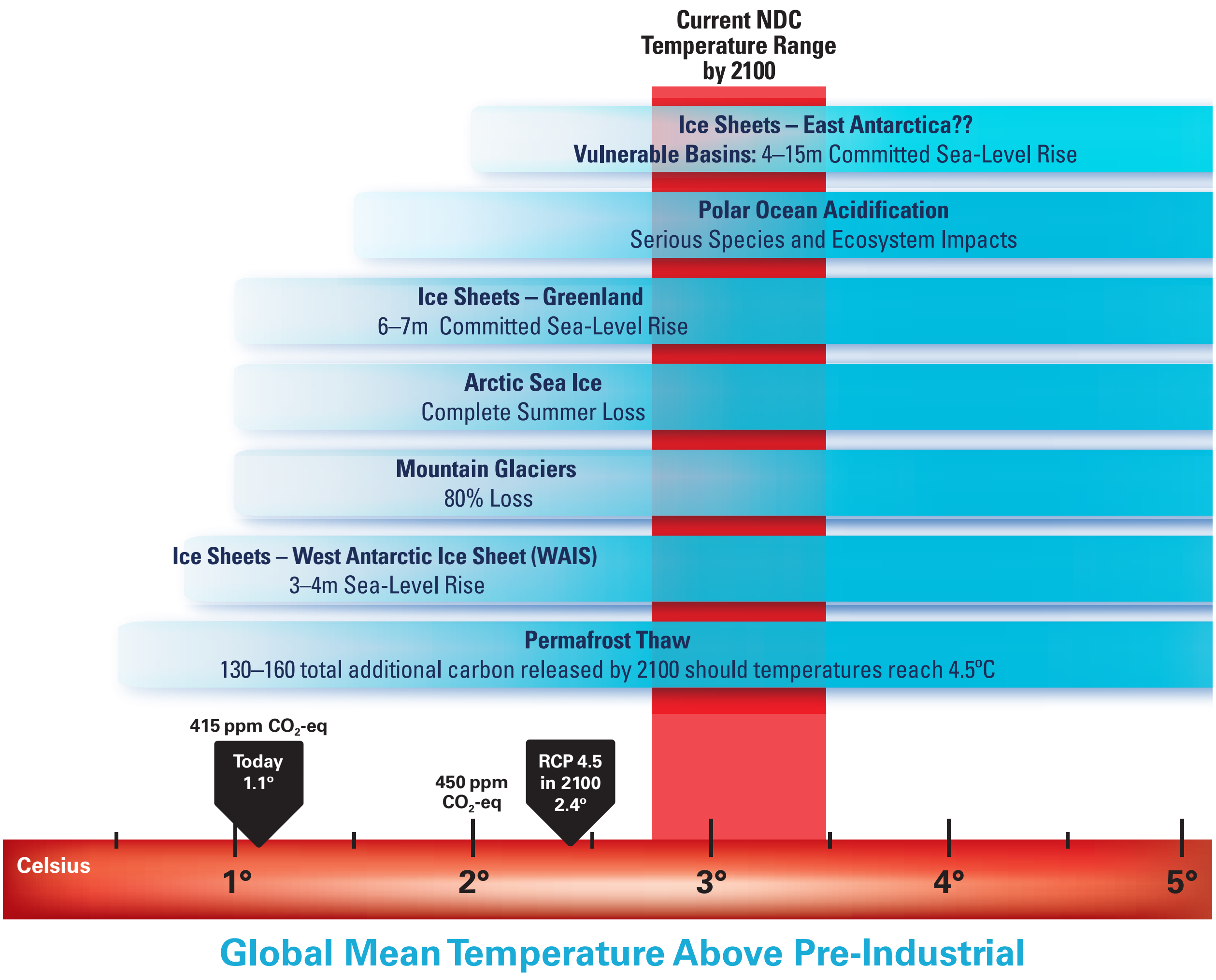
- At today's temperature of 1°C over pre-industrial, we have locked in about 1–3 meters of sea-level rise over the next centuries from loss of mountain glaciers and a portion of the polar ice sheets, even if we could hold temperatures at 1°C.
- Risks rise substantially at 1.5°, with the Earth showing a pattern of 6–9 meters compared to today when it was this warm in the past; coming from additional loss of Greenland and most of the West Antarctic Ice Sheet (WAIS).
- 2°C however shows a much sharper rise: between 12–20 meters as the new global sea level, locked in over millennia. This is because both the WAIS and Greenland melt nearly completely at a sustained 2°C; with vulnerable portions of East Antarctica also posing a threat; and up to 25 meters occurring between 2° and 3°C.
- Most seriously, periods of time well in excess of 2°C – especially if we reach 3°C, 4°C or more, which is our current emissions pathway – increase the risk, speed and potential inevitability of the above changes. The rate of change can itself become a risk: at the end of the last Ice Age, sea levels rose by up to 4 cm per year, and 12–14 meters in the space of a few centuries.

The good news: these processes, especially the collapse of the West Antarctic Ice Sheet can be slowed if temperatures remain close to 1.5°, allowing far more time for communities to adapt to the rising seas. Much of the WAIS may have passed a threshold of collapse sometime between 2010 and 2015, at around 0.8°C; but at lower temperatures such as 1.5°C, this collapse can be slowed to perhaps thousands of years, rather than (in the worst projections) just a few centuries. Even at today's 1°C, Greenland's ice loss has doubled in the past 20 years; and Antarctica's has tripled.

Mountain Glaciers and Snow

Few glaciers near the Equator, such as the northern Andes and East Africa can survive even today's 1°C. Some of these were shrinking anyway after the last ice age; but global warming has speeded their disappearance by many centuries. Glaciers and snow in the northern Andes provided a reliable seasonal source of water, and their loss especially will impact rural populations in Peru and Chile.

FIGURE S-1. **Cryosphere Dynamics and Temperature**



Approximate temperature ranges at which five important cryosphere dynamics or "thresholds" may be triggered, some irreversibly on human timescales, based on updated observations and models.

Mid-latitude glaciers and snow in the Alps, southern Andes/Patagonia, Iceland, Scandinavia, New Zealand and North American Rockies can survive at 1.5°, but these glaciers will disappear almost entirely at 2°C, and snow cover decrease. For these glaciers and mountain snowpack, that half a degree spells the difference between sufficient seasonal water supply, such as in the American West, Tarim and Indus river basins; and water scarcity.

The essential watersheds of the Himalayas/Central Asia at 1.5°C maintain around half to about two-thirds of their ice. At 2°C, much more will be lost, with regional impacts on water supply and increasing political instability, especially as monsoon rains become far more unpredictable at 2°C as well.

Permafrost and Carbon Budgets

Limiting warming to 1.5° rather than 2°C saves 2 million square kilometers of permafrost. Permafrost carbon release (as both methane and CO2) is greater at 2°, especially in "overshoot" scenarios because once thawed, former permafrost irreversibly continues to release carbon for centuries:

- If we can hold temperatures to 1.5°C, cumulative permafrost emissions by 2100 will be about equivalent to those currently from Canada (150–200 Gt CO_2-eq).
- In contrast, by 2°C scientists expect cumulative permafrost emissions as large as those of the EU (220–300 Gt CO_2-eq).

- If temperature exceeds 4°C by the end of the century however, permafrost emissions by 2100 will be as large as those today from major emitters like the United States or China (400–500 Gt CO_2-eq), the same scale as the remaining 1.5° carbon budget.

These permafrost carbon estimates include emissions from the newly-recognized abrupt thaw processes from "thermokarst" lakes and hillsides, which expose deeper frozen carbon previously considered immune from thawing for many more centuries.

The "anthropogenic" carbon budget to reach carbon neutrality and remain within 1.5° of warming must begin to take these "country of Permafrost" emissions into account. Only lower emissions pathways that preserve as much permafrost as possible can minimize this potentially large contribution to future global warming, and the need for future generations to maintain negative emissions efforts to compensate for those from thawed former permafrost.

Sea Ice and Polar Ocean Acidification and Fisheries

At 1.5°C global warming, it is unlikely that Arctic sea ice will melt completely in any given summer; and if it does melt completely, that ice-free period will be brief. In contrast, by 2°C the Arctic Ocean is expected to be ice free in summer for several months. This long ice-free period will warm the Arctic Ocean, feeding back to raise regional air temperatures and accelerating Greenland melt and associated sea level rise; increasing permafrost thaw and associated carbon emissions; and also leading to a decrease in snow cover. All of these will in turn make for faster rates and scale of overall global warming, making efforts to address the problem that much harder.

Many parts of the Arctic ecosystem depend on the existence of thicker, multi-year sea ice. These will likely collapse with the complete disappearance of multi-year ice cover at 2.0°C global warming. This impact is amplified by our observation already today of more frequent ocean "heat waves." Human communities are of course also impacted, especially Arctic indigenous cultures reliant on the reliable presence of sea ice for many thousands of years.

Fish stocks such as cod are much more negatively affected by changes in the polar oceans at 2°C global warming than at 1.5°C global warming. These changes include ocean acidification, warmer and less salty sea water from increased river runoff, glacier melt and ice sheet melt; as well as greater competition from mid-latitude species moving polewards. In contrast, polar species and ecosystems have nowhere further to migrate.

Today's rates of ocean acidification are greater than at any time in 3 million years, and pose an immediate and serious threat in cold polar waters, which absorb CO2 more quickly. The oceans will need 50–70,000 years to return to normal pH levels, a key argument for keeping CO_2 levels as low as possible and against schemes aiming to decrease solar radiation rather than CO_2.

Conclusions

Current rates of warming and CO2 increase have not occurred in the past 60 million years of Earth's geologic history. Most "uncertainties" trend towards greater damage and risk, not less. There is no real geologic precedent for predicting the cryosphere response and its risks.

Overshoot is not an option. The risk of triggering these dynamics irreversibly grows with each tenth of a degree over 1.5°, and especially once we exceed 2°C.

1.5°C remains both possible, and imperative. The SR1.5 made clear that pathways to remain below 1.5° globally remain, but will require immediate and transformative action. Many countries and sub-national stakeholders are moving to answer this call, taking concrete steps towards emissions that if adopted globally, will keep the planet below 1.5°. More countries and actors need to join their ranks and intensify their 2020–2030 reductions to 1.5° levels.

The message is clear: 2°C means a completely unacceptable risk of loss and damage to human society, from cryosphere dynamics alone. We must aim for 1.5°C, and to be frank, to the extent possible plan for a return to 1°C as soon as possible because of the way the cryosphere will respond even at the long-term 1.5° level, through negative emissions measures.

This is an issue of generational justice, and the legacy we leave behind.

Temperatures, “Nationally Determined Contributions” and Carbon Budgets in This Report

To calculate future temperature impacts, scientific studies largely use a set of three greenhouse gas pathways (called RCPs, for “Representative Concentration Pathways”) through 2100 that lead to changes in the planet’s energy balance, expressed as watts per square meter (W/m^2). So RCP 2.6 results in 2.6 W/m^2, RCP 4.5 leads to 4.5 W/m^2 in 2100, and so on.

These different levels of “climate forcing” translate into certain temperature ranges by 2100. RCP2.6 is used by many scientists and policy makers as a proxy for 1.5°C pathways, but actually overshoots a 1.5°C limit by a bit (see Table below). For the purposes of this report, RCP4.5 is used as a proxy for 2°C; though in the models, RCP4.5 actually results in a temperature above 2°C, reaching about 2.4°C in 2100.

“High emissions” scenarios refer to RCP8.5, the highest level of human emissions considered. Despite the Paris Agreement, emissions today still appear to follow such a “business as usual” pathway, which has the world exceeding 4°C by 2100. Although far above what cryosphere scientists would define as a lower-risk pathway, this report occasionally outlines what scientists project will occur if emissions continue on a high emission, RCP8.5 pathway.

Because the cryosphere in the past has responded most clearly to temperature, much of this report focuses on temperature rather than CO_2 emissions, because changes in Earth’s temperature in the past sometimes came from other shifts such as slow changes in the Earth’s orbit around, or orientation towards the sun. For polar as well as global ocean acidification, however, CO_2 concentrations are key; and once this CO_2 is absorbed into the ocean and acidification occurs, these more “acidic” waters will persist for tens of thousands of years, as outlined in the Polar Oceans chapter.

In reality, scientists today are quite certain that today’s temperature rise does come from human emissions of CO_2; so one way to express human decisions to either continue, or slow down warming is through carbon budgets: the amount of CO_2 and other carbon emissions that can occur before a certain temperature level is breached. The table below lists the remaining range of possible carbon emissions as outlined in the SR1.5. The limit amount – or budget – of carbon emissions related to a specific temperature boundary is especially important as regards the contribution of permafrost emissions due to thaw at higher temperatures, a main focus of the Permafrost chapter. Usually such emissions are not included in carbon budgets, and would need to be added in order to accurately guide mitigation efforts limiting anthropogenic emissions.

Country commitments, or “Nationally Determined Contributions” (NDCs) were first made in connection with the Paris Agreement in 2015, and are scheduled to be updated by COP-26 in November 2020: in most cases, covering the period 2025–2030. Scientists agreed in the IPCC Special Report on 1.5 Degrees of Warming (SR1.5) that 2030 is the outer boundary for remaining on a 1.5°C pathway, which this Report makes clear has become an outer boundary for avoiding the most catastrophic future impacts from cryosphere dynamics. The SR1.5 identified different actions, or “emissions pathways” that will allow the Earth’s global mean temperature to remain within 1.5°C. This Report uses the calculations of the Climate Action Tracker (CAT) to evaluate where current NDCs, or climate commitments will take the globe in terms of future temperatures, whether at the country or global level. The CAT is produced by a consortium of European research institutions[1].

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TABLE S-1. **Emissions Pathways, Temperatures and Carbon Budgets**

RCP	T in °C, 2100	Peak T in °C	Peak Emissions Year	Peak PPM	Remaining Carbon from 2018 (Gt CO2-eq)
2.6	1.6	1.6	2020	450	420*
4.5	2.4	3.1	2040	650	1170*
8.5	4.3	8–12+	2100	1250+	N/A

* from SR1.5, Table 2.2. Refers to 1.5°C and 2°C rather than RCP2.6 and 4.5, respectively, both with at least 66% chance with respect to uncertainties in the carbon cycle and in the climate system’s response to emissions, but not including the effects of – and uncertainty in – permafrost thawing.

[1] Climate Analytics, NewClimate Institute and Potsdam Institute for Climate Research

CHAPTER 1

Ice Sheets

SLEEPING GIANTS NO LONGER

SUMMARY For the Earth's polar ice sheets on Greenland and Antarctica, holding enough combined 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 between 1°, 1.5° and 2°C has resulted in very different states on Greenland and Antarctica at several times in Earth's past. By 2°C, the Earth has had sea levels between 12–20m above today, from extensive melting of the West Antarctic Ice Sheet (WAIS), Greenland and likely parts of East Antarctica. These changes occured very slowly in the past, over thousands of years, because the processes that caused them also occured slowly. However, the observed rise in temperature over the past decades is much faster than anything documented in Earth's past, making the rate of ice sheet loss and sea-level rise (SLR) difficult to predict. It may occur more quickly than both the models, and Earth's past might show. Some studies show the WAIS threshold for collapse may have been crossed by 2015, at around 0.8°C global warming.

Regardless, there is strong consensus that the risks of extensive melting from the ice sheets increases as both the peak in global temperatures, and the rate of warming rises. Today, if we could hold at 1° above pre-industrial temperatures, we are still likely committed to a very slow but unavoidable 1–3 meters minimum SLR, yet over thousands of years. Risks increase substantially at 1.5°, with the possibility of 6–9 meters SLR compared to today, coming from additional loss of Greenland and the West Antarctic Ice Sheet (WAIS), though this too would likely take many centuries to occur. 2° however shows an even greater risk of devastating sea-level rise, because both the West Antarctic Ice Sheet and Greenland have thresholds for near-complete melt somewhere near the 2° level, with vulnerable portions of the much larger East Antarctic ice sheet also posing a threat.

The duration and extent of warming above 2° will increase the risk, speed and inevitability of the above changes. However, these processes, even WAIS collapse can be slowed, potentially by thousands of years if temperatures remain close to 1.5°, with an aim to return below that level as soon as possible.

Background

The massive ice sheets of Greenland and Antarctica consist of compressed snow that fell, in its oldest sections, up to a million or more years ago. In equilibrium, calving of icebergs and outflow of melt water into the ocean balance the snowfall adding mass to the ice sheets. Observations now confirm that this equilibrium has been lost on Greenland, the West Antarctic Ice Sheet (WAIS) and Antarctic Peninsula; and key portions of East Antarctica.

Any change in the total mass of land ice bound within the land-based ice sheets of our planet has direct consequences for global sea level. During ice-age periods, when the ice sheets expanded significantly, sea level was more than 100 meters lower than today. During periods of warming, when the ice sheets lost mass, sea level rose accordingly. In addition, the topography of the ice sheets strongly influences atmospheric circulation at high latitudes. Changes in the height and extent of the ice sheets, together with incursion of new cold water into ocean currents from ice sheet melt, are reflected by changes in Earth's weather patterns not only near the poles, but at lower latitudes.

The Greenland ice sheet and parts of the Antarctic ice sheet have discrete thresholds where melt becomes inevitable, and (in the case of the West Antarctic Ice Sheet) potentially relatively rapid. In Earth's past, several of these thresholds (driven by slow Earth's orbital changes) have occurred somewhere between 1 and 2 degrees: about 1° for the WAIS and Antarctic Peninsula (3–5 meters SLR); and between 1.5° and 2° for Greenland (7 meters SLR). Parts of East Antarctica, especially the massive Wilkes Basin (4 meters of potential SLR), may also have a threshold around or just beyond 2°. This combination likely explains why, in the Earth's past, sea levels peaked at around 12–20 meters higher than today during sustained periods when temperatures reached 2°. During the height of the Pliocene 3 million years ago, when temperatures were between 2–3° higher than pre-industrial, sea levels peaked at around 20–25 meters.

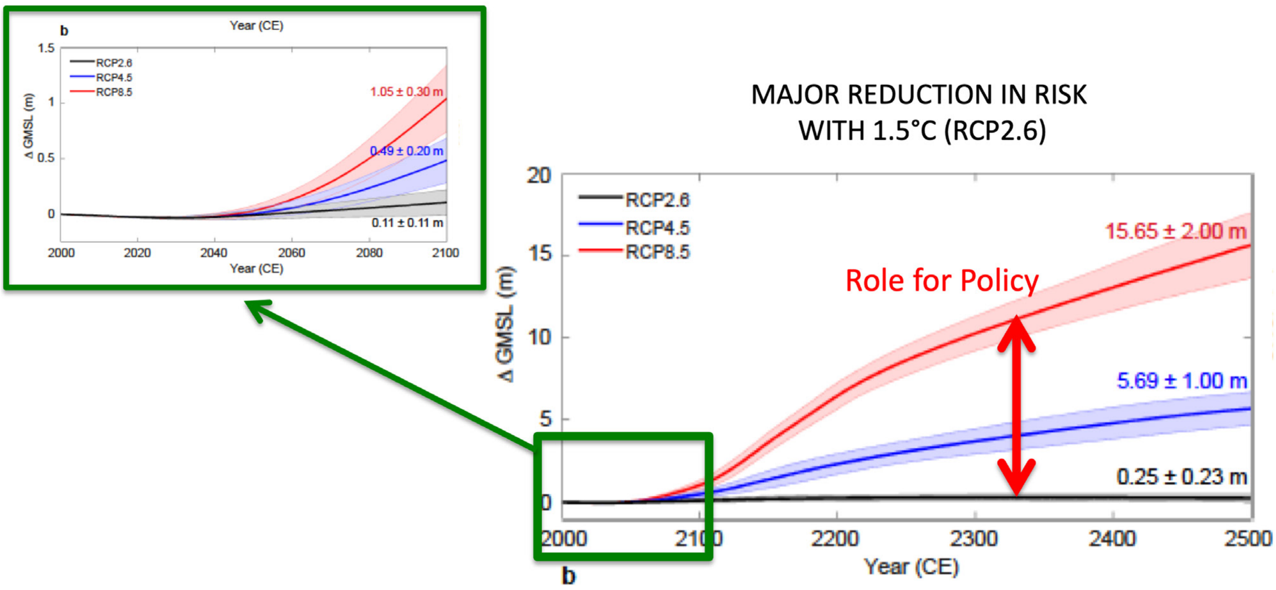
Greenland will not reach a so-called tipping point until melting lowers its altitude, presumably over several centuries. The Greenland ice sheet is over 3000 m thick and above 3000 m altitude in the interior. If the height of this ice sheet is lowered through melting, it eventually becomes exposed to above-freezing temperatures for longer time periods throughout the year, leading to eventual unstoppable loss of the entire ice sheet. The WAIS is a very different story: it does not really sit over land, but a vast archipelago of islands similar to Indonesia today (Figure). Much of its ice therefore rests on bedrock that is actually below sea level, sloping downwards from the coast inland (Figure). This allows warming water to eat away at the ice from below, and it can rapidly become unstable, collapsing into the ocean and raising sea level.

This kind of instability is also true for some sectors of East Antarctica, for example the Wilkes Basin noted above; which might account for sea levels in the past higher than could have been caused by the loss of the WAIS (5 meters), Greenland (7 meters) and mountain glaciers (1–2 meters) alone.

The main question for scientists and policy makers is the rate of change, and at what point these higher sea levels become locked in. In general, scientists agree that higher temperatures, sustained for longer periods of time will result in both faster melt, and more rapid rates of sea-level rise – as fast as several cm a year should temperatures exceed 4°, for example (today, sea level rise is measured in mm per year). A key message for policy makers is that as the melt process accelerates, for significant sectors of the polar ice sheets it cannot be stopped or reversed until either temperatures go well below pre-industrial (initiation of a new Ice Age), or much of the ice sheet has flowed into the ocean. Practically speaking in other words, sea level rise is not reversible on human time scales.

Many scientists believe that this point of instability was already reached sometime before 2015 for parts of the WAIS and Antarctic Peninsula, when temperatures were

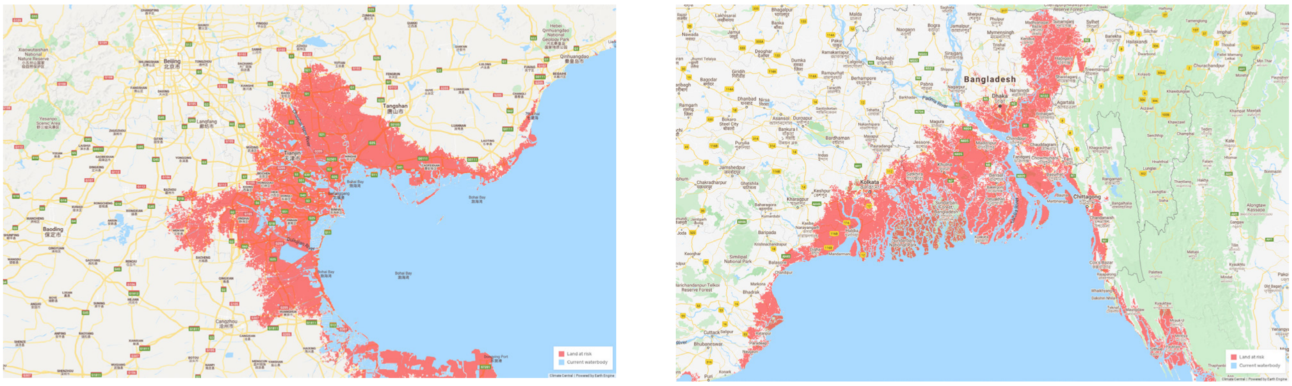
FIGURE 1-1. **Committed Sea-level Rise Beyond 2100 at Different CO_2 Emissions and Temperatures**



Over the long term, sea levels should rise very slowly if temperatures stay below 1.5°C (black bar, RCP2.6); but with high emissions (red bar, RCP8.5) sea levels are projected to rise exponentially for centuries, with 2100 only the beginning.

DECONTO AND POLLARD, 2016

FIGURE 1-2. **Annual Flood Events on Vulnerable Coastlines – 2050**



Improved satellite mapping shows more frequent and damaging flooding each year in many high-population areas by 2050. Left: City of Tianjin near Beijing, Right: Bangladesh and Kolkata, India region.

CLIMATE CENTRAL

around 0.8° above pre-industrial. Even if this is the case, however, modeling shows that the inevitable collapse can be slowed substantially if we remain below 1.5°, allowing human communities and ecosystems centuries, rather than decades, to adapt to higher sea levels should temperatures climb far higher (Figure based on Joughin et al. 2014).

A key uncertainty in this picture involves the degree of stability of the ice cliffs that will form as the floating ice shelves currently "holding back" the WAIS melt, leaving ice cliffs along the edges of the ice sheet that could be hundreds of meters high. Eaten underneath by warmer water and broken apart by summer meltwater on the ice sheet surface, such ice cliffs would be inherently unstable and could collapse rapidly, potentially raising sea levels up to an additional meter within a century or two. (Figure, link to animation online version). The risk of this more rapid sea-level rise occurring becomes greater as temperatures pass 2°.

Regardless of the uncertainties surrounding the rate of future melt, we know that Greenland melt today is twice what it was 20 years ago; and three times higher from Antarctica. For a growing number of ice sheet experts therefore, the true "guardrail" to prevent dangerous levels and rates of sea-level rise is not 2° or even 1.5°, but 1° above pre-industrial. For these scientists, a key argument in favor of a 1.5° limit is that it will allow us to return more quickly to the 1° level, drastically slowing global impacts from WAIS collapse especially, preserving the ability of low-lying communities to adapt through sustainable development, though sea levels will continue to rise for many centuries even after a return to lower temperatures.

Conversely, sea-level rise at rates of centimeters per year allows for neither adaption, nor development. The rate of future sea-level rise and associated risks to security and development depends entirely on future human emissions of greenhouse gases. To maintain the possibility of staying below 1.5°, such steps must be determined by 2020 and taken by 2030, in accordance with the IPCC SR1.5. Our human emissions will determine whether sea-level continues to rise on scales of millimeters, or centimeters per year and several meters in the long run; and thereby ruling whether impacts will be technically and economically manageable, or devastating and catastrophic.

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LITERATURE

Alley RB, Anandakrishnan S, Christianson K, Horgan HJ, Muto A, Parizek BR, Pollard D, Walker, RT (2015) Oceanic Forcing of Ice-Sheet Retreat: West Antarctica and More. Annual Review of Earth and Planetary Science 43: 207-231, doi:10.1146/annurev-earth-060614-105344

Applegate PJ, Parizek BR, Nicholas RE, Alley RB, Keller K (2014) Increasing temperature forcing reduces the Greenland Ice Sheet's response time scale. Climate Dynamics, 45: 2001-2011, doi:10.1007/s00382-014-2451-7

Cook CP, Van De Flierdt T, Williams T, Hemming SR, Iwai M, Kobayashi M, Jimenez-Espejo F.J, Escutia C, González JJ, Khim BK, McKay RM, Passchier S, Bohaty SM, Riesselman CR, Tauxe L, Sugisaki S, Galindo AL, Patterson MO, Sangiorgi F, Pierce EL, Brinkhuis H, Klaus A, Fehr A, Bendle JAP, Bijl PK, Carr SA et al. (2013) Dynamic behavior of the East Antarctic ice sheet during Pliocene warmth. Nature Geoscience, 6: 765-769, doi:10.1038/ngeo1889

DeConto RM & Pollard D (2003) Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2. Nature, 421: 245-249, doi:10.1038/nature01290

DeConto RM & Pollard, D (2016) Contribution of Antarctica to past and future sea-level rise. Nature, 531: 591-597, doi:10.1038/nature17145

Dutton A, Carlson AE, Long AJ, Milne, GA, Clark P, DeConto, RM, et al. (2015) Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science, 3491 (6244), doi:10.1126/science.aaa4019

Etourneau L, Sgubin G, Crosta X, Swingedouw D, Willmott V, Barbara L, Houssais MN, Schouten S, Damste JSS, Goose H, Escutia C, Crespin J, Masse G, Kim JH (2019) Ocean temperature impact on ice shelf extent in the eastern Antarctic Peninsula. Nature Communications, 10: 304, doi:10.1038/s41467-018-08195-6

Feldmann J & Levermann A (2015) Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin. Proceedings of the National Academy of Sciences, 112: 14191–14196, doi:10.1073/pnas.1512482112

Greenbaum JS, Blankenship DD, Young DA, Richter TG, Roberts JL, Aitken ARA, Legresy DM, Schroeder DM, Warner RC, van Ommen TD, Siegert MJ (2015) Ocean access to a cavity beneath Totten Glacier in East Antarctica. Nature Geoscience, 8: 294–298, doi:10.1038/ngeo2388

Joughin I, Smith BE, Medley B (2014) Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. Science, 344: 735-738, doi:10.1126/science.1249055

Marzeion B & Levermann A (2014) Loss of cultural world heritage and currently inhabited places to sea-level rise. Environmental Research Letters, 9: 034001, doi:10.1088/1748-9326/9/3/034001

Mengel M & Levermann A (2014) Ice plug prevents irreversible discharge from East Antarctica. Nature Climate Change, 4: 451-455, doi:10.1038/nclimate2226

Mouginot J, Rignot E, Scheuchl B, Fenty I, Khazendar A, Morlighem M, Buzzi A, Paden J (2015) Fast retreat of Zachariæ Isstrøm, northeast Greenland. Science, 350: 1357–1361, doi:10.1126/science.aac7111

Naish T, Powell R, Levy R, Wilson G, Scherer R, et al. (2009) Obliquity-paced Pliocene West Antarctic ice sheet oscillations. Nature, 458, doi:10.1038/nature07867

Pattyn F, Ritz C, Hanna E, Asay-Davis X, DeConto R, Durand G, et al. (2018) The Greenland and Antarctic ice sheets under 1.5°C global warming. Nature Climate Change, 8: 1053-1061, doi:10.1038/s41558-018-0305-8

Rignot E, Mouginot J, Morlighem M, Seroussi H, Scheuchl B (2014) Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. Geophysical Research Letters, 41: 3502-3509. doi:10.1002/2014GL060140

Rignot E, Mouginot J, Scheuchl B, van den Broeke M, van Wessem MJ, Morlighem M (2019) Four decades of Antarctic Ice Sheet mass balance from 1979–2017. PNAS, 116:1095-1103, doi:10.1073/pnas.1812883116

Robinson A, Calov R, Ganopolski A (2012) Multistability and critical thresholds of the Greenland ice sheet. Nature Climate Change, 2: 429-432, http://doi.org/10.1038/nclimate1449

Winkelmann R, Levermann A, Ridgewell A, Caldeira K (2015) Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet. Science Advances, 1: e1500589. doi:10.1126/sciadv.1500589

Wouters B, Martin-Español A, Helm V, Flament T, Van Wessem JM, Ligtenberg SRM, Broeke MRVD, Bamber JL (2015) Dynamic thinning of glaciers on the Southern Antarctic Peninsula. Science, 348: 899-903, doi:10.1126/science.aaa5727

CHAPTER 2

Mountain Glaciers and Snow

PRESERVING GREATER REMNANTS AND WATER SUPPLIES AT 1.5°

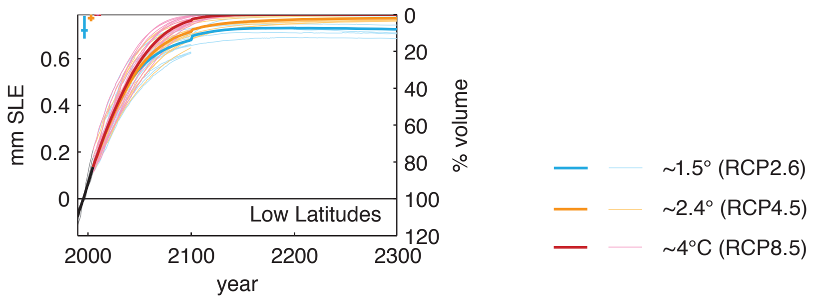
SUMMARY The tropical glaciers of the northern Andes, East Africa and Indonesia are disappearing too rapidly to be saved, even at today's temperature of 1°C above pre-industrial. Many glaciers close to the equator are small and marginal in any case, and would have slowly disappeared after the last Ice Age; but global warming has accelerated this loss. Some of these highly symbolic tropical glaciers, especially in the northern Andes still likely would have provided a reliable seasonal source of water for many hundreds of years without current warming. Their early loss will impact rural populations in Peru, Bolivia and northern Chile. Severe losses also are occurring today from mid-latitude glaciers: the Alps, southern Andes and Patagonia, Iceland, Scandinavia, New Zealand and the North American Rockies. The good news is that these glacier regions can still preserve small but significant amounts of their ice if global temperatures remain at or below 1.5°C. With 2°C of sustained warming however, most of these mid-latitude glaciers will disappear entirely within a few centuries. At higher temperatures, their loss becomes even more rapid. In the essential watersheds of the Hindu Kush Himalaya and Central Asia, 1.5°C maintains around half to about two-thirds of their ice. At 2°C, much more will be lost, with regional impacts on water supply and potential for increasing political conflict, especially since projections show monsoon rains becoming far more unpredictable at 2°C as well. The very large glaciers in the Arctic and Antarctic Peninsula are also losing ice mass at today's 1°C above pre-industrial, but like the Himalayas will lose much more at higher temperatures. While populations near these glaciers are small, their increased loss, together with loss of mid-latitude glaciers will affect large global populations due to higher sea-level rise, especially for the rest of this century. In addition to glaciers, mountains actually hold far more seasonal water in the form of snow. Snowfall has however become more unreliable in many mountain watersheds, with extremes of snow drought alternating with high amounts that increase risk of avalanche and flood. In many mountain snow systems, it now appears that snow generally is following the same trends as the glaciers: smaller amounts, with more snow today instead falling as rain; with economic impacts on farming, tourism, and sufficient water supplies for large urban populations even greater than impacts of retreating glaciers. Staying below 1.5°C will lessen all these impacts.

Background

Receding mountain glaciers in the European Alps, American Rockies, Andes, East Africa and elsewhere were among the first identified, visible impacts of climate change. Most of this observed retreat however arose from ongoing warming from the end of the Little Ice Age, with rising greenhouse gases only slightly speeding that retreat. Sometime in the past 50 years however, anthropogenic climate change became the main driver of retreat for most glacier systems.

Glaciers and alpine snowpack have varying importance to nearby communities as a source of water for drinking or irrigation, with some contributing only a few percent over the course of a year, but of enhanced importance during dry seasons, heat waves and droughts.

FIGURE 2-1. **Tropical Glaciers**

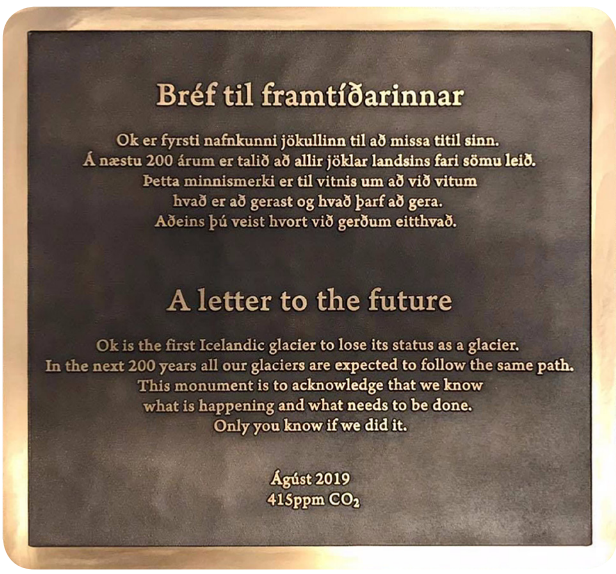


Few tropical glaciers will survive even today's 1°C, aside from remnants at altitudes above 6000 m.

FIGURES BASED ON MARZEION ET AL. (2012)

Glaciers in the Andes, and those in the Indus and Tarim basins in the Greater Himalaya region, contribute most strongly to human water supply. While the increased melting of glaciers temporarily increases water supply, eventually the decrease and ultimate loss of glacial water resources may make current economic activities, including agriculture impossible in some regions, as well as decreasing supplies for drinking water and basic household needs. This makes extensive adaptation or even leaving retreat as the only option, including by many indigenous mountain communities.

Glacier melt is accelerating, and expected to reach its peak in most regions sometime around 2050, after which (if temperatures rise to 2°C and beyond) eventually little or no ice remains to melt, as occurred with the Icelandic glacier Ok sometime around 2015 (Picture). Many glaciers however are disappearing every year, and with far less fanfare: in the U.S.'s Glacier National Park, only 26 of the original 150 glaciers present in 1900 still remained in 2017. Glaciers "work" by gaining snow at higher altitude, and losing it as meltwater at lower altitude. Warming means a rise in the altitude that separates net annual gain by snowfall turning to ice, from net annual loss by melting. A threshold is crossed when that altitude rises above the glacier's highest point. It then suffers net loss over its entire surface every year, and is doomed to eventually disappear entirely.



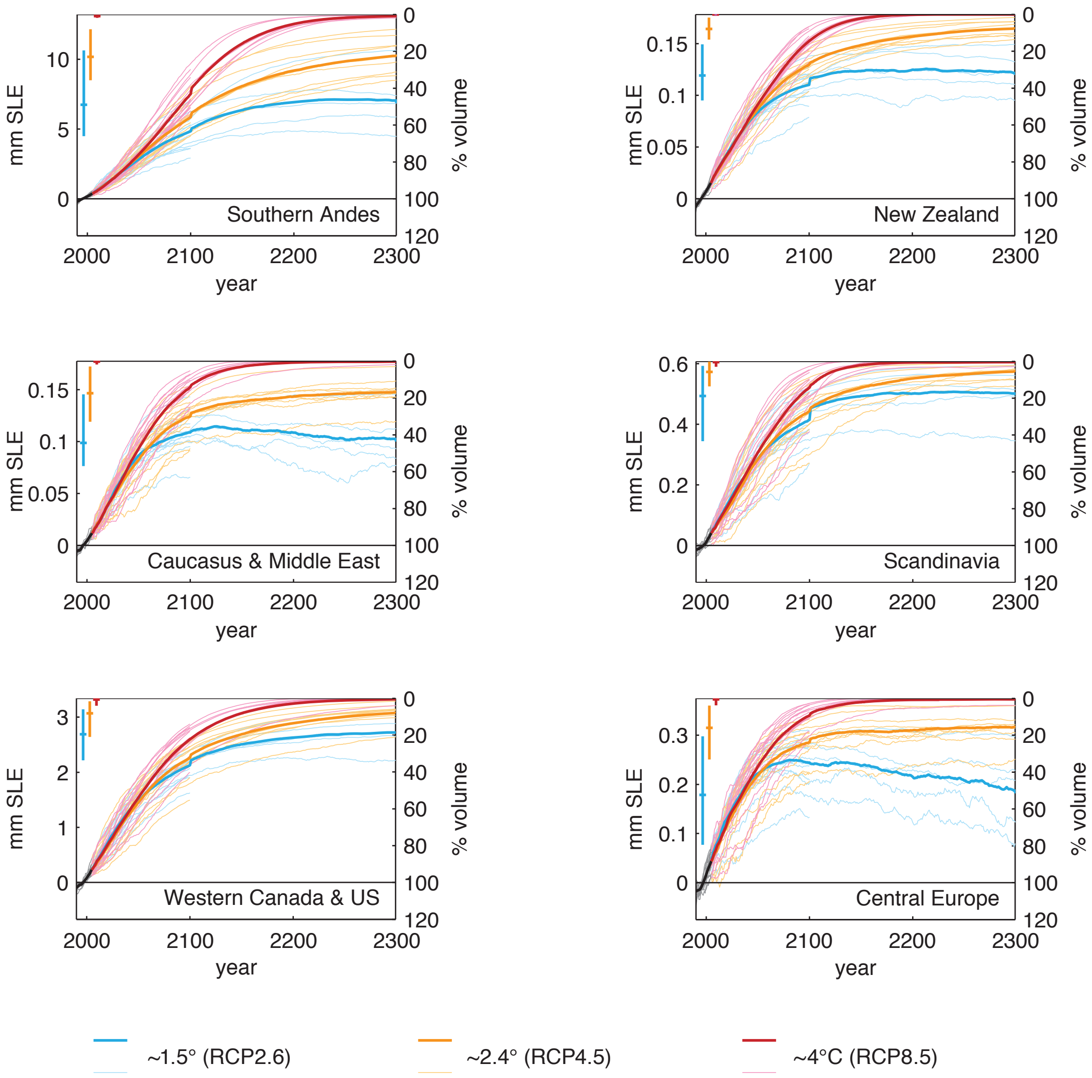
Rice University

Many glacier systems have little resilience to rising temperatures. This is true especially in regions where climate change also leads to long-term drought such as the Tarim Basin of Northwestern China. Glaciers such as the tropical glaciers in East Africa and the northern and central Andes are not expected to survive at even 1.5°C of warming above pre-industrial. Those in western North America, the Alps, Iceland, Scandinavia, Svalbard and New Zealand similarly are unlikely to survive at 2°C of warming. However, modeling taken out to 2300 shows that 1.5°C pathways preserve at least some remnant of ice (between 10–30%) of these mid-latitude glacier systems. (Figure).

In regions at higher latitude or altitude – the High Mountain Asia and high Arctic glaciers – about 50–60% of glacier ice will survive even 2°C degrees of warming, with losses potentially higher in the Hindu Kush Himalayas. However, a 1.5°C goal preserves far greater amounts; especially for key regions of India, Pakistan, northwestern China and Nepal that rely on seasonal meltwater from these high altitude glacier systems.

Snowpack, an even greater source of seasonal water supplies than the glaciers, now appears to be following a similar path of loss as mountain glaciers: with more swings and extremes of high snowfall and snow drought, but overall loss as temperatures rise above freezing at higher altitudes. This means that precipitation that would have fallen as snow in past decades, increasingly comes down

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



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

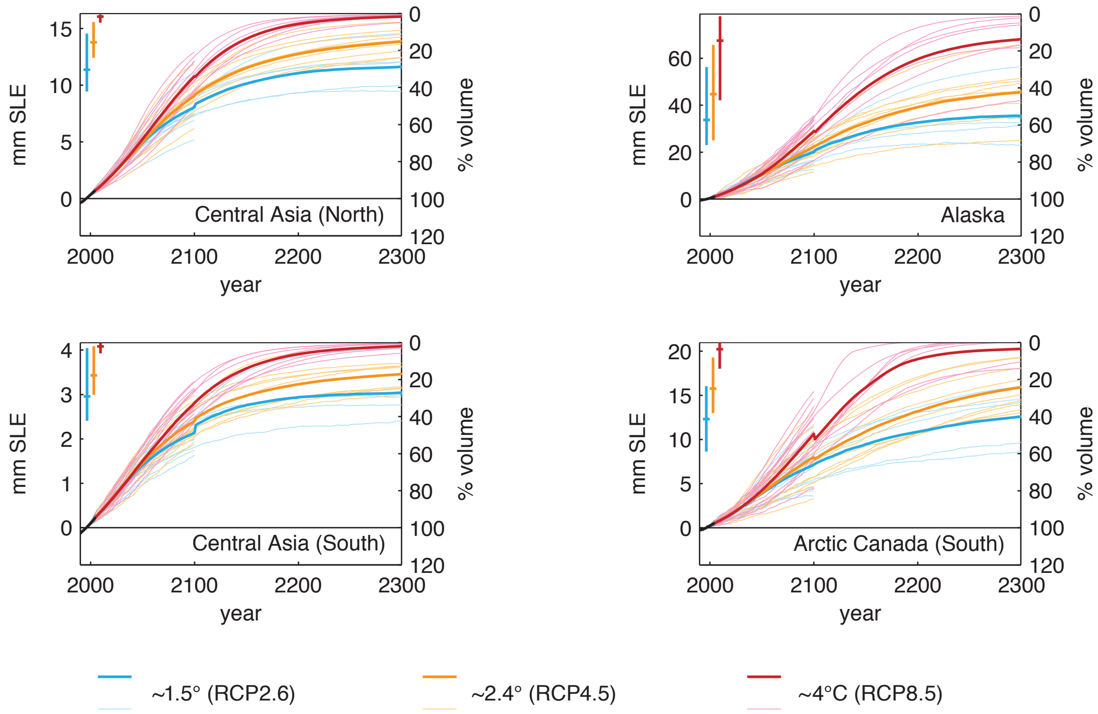
FIGURES BASED ON MARZEION ET AL. (2012)

as rain. At lower elevations and latitudes, snow will fall less often or not at all; and seasonal snowpack will not form, resulting in loss of stored water in the snow itself and underground aquifers. Mountain snow sustains water supplies for people far beyond mountain regions, travelling great distances across grasslands and deserts to densely populated coastal regions. People in cities such as Los Angeles, Marrakech and in the Ebro-Duero basin of northern Spain and Portugal are especially dependent on the water from snow.

This decreasing high-altitude snowfall has a counterpart in the very well-documented decrease in snow cover and amounts in the Arctic since 1990. In both the Arctic and mountain regions, the well-being of people and many species depends on seasonal snow cover. In addition to threatening water supplies, decreases in snow cover negatively impact snow tourism, especially in the U.S. West, New England and central Europe. Lack of mountain snow cover also appears to be increasing risk of wildfires, as well as catastrophic events such as mudslides in the wake of such wildfires.

A sharp strengthening of NDCs in 2020 towards 1.5°C, including preferably stronger commitments in the near-term 2030–40 time frame, could make the difference between rapid and disruptive loss of regionally-important snow and glacier systems, and significant slowing of glacier

FIGURE 2-3. **Himalayan and Polar Glaciers**



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

FIGURES BASED ON MARZEION ET AL. (2012)

loss that allows local communities time to adapt, even in those regions where glaciers are doomed to disappear completely at 1° or 1.5°C. This will have greatest benefit for communities in the Andes and Central Asia that are most dependent on glaciers as a seasonal source of water for drinking and irrigation, and on economies dependent on glaciers and associated snowpack for revenue from tourism, such as the Alps and North American West.

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LITERATURE

Bliss A, Hock R, Radić V (2014) Global response of glacier runoff to twenty-first century climate change. *Journal of Geophysical Research: Earth Surface*, 119:717-730, doi http://dx.doi.org/10.1002/2013JF002931

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn PD, Payne AJ, Pfeffer WT, Stammer D, Unnikrishnan AS (2013) Sea Level Change. *In* Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, doi:10.1017/CBO9781107415324

Gregory JM, White NJ, Church JA, Bierkens MFP, Box JE, van den Broeke MR, Cogley JG, Fettweis X, Hanna E, Huybrechts P, Konikow LF, Leclercq PW, Marzeion B, Oerlemans J, Tamisiea ME, Wada Y, Wake LM, van de Wal RSW (2013) Twentieth-century global-mean sea-level rise: is the whole greater than the sum of the parts? Journal of Climate, 26: 4476-4499, doi: 10.1175/JCLI-D-12-00319.1

Huss M (2001) Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe. Water Resources Research, 47:W07511. doi:10.1029/2010WR010299

Hock R, Bliss A, Marzeion B, Giesen R, Hirabayashi, Huss M, Radic V, Slangen, ABA (2019) Glacier MIP: A model inter-comparison of global scale glacier mass-balance models and projections. Journal of Glaciology: 05: 1-15. doi: 10.1017/jog.2019.22

Huss M, Hock R (2015) A new model for global glacier change and sea-level rise. Frontiers in Earth Science, 3:54. doi: 10.3389/feart.2015.00054

Huss M, Hock R (2018) Global-scale hydrological response to future glacier mass loss. Nature Climate Change, 8:135-140. Doi: 10.1038/s41558-017-0049-x

IPCC, Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T(eds.)] (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.

Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Nicolai M, Okem A, Petzold J, Rama B, Weyer N (eds.), IPCC (2019) Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Kaser G, Großhauser M, Marzeion B (2010) Contribution potential of glaciers to water availability in different climate regimes , *Proceedings of the National Academy of Sciences*, 107:20223-20227, doi: 10.1073/pnas.1008162107

Kraaijenbrink PDA, Bierkens MFP, Lutz AF, Immerzeel WW, (2017) Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. Nature, 549: 257-260, doi: 10.1038/nature23878

Mankin JS, Viviroli D, Singh D, Hoekstra A, Diffenbaugh NS (2015) The potential for snow to supply human water demand in the present and future. Environmental Research Letters, 10:11. doi.org/10.1088/1748-9326/10/11/114016

Marzeion B, Cogley JG, Richter K, Parkes D (2014) Attribution of global glacier mass loss to anthropogenic and natural causes. *Science, 345(6199)919-21.* doi: 10.1126/science.1254702

Marzeion B, Jarosch AH, Gregory JM (2014) Feedbacks and mechanisms affecting the global sensitivity of glaciers to climate change. *The Cryosphere*, 8:59–71, doi: 10.5194/tc-8-59-2014

Marzeion B, Jarosch AH, Hofer M (2012) Past and future sea-level change from the surface mass balance of glaciers. *The Cryosphere*, 6:1295 - 1322, doi: 10.5194/tc-6-1295-2012

Vaughan DG, Comiso JC, Allison I, Carrasco J, Kaser G, Kwok R, Mote P, Murray T, Paul F, Ren J, Rignot R, Solomina O, Steffen K, Zhang T (2013) Observations: Cryosphere. *In* Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 317–382.

Wester P, Mishra A, Mukherji A, Shrestha A (2019) The Hindu Kush Himalaya Assessment. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal. doi.org/10.1007/978-3-319-92288-1

Yao J, Zhao Y, Yu X (2018) Spatial-temporal variation and impacts of drought in Xinjiang (Northwest China) during 1961–2015. PeerJ. 6:4926, doi: 10.7717/peerj.4926

CHAPTER 3

Permafrost

IRREVERSIBLE EMISSIONS CUT CARBON BUDGETS: PEAK TEMPERATURES DETERMINE BY HOW MUCH

SUMMARY About one quarter of Northern Hemisphere land area contains permafrost – ground that remains frozen throughout the year and holds vast amounts of ancient organic carbon. Observations confirm that it is rapidly warming, and releasing that thawed carbon into the atmosphere as both 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. In addition, new observations since the SROCC confirm that abrupt thaw processes, often triggered by extreme weather, can almost double emissions compared to earlier projections; and once thawed, former permafrost continues emitting carbon for centuries. Urgent human emission reductions, without temperature overshoot can therefore drastically lower permafrost carbon emissions. If we can hold temperatures to 1.5°C, cumulative permafrost emissions by 2100 will be about equivalent to those of Canada (150–200 Gt CO_2-eq). In contrast, by 2°C scientists expect cumulative permafrost emissions as large as those of the EU (220–300 Gt CO_2-eq). If global temperature exceeds 4°C by the end of the century however, permafrost emissions will be as large as those anticipated by 2100 from major emitters like the United States or China (400–500 Gt CO_2-eq). These permafrost carbon estimates include emissions from the newly-recognized abrupt thaw processes from "thermokarst" lakes and hillsides, which expose deeper frozen carbon previously considered immune from thawing for many more centuries. As a result, the "anthropogenic" carbon budget to reach carbon neutrality and remain within 1.5° of warming must begin to take these "country of Permafrost" emissions into account. Only lower temperature emissions pathways that preserve as much permafrost as possible can minimize this potentially large contribution to future global warming.

Background

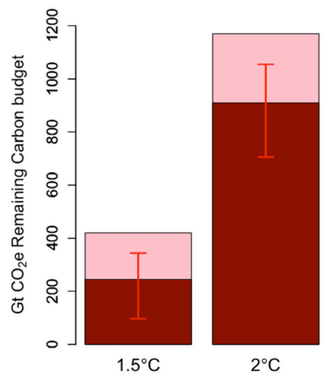
Permafrost is ground that remains frozen for at least two consecutive years, and covers nearly 25% of the Northern Hemisphere land area. It stretches across vast regions of the Arctic, especially Siberia, sometimes to a depth of over a thousand meters, and also occurs in mountain regions globally. Permafrost is a frozen mixture of soil, rocks, ice and organic material holding about twice as much carbon as currently exists in earth's atmosphere. Cold temperatures have protected this organic matter from thawing, decomposing and releasing its stored carbon to the atmosphere for many thousands of years.

Models project that the area covered by near-surface permafrost (in the first few meters of soils) will decline across large regions as temperatures rise. Today, at about 1°C; the area of near-surface permafrost already has declined by about 25%. Scientists anticipate that 40% of permafrost area will be lost by 2100 even if we hold temperatures close to 1.5°C globally. Over 70% of near-surface permafrost will disappear by 2100 should temperatures exceed 4°C, however.

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

Permafrost thaw occurs gradually over large areas, but is also vulnerable to abrupt thaw events that can result in large-scale erosion, ground collapse along hillsides and cliffs, and rapid building of new lakes or wetlands (called "thermokarst" processes). The collapsed ground rapidly exposes deeper carbon pools previously thought immune to warming over the near-term. The number of these rapid thaw events has increased as the Arctic warms, and might increase permafrost carbon emissions by as much as 50% as the planet warms to 1.5°C or more. Increasing wildfires in the Arctic due to warmer and drier conditions also cause deeper and more rapid thawing post-fire. Both gradual, and abrupt thermokarst thaw processes and their emissions are irreversible on human timescales, because new permafrost carbon will take many thousands of years to form. While new vegetation growing on thawed former permafrost soils might take up some portion of these emissions, that amount is dwarfed by the sheer scale of permafrost emissions expected at warmer temperatures. In addition, some "permafrost" is actually located beneath the near-coast waters of the Arctic Ocean, on lands flooded at the end of the last Ice Age when sea-levels rose. Its current and future contribution to carbon emissions remains uncertain, but could be significant.

FIGURE 3-1. **Proportion of Permafrost Emissions**

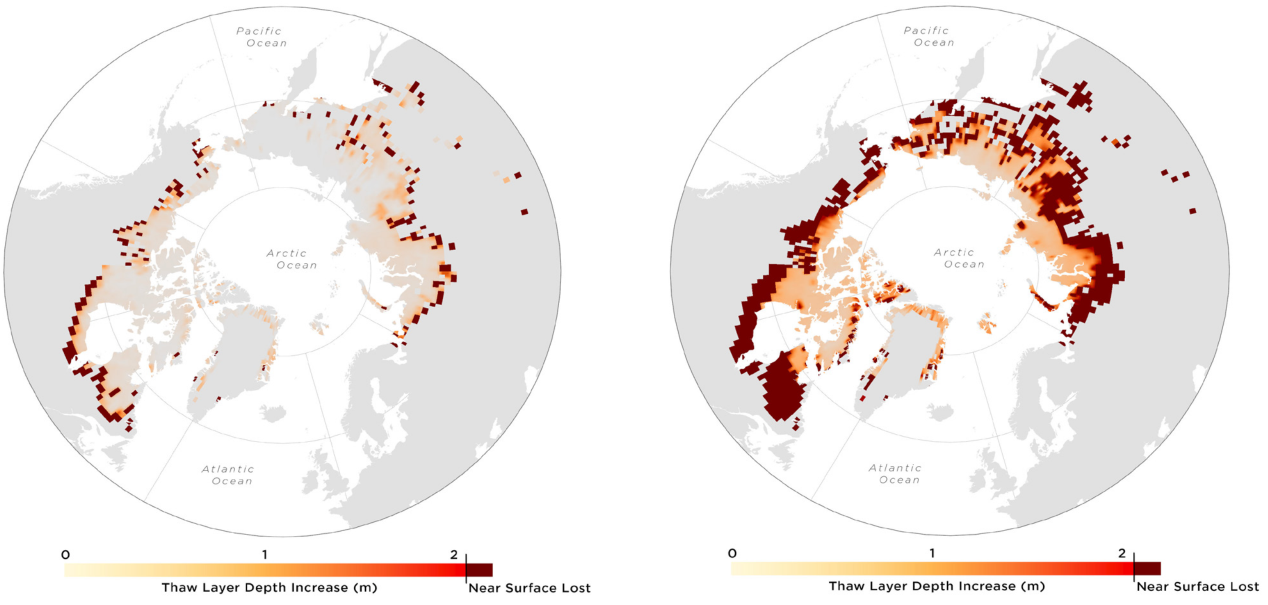


Bars show total carbon budgets to stay below 1.5° and 2°. Light pink portion shows projected emissions from permafrost at these temperature levels.

SARAH CHADBURN

Permafrost emissions today and in the future are on the same scale as large industrial countries, but can be minimized if the planet remains at lower temperatures. If we limit warming to 1.5°C, emissions through 2100 will be about as large as those of Canada (around

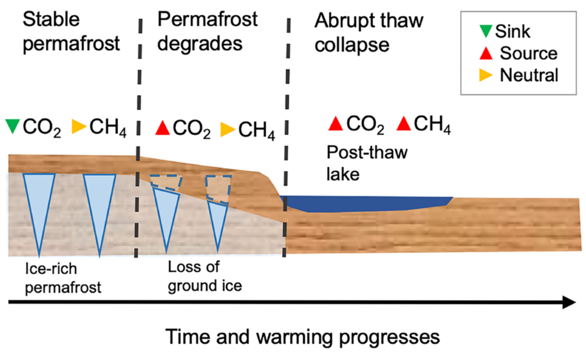
FIGURE 3-2. **Additional Near-Surface Permafrost Lost at 1.5°C v 3°C**



Much more permafrost thaws and releases its stored carbon at 3°C as compared to 1.5°C. (Left) Loss of permafrost between now and 1.5°C, and (right) loss of permafrost between now and 3°C.

DATA: COMMUNITY LAND MODEL, CMIP6 DATA ARCHIVE

FIGURE 3-3. **Abrupt Thaw of Permafrost**



Abrupt thaw of permafrost causes large and sudden releases of carbon, with a greater percentage of fast-warming methane.

GUSTAF HUGELIUS/BOLIN CENTRE

150–200 Gt CO_2-eq). Should we instead reach 2°C, permafrost emissions will about equal those of the entire European Union, about 220–300 Gt CO_2-eq by 2100. Even higher temperatures, exceeding 4° by 2100 if it maintains current emissions levels, will however result in up to 400–500 Gt CO_2-eq additional carbon release, adding the equivalent of another United States or China to the global carbon budget, the same scale as that for the current carbon budget to remain within 1.5°C.

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. Once thawed, former permafrost will continue to emit carbon for many hundreds of years, committing future generations to continually offset permafrost carbon emissions through negative emissions for some time, even after temperatures stabilize. To remain valid, future studies must begin to count permafrost emissions as another "NDC-P" or the *Naturally* Determined Contribution of Permafrost.

Additional Risks

Thawing permafrost also can damage infrastructure, like roads, pipelines and houses, as the ground sinks unevenly beneath them. Coastal permafrost erosion has already required some communities in Alaska to abandon their homes. Russia faces the most extensive risk, with recent studies estimating infrastructure loss and damage of up to $100 billion by 2050 if current warming continues.

The greatest global risk however arises from the additional carbon released, which will decrease the carbon budget available to countries to prevent temperatures from rising above 1.5°, 2°C or more. Warming in the Arctic already is occurring more than two times faster than the rest of the planet, due in part to the loss of snowpack, glaciers and sea ice. The exposed bare ground and sea water

Susan Natali/WHRC

Abrupt thaw ("thermokarst") cliff showing newly-exposed ice and permafrost.

absorb far more heat, further accelerating Arctic warming and additional loss of snow and ice. A 2°C higher annual temperature globally translates into 4–6°C higher annual temperatures in the Arctic, including increasing heat waves where temperatures exceed 20°C sometimes for weeks on end, leading to much greater permafrost loss in a continuing feedback loop.

The only means available to minimize these growing risks is to keep as much permafrost as possible in its current frozen state, holding global temperature increases to 1.5°C to also minimize negative emissions efforts by future generations. This will greatly decrease the amount of new carbon entering the atmosphere from permafrost thaw, and minimize the long-term burden of negative emissions efforts by future generations.

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LITERATURE

Chadburn SE, Burke EJ, Cox PM, Friedlingstein P, Hugelius G and Westermann S (2017) An observation-based constraint on permafrost loss as a function of global warming. Nature Climate Change ,7(5): 340, doi: 10.1038/nclimate3262

Comyn-Platt E, Hayman G, Huntingford C, Chadburn SE, Burke EJ, Harper AB, Collins WJ, Webber CP, Powell T, Cox PM, Gedney N and Sitch S (2018) Carbon Budgets for 1.5 and 2 C targets lowered by natural wetland and permafrost feedbacks. Nature Geoscience, 11(8): 568, doi: 0.1038/s41561-018-0174-9

von Deimling TS, Grosse G, Strauss J, Schirrmeister L, Morgenstern A, Schaphoff S, Meinshausen M and Boike J (2015) Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. Biogeosciences, 12(11) 3469–3488 doi:10.5194/bg-12-3469-2015

Gasser T, Kechiar M, Ciais P, Burke EJ, Kleinen T, Zhu D, Huang Y, Ekici A and Obersteiner M (2018) Path-dependent reductions in CO2 emission budgets caused by permafrost carbon release. Nature Geoscience, 11(9): 830-835, doi: 0.1038/s41561-018-0227-0

Hugelius G, Strauss J, Zubrzycki S, Harden JW, Schuur EAG, Ping CL, Schirrmeister L, Grosse G, Michaelson GJ, Koven CD, O'Donnell JA, Elberling B, Mishra U, Camill P, Yu Z, Palmtag J and Kuhry P (2014) Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. Biogeosciences, 11 6573–6593, doi: doi.org/10.5194/bg-11-6573-2014

Hugelius et al. (In review) Large peatland carbon and nitrogen stocks are vulnerable to permafrost thaw. Proceedings of the National Academy of Sciences of the United States of America

Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M and Waterfield T (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

Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Nicolai M, Okem A, Petzold J, Rama B and Weyer N (2019) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate

Koven CD, Lawrence DM and Riley WJ (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, doi: 10.1073/pnas.1415123112

Lawrence DM, Slater AG and Swenson SC (2012) Simulation of Present-day and Future Permafrost and Seasonally Frozen Ground Conditions in CCSM4. Journal of Climate, 25(7) 2207-2225, doi: 10.1175/jcli-d-11-00334.1

MacDougall AH, Avis CA and Weaver AJ (2012) Significant contribution to climate warming from the permafrost carbon feedback. Nature Geosciences, 5(10) 719–721, doi: 10.1038/NGEO1573

McGuire AD, Lawrence DM, Koven C, Clein JS, Burke E, Chen G, Jafarov E, MacDougall AH, Marchenko S, Nicolsky D, Peng S, Rinke A, Ciais P, Gouttevin I, Hayes DJ, Ji D, Krinner G, Moore JC, Romanovsky V, Schädel C, Schaefer K, Schuur EAG and 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, doi: 10.1073/pnas.1719903115

Romanovsky V, Isaksen K, Drozdov D, Anisimov O, Instanes A, Leibman M, McGuire AD, Shiklomanov N, Smith S and Walker D (2017) Changing permafrost and its impacts; Snow, Water, Ice and Permafrost in the Arctic (SWIPA). Monitoring and Assessment Programme (AMAP), pp. 65-102.

Schädel C, Bader MKF, Schuur EAG, Biasi C, Bracho R, Capek P, De Baets S, Diakova K, Ernakovich J, Estop-Aragones C, Graham DE, Hartley IP, Iversen CM, Kane ES, Knoblauch C, Lupascu M, Martikainen PJ, Natali SM, Norby RJ, O'Donnell JA, Chowdhury TR, Santruckova H, Shaver G, Sloan VL, Treat CC, Turetsky MR, Waldrop MP, Wickland KP, O'Donnell JA, Chowdhury TR, Santruckova H, Shaver G, Sloan VL, Treat CC, Turetsky MR, Waldrop MP and Wickland KP (2016) Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. Nature Climate Change, 6(10), 950–953, doi: 10.1038/nclimate3054

Schaefer K, Lantuit H, Romanovsky VE, Schuur EAG and Witt R (2014) The impact of the permafrost carbon feedback on global climate. Environmental Research Letters, 9 085003, doi: 10.1088/1748-9326/9/8/085003

Schaefer K, Lantuit H, Romanovsky VE, Schuur EAG (2012). Policy Implementations of Warming Permafrost, United Nations Environment Programme (UNEP), Nairobi, Kenya, 30 p.
Schuur EAG, McGuire AD, Schädel GG, Harden JW, Hayes DJ, Hugelius G, Koven CD, Kuhry P, Lawrence DM, Natali SM, Olefeldt D, Romanovsky VE, Schaefer K, Turetsky MR, Treat CC, Vonk JE (2015). Climate change and the permafrost carbon feedback. *Nature*, 520: 171–179, doi:10.1038/nature14338
Turetsky MR, Abbott BW, Jones MC, Anthony KW, Olefeldt D, Schuur EAG, Koven C, McGuire AD, Grosse G, Kuhry P, Hugelius G, Lawrence DM, Gibson C and Sannel ABK (2019) Permafrost collapse is accelerating carbon release. Nature, 569: 32-34. doi:10.1038/d41586-019-01313-4
Turetsky et al. (in review) Carbon release through abrupt permafrost thaw, Nature Geoscience.
Zhuang Q, Melillo JM, Sarofim MC, Kicklighter DW, McGuire AD, Felzer BS, Sokolov A, Prinn RG, Steudler PA, Hu S (2006) CO_2 and CH_4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st. Geophysical Research Letters 33 (17): L17403, doi: 10.1029/2006GL026972

CHAPTER 4

Arctic Sea Ice

INCREASING ICE-FREE CONDITIONS EMERGE BETWEEN 1.5 AND 2 DEGREES, WITH GLOBAL CONSEQUENCES

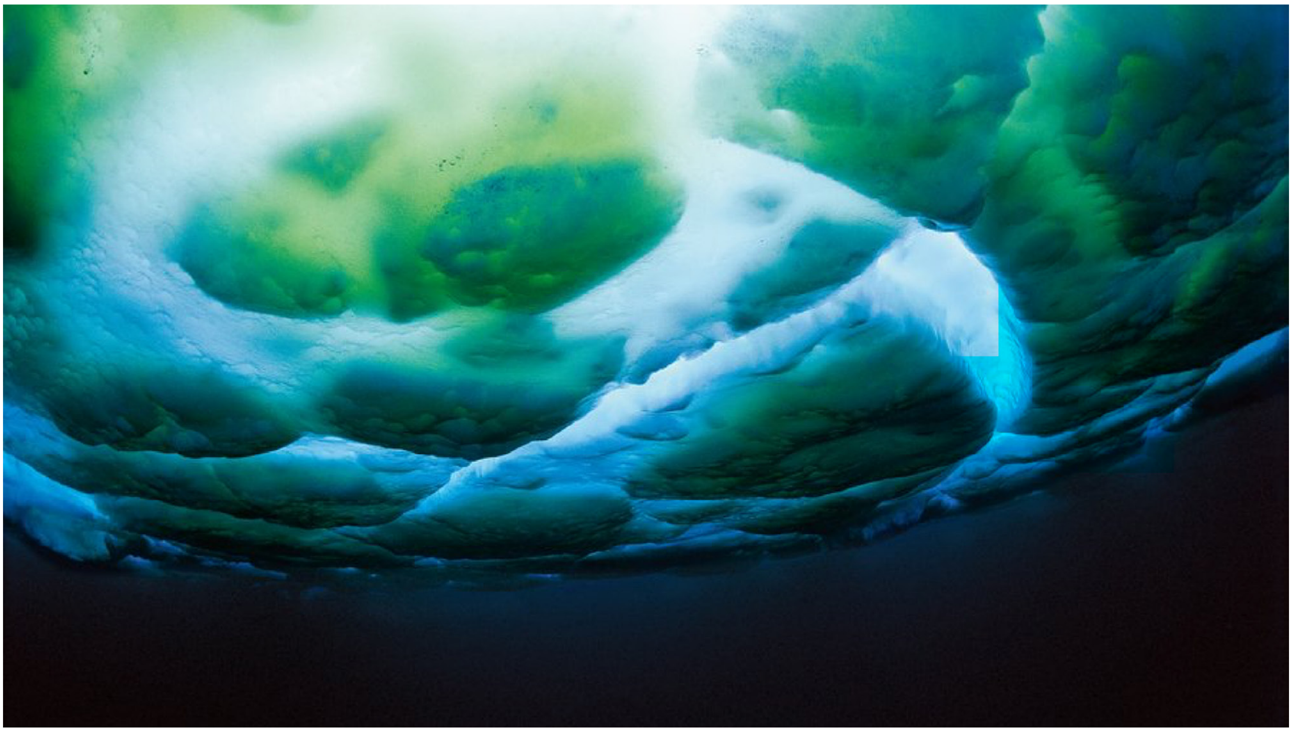
SUMMARY At 1.5°C global warming, Arctic sea ice remains unlikely to melt completely in any given summer. Even if it does, that ice-free period will be brief, with occasional ice-free summers (in September, at the annual minimum). As temperatures move just a bit higher however, to around 1.7°C, ice-free Septembers are expected to occur in most years. By 2°C global warming, the Arctic Ocean will usually be ice free in summer for several months. This longer ice-free period will cause increased Arctic ocean warming, feeding back on air temperatures that in turn accelerate Greenland melt and associated sea level rise; accelerate permafrost thaw and associated carbon emissions; and also lead to a decrease in snow cover. All of these will make for faster rates, and greater scale, of overall global warming, making efforts to address the problem that much harder. Many parts of the Arctic ecosystem also depend on the existence of thicker, multi-year sea ice. These habitats might collapse with the complete disappearance of multi-year ice cover at 2°C global warming, an impact amplified by observations already today of more frequent ocean "heat waves." Human communities also suffer direct consequnces, especially Arctic indigenous cultures reliant on the reliable presence of sea ice for many thousands of years. If we allow temperatures to reach and exceed 2°C above pre-industrial, which will occur at current NDCs, ice cover will become entirely seasonal: with the Arctic Ocean losing all ice in summer and regaining a new cover in winter that melts rapidly each spring.

Background

Arctic sea ice serves as an important regulator of temperature in the northern hemisphere, acting as a "global refrigerator" because 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. It has served this role in the climate system almost continuously for over 200,000 years.

The extent of Arctic sea ice that survives the entire summer has however declined by at least 35% since 1972, when reliable satellite measurements became available. In contrast to reflective ice, the darker ocean water absorbs heat, amplifying Arctic and overall global warming. In addition, whereas until quite recently most of the sea ice in the Arctic was very thick multi-year ice, with an average lifetime of several years and wide-spread winter sea-ice thickness of 3 meters or more, today's ice is mostly formed the previous winter, and thinner than 2 meters. The total volume of Arctic sea ice has therefore declined by nearly two-thirds, far more than its area.

This extreme recent loss of summer sea ice is one of the causes of "Arctic amplification", which refers to the greater rise in temperature that has been observed in the high latitudes of the northern hemisphere compared to the rest of the globe. It also carries significant weather, ecological, and economic consequences. These include loss of livelihood for indigenous cultures dependent on stable sea ice for hunting and fishing. It also has been suggested to include influences on the jet stream, which has changed mid-latitude weather systems, as exemplified by the extreme cold or warm periods in recent years that can be related to a more "wobbly" jet stream and less stable polar front zones. Sea ice loss relates to ecosystem loss, especially for marine species that have evolved with an ice

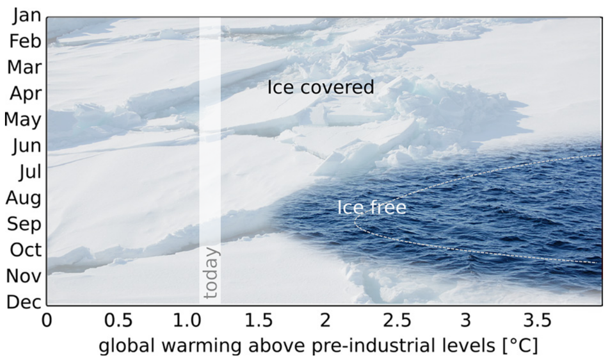


Thick, multi-year ice provides a rich ecosystem not visible from above.

"ceiling" much of the year, and those that depend on these in the food chain.

Sea ice around the continent of Antarctica has been comparatively stable over the past few decades of satellite observation, growing in some regions and decreasing in others. However, recent observations document very sharp declines beginning in 2014, equal to or exceeding those in the Arctic but occurring over the space of only a few years, rather than decades. If this trend holds, sea ice-dependent habitats along Antarctica's coast and in the Southern Ocean would begin to show similar negative impacts as those in the Arctic.

FIGURE 4-1. **Ice-free Conditions by Month and Temperature**



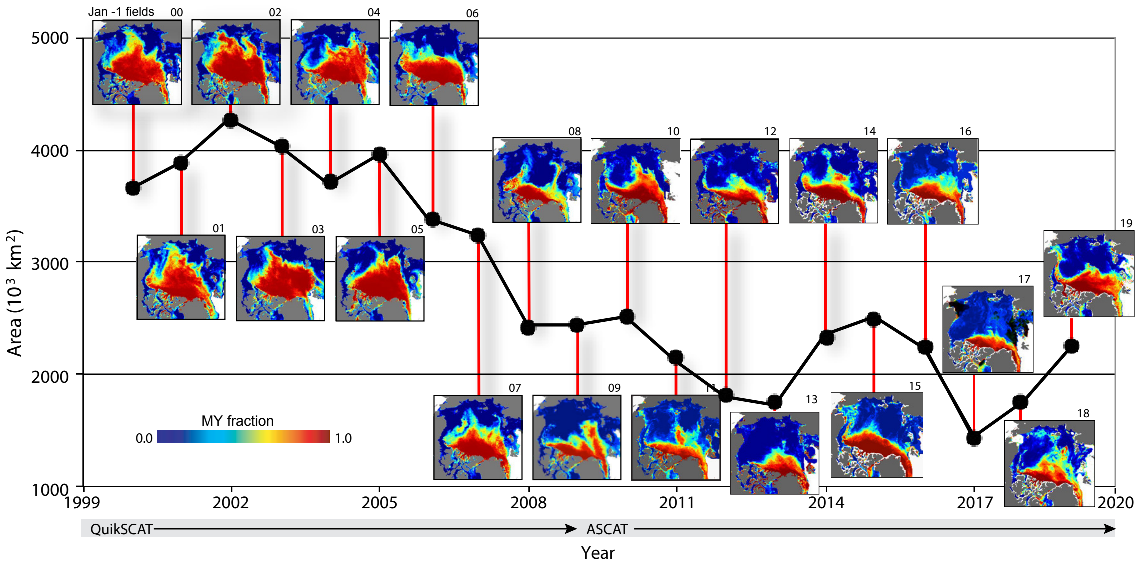
Latest research projects ice-free conditions ranging from briefer periods in September around 1.7°, to several months by 2°C.

BASED ON NOTZ AND STROEVE, 2018

Summer Arctic sea ice extent has often been seen as a bellwether of climate change, with great attention paid to the September minimum each year. In reality however, sea ice thickness and extent has declined for all months; and the consensus of sea ice scientists is that the nature of Arctic Ocean ice cover already has fundamentally changed and crossed a threshold to a new state. Thinner and younger ice has replaced much of the multi-year ice that circulated several years around the North Pole, before being discharged south along Greenland through the Fram Strait. This "ecosystem of ice" no longer exists. Instead, more than half of Arctic sea ice now consists of first-year ice that largely melts each summer, and with the "older" ice existing on average for only 2–3 years.

Despite this fundamental change already at today's temperatures, public focus remains on when the first ice-free summer will occur: something which the Arctic likely has not experienced since at least the Holocene spike in warming after the last Ice Age 8,000 years ago; and possibly not since the warm Eemian period 125,000 years ago, which today's temperatures almost equal (and when sea-level was 4–6 meters (13–20 feet) higher than today). Like many climate change impacts, Arctic sea ice loss over the past three decades has not occurred gradually, but sometimes in abrupt loss events when combinations of wind, as well as warmer temperatures pressed extent lower. It is likely that near-complete loss of summer sea ice

FIGURE 4-2. **Multi-year Arctic Sea Ice Loss 2000–2019**



Thicker multi-year sea ice, which used to dominate the Arctic environment has nearly vanished today.

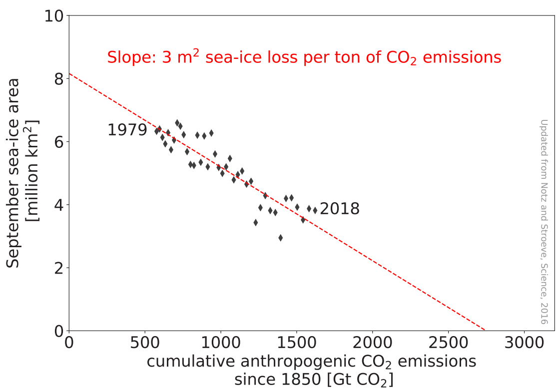
RON KWOK, JPL

(defined as dipping below 15% of the Arctic Ocean, or 1 million square kilometers) will occur with such a sudden event, then perhaps not occur again for several years; until total-loss summers become more frequent and (if temperatures continue to rise) by the end of this century, become the norm for some portion of each summer.

The occurrence of the first ice-free summer is therefore very unpredictable, but most scientists are fairly confident one could occur before 2040 given current temperature pathways. In making their projections, the SROCC and SR1.5 relied on the more numerous global studies, since fewer focus on the Arctic region or take into account recent observations of sea ice decline. Global models however, especially in the past but even those currently used, underestimate the actual sea ice loss that has been observed since about 1990. In contrast, studies that incorporate more regional models, together with observations (even if these are fewer in number) track current sea ice much better, though still underestimating current losses slightly. These predict ice-free summers starting somewhere around 1.7 degrees, with longer ice-free periods each summer by 2°C.

Both regional and global models however agree that ice-free summers will become the norm in the Arctic should temperatures rise much above 2°C, with ice-free summers far more rare at 1.5°C. This in turn will minimize the impacts noted above in terms of lower ice sheet and glacier loss; lower levels of permafrost thaw and carbon release; and less disruption to Arctic marine ecosystems.

FIGURE 4-3. **Sea Ice and CO_2 Emissions**



Arctic sea ice has declined in close correlation to the rise in CO2 emissions.

Additional Risks

The global impact of complete Arctic summer sea ice loss is likely to further accelerate global warming and its impacts. Given the greater absorption of solar heat from open water, it will lead to higher fall and winter temperatures in the Arctic, as well as potentially affecting the weather patterns of the middle latitudes of the northern hemisphere with unusual weather patterns that remain difficult to predict, but likely involve incidences of persistent weather (drought or rainy periods) such as the extreme drought seen in Scandinavia in the summer of 2018, which led to crop and livestock losses as well as extensive wildfires.

Additional permafrost loss and especially melting on the margins of Greenland and from Arctic land glaciers would lead to greater release of greenhouse gases from permafrost, and higher sea-level rise. The scale of such impacts is highly unpredictable, as the Arctic has never been ice-free in modern human existence.

Finally, while some Arctic governments declare that an ice-free summer Arctic will bring economic opportunity, it is important to balance such statements with the global impacts elsewhere. In other words, the 2°C above pre-industrial that creates the summer ice-free conditions that will allow exploitation of Arctic resources, will also lead to the risks and societal disruptions noted elsewhere in this report, such as 4–10 (or more) meters committed long-term sea-level rise, and potential fisheries/ecosystem damage from acidification. Such adverse impacts almost certainly will eclipse temporary economic benefits brought by an ice-free summer Arctic, even among Arctic states and those moving to invest there.

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LITERATURE

Bathiany S, Notz D, Mauritsen T, Raedel G and Brovkin V (2016) On the potential for Abrupt Arctic Winter Sea ice loss. Journal of Climate, 29 2703–19, doi: 10.1175/JCLI-D-15-0466.1

Burgard C and Notz D (2017) Drivers of Arctic Ocean warming in CMIP5 models. Geophysical Research Letters, 44 4263–71, doi: 10.1002/2016GL072342

Cvijanovic I, Santer BD, Bonfils C, Lucas DD, Chiang JCH and Zimmerman S (2017) Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall. Nature Communications, 8 1947, doi: 10.1038/s41467-017-01907-4

Ding Q, Schweiger A, L'Heureux M, Battisti DS, Po-Chedley S, Johnson NC, Blanchard-Wrigglesworth E, Harnos K, Zhang Q, Eastman R and Steig EJ (2017) Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. Nature Climate Change, 7 289–95, doi: 10.1038/nclimate3241

Haine TWN and Martin T (2017) The Arctic-Subarctic sea ice regime is entering a seasonal regime: implications for future Arctic amplification. Nature Scientific Report, 7 4618, doi: 10.1038/s41598-017-04573-0

Holland M, Blitz CM and Tremblay B (2006) Future abrupt reductions in the summer Arctic sea ice. Geophysical Research Letters, 33 L23503, doi: 10.1029/2006GL028024

Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M and Waterfield T (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

Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Nicolai M, Okem A, Petzold J, Rama B and Weyer N (2019) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate

Jahn A (2018) Reduced probability of ice-free summers for 1.5°C compared to a 2°C warming. Nature Climate Change, 8 409–13, doi: 0.1038/s41558-018-0127-8

Jahn A, Kay JE, Holland MM and Hall DM (2016) How predictable is the timing of a summer ice-free Arctic? Geophysical Research Letter, 43 9113–20, doi: 0.1002/2016GL070067

Niederdrenk A L and Notz D (2018) Arctic sea ice in a 1.5°C warmer world. Geophysical Research Letters, 45 1963–7, doi: 10.1002/2017GL076159

Notz D and Marotzke J (2012) Observations reveal external driver for Arctic sea-ice retreat. Geophysical Research Letters, 39 8 L08502, doi:10.1029/2012GL051094

Notz D and Stroeve J (2016) Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emissions. Science, 354:747-750, doi: 10.1126/science.aag2345

Notz D and Stroeve J (2018) The trajectory towards a seasonally ice-free Arctic Ocean. Current Climate Change Reports, 4, doi: 10.1007/s406

Overland JE and Wang M (2013) When will the summer Arctic be nearly sea ice free? Geophysical Research Letters, 40 10 2097-2101, doi: 10.1002/grl.50316

Onarheim IH and *Årthun* M (2017) Toward an ice-free Barents Sea. Geophysical Research Letters, 44 8387–95, doi: 10.1002/2017GL074304

Parkinson C (2019) A 40-year 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 of the United States of America, 116 29 14414-14423, doi: 10.1073/pnas.1906556116

Stroeve JC, Kattsov V, Barrett A, Serreze M, Pavlova T, Holland M and Meier WN (2012) Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters*, 39 L16502, doi: 10.1029/2012GL052676

Stroeve J and Notz D (2018) Changing state of Arctic sea ice across all seasons. Environmental Research Letters, 13 10, doi: 10.1088/1748-9326/aade56

Tang Q, Zhang X and Francis JA (2013) Extreme summer weather in northern mid-latitudes linked to a vanishing cryosphere. Nature Climate Change, 4 45–50, doi: 10.1038/nclimate2065

Wagner TJW and Eisenma I (2015) How Climate Model Complexity Influences Sea Ice Stability. Journal of Climate, 28 3998–4014, doi: 10.1175/JCLI-D-14-00654.1

Polar Ocean Acidification, Warming and Freshening

STRESSORS ON POLAR ECOSYSTEMS AND FISHERIES: NO FURTHER PLACE TO SWIM

SUMMARY The Arctic Ocean and Southern Oceans contain some of the world's richest fisheries and most diverse marine ecosystems. Their cold waters absorb carbon dioxide (CO_2) from the atmosphere much faster than those at lower, warmer latitudes. This makes them an important carbon sink, drawing CO_2 from the atmosphere and helping to hold down global heating. This "sink" comes at a cost for polar marine environments, however, because it also results in higher rates of acidification than anywhere else on Earth; and at a time when they face extreme stress from other climate change impacts as well, especially in the Arctic. Warming there has caused a decrease in sea ice coverage throughout the year. As important, at today's 1°C above pre-industrial it has caused the near-total disappearance of the thick multi-year ice that used to be many meters thick and persist for 7–10 years. This older and thicker ice can be thought of as the "coral reefs" of polar oceans, where many species at the base of the Arctic food chain live. With all multi-year ice projected to disappear by 2°C, so too may the species that rely on them. Polar waters are also warming, with more extreme heat events, and temperatures beyond which polar species evolved to survive. At the same time, these warming waters bring competition from new invasive species moving further polewards: but polar ocean species eventually cannot move any further north (or south) to survive. Other changes include freshening of polar waters from glacier and ice sheet melting, adding additional stress on high-latitude species and ecosystems, with effects that we already are seeing today. At 2°C or higher, the combination of sea ice loss for several months of the year, no multi-year sea ice at all, ocean warming, acidification and freshening will alter polar marine ecosystems, and the fisheries and aquaculture that depend on them, beyond our recognition. A world at 1.5°C or lower can limit these irreversible effects on polar ocean ecosystems and fisheries.

Background

Increasing CO_2 concentrations lead not only to climate change, but also to increasing rates of acidification of the world's oceans. In addition to providing valuable food and other resources, the ocean provides a vital but less visible service to the global climate system by absorbing CO_2 and limiting global warming, despite sharp increases in human carbon emissions. However, this carbon absorption comes with a price: when dissolved into seawater, CO_2 forms carbonic acid. This phenomenon is known as ocean acidification; and its levels today are higher than at any point in the past three million years.

Ocean acidification is more severe in cold-water ocean environments, which absorb CO_2 more quickly. The Southern Ocean (around Antarctica), the Arctic Ocean, and associated high-latitude seas are home to important fisheries; and are acidifying far more quickly than any other oceans on the planet.

Since pre-industrial times, as human emissions of CO_2 have grown, global average acidification levels have increased by 30%; with atmospheric CO_2 now above 400 ppm and temperatures about 1°C above pre-industrial. In some parts of the polar oceans however, acidification has increased by 40% or more, fundamentally changing polar ocean chemistry.

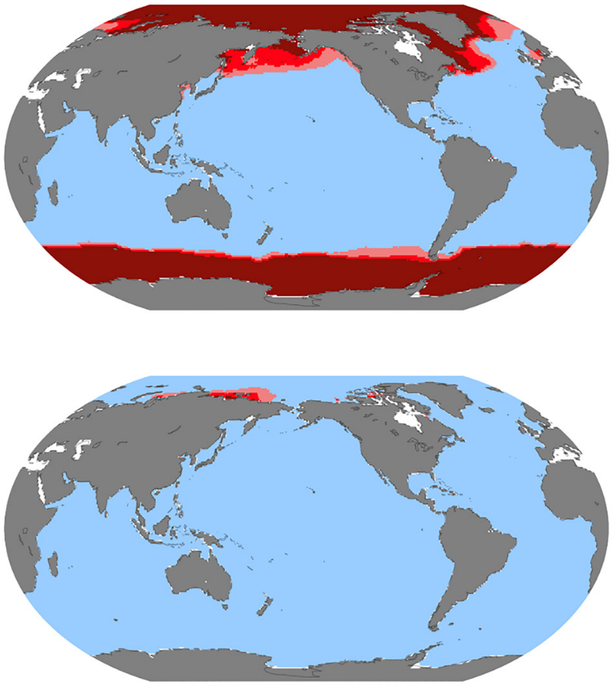
Global temperatures peaking at 1.5°C will occur at atmospheric CO_2 levels of around 450 ppm, which scientists of the Inter-academy Panel (a consortium of national Academies of Sciences) identified in 2009 as an upper boundary for global ocean acidification. This represents an additional 30% increase in acidification globally, with higher levels again projected in polar waters. However, by 2°C CO_2 levels will have reached around 550 ppm; acidity will have increased by nearly 100% globally from pre-industrial times, and more than doubled in polar oceans.

Ocean acidification dissolves the minerals that marine animals need to make their shells and structures, such as a coral's skeleton. As the seawater becomes "corrosive" due to CO_2, these shell-building minerals break down. In this way, ocean acidification harms the ability of organisms such as snails, urchins, clams, and crabs to build and maintain their shells. Acidification also challenges non-shell-building organisms, preventing them from growing and reproducing normally.

Atmospheric CO_2 levels above 510 ppm, which will be passed sometime between 1.5°C and 2°C, are projected to cause widespread areas of corrosive waters in the Southern Ocean for these shell-building species. The Arctic Ocean appears to be even more sensitive: it likely has large regions of corrosive waters already seasonally at atmospheric CO_2 levels between 400 and 450 ppm, well within even the 1.5°C boundary. Indeed, the world is at 410 ppm today, and shell damage has been observed for several years now in some regions of the polar oceans where acidification thresholds have been exceeded already due to local conditions. These corrosive areas began expanding in the Arctic Ocean in the 1990s.

In other words, because of their greater sensitivity, polar oceans already appear to be nearing a critical ocean acidification chemical threshold. There is high likelihood that these changes are a harbinger of much worse to come, due to CO_2 already in the atmosphere continuing to be absorbed in coming years and decades, until, and unless, CO_2 levels begin to fall sharply. In the Southern Ocean, the ability of some vulnerable organisms to build shells declined by around 4% between 1998 and 2014. Pteropods – tiny marine snails known as "sea butterflies" – are particularly susceptible to ocean acidification and these expanding corrosive waters, with some shell damage observed today in portions of the Gulf of Alaska, Bering and Beaufort seas; as well as in portions of the Southern Ocean. Pteropods are hugely important in the polar food web, serving as an important source of food for young salmon, cod and other species.

FIGURE 5-1. **Corrosive Shell-Building Conditions at Higher Emissions**



Difference between acidification conditions in a 1.5° world (RCP2.6) (lower map), and a 4° world (RCP8.5) (upper 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).

Global ocean acidity has been relatively stable over the past several million years. Almost all marine life today, including that of the polar oceans evolved to live in this relatively narrow band of ocean chemistry. Although some older marine organisms, such as horseshoe crabs managed to survive changes equivalent to those occurring today in the geologic past, those changes always took place over many thousands of years. Today's rate of change is unprecedented however in at least the past 65 million years, when severe oceans changes, including acidification occurred, resulting in the mass extinction of many shelled organisms. The speed of today's acidification is therefore a key part of its threat: it is simply occurring far too quickly to allow many species to evolve and survive.

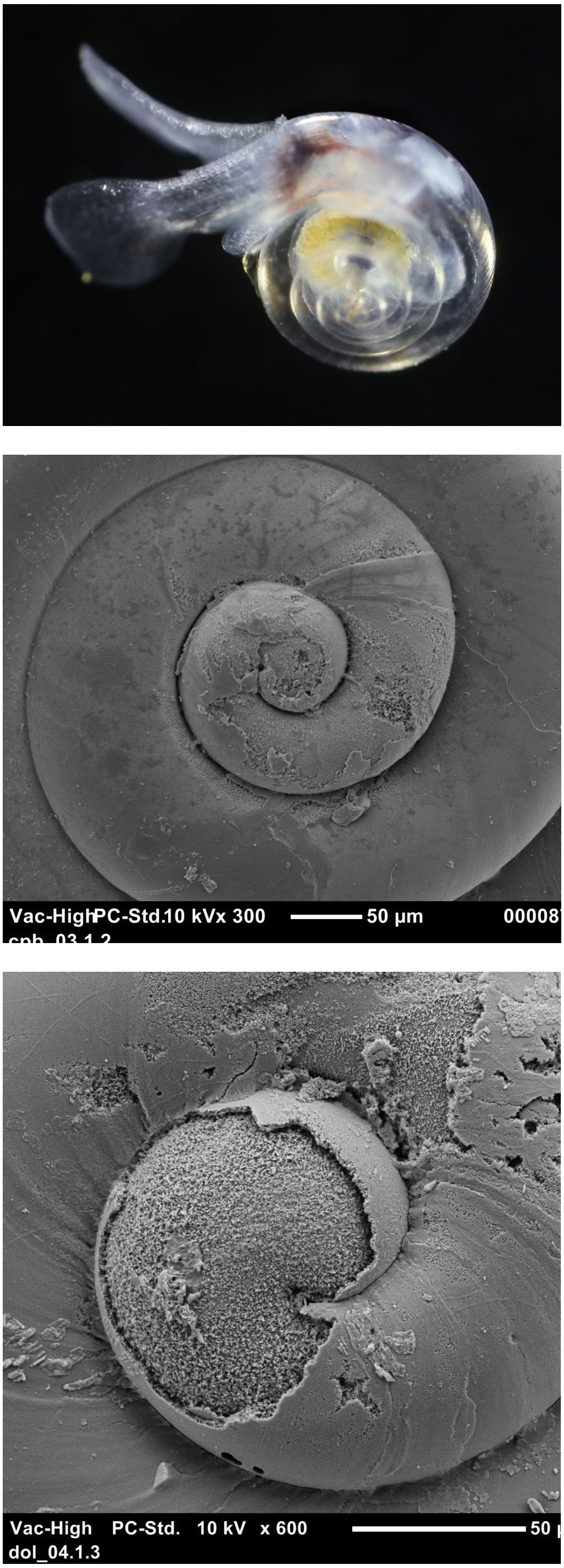
The chemical process of ocean acidification is well understood. The difficult reality for polar ecosystems is that the exact threshold for serious impacts from higher

CO_2 concentrations on marine organisms and ecosystems, as compared to these laboratory studies, will not really be known until they actually occur: first in isolated regions and with early-warning vulnerable species, such as the sea butterflies of some Arctic and Antarctic waters noted above; but then spreading to more regions and species.

At that point however, there is no known way for humans to reverse this damage, because these more acidic conditions will then persist for many thousands of years. This is because processes that buffer (remove) the acidity from the ocean occur very slowly, over nearly geologic time scales. Although CO_2 "only" lasts for 800–1000 years in the atmosphere, it will take several thousands of years before ocean acidification levels begin to decline. Indeed, tens to hundreds of thousands of years will be necessary to bring acidification and its impacts back to pre-industrial levels, following the weathering of rocks on land into the ocean. This very long lifetime of acidification in the oceans is one reason why mitigation efforts focused on "solar-radiation management," as opposed to decreasing atmospheric CO_2 represent a special threat to the health of the world's oceans, especially those at the poles.

The impacts of acidification come as both the polar oceans are warming at increasing rates, with marine "heat waves" occurring further polewards, with greater intensity and more frequently. The Southern Ocean has warmed more than many other ocean regions, and seems increasingly important in overall global ocean heat increase. Over large areas of the seasonally ice-free Arctic, summer surface water temperatures have increased by around 0.5°C per decade since 1982, primarily due to sea ice loss and an inflow of ocean heat from lower latitudes beginning in the 2000s. Future projected Arctic warming will result in continued loss of sea ice, increased river run-off into the oceans and freshening of seawater. Warming waters result in a poleward movement of other species, decreasing the ranges of polar species as they face increased competition for food resources. In some instances, especially where extreme heatwaves occur in the ocean, polar species have apparently even experienced lethal temperatures. Large die-offs of seabirds and gray whales in regions of the Bering Sea in summer 2019 seem to be associated with these marine heatwaves.

The freshening of polar oceans represents an additional stress for polar species. Polar oceans already have a lower salinityfrom freshwater coming off melting sea and land ice, but this incursion of freshwater will increase as the ice sheets, local glaciers and permafrost melt as temperature rises. Ice-associated algae (plants) and animals also are being lost as sea ice declines due to warming. Therefore the loss of Arctic sea ice, especially thicker multi-year ice, which served as a kind of "polar ice reef" on which many species built their existence, further stresses the polar food chain. The projected effects of climate-induced stressors on



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

Images courtesy Dr. Nina Bednaršek

polar marine ecosystems present risks for commercial and subsistence fisheries, with implications for regional economies, cultures and the global supply of fish and shellfish.

The bottom line is that ocean acidification will have earlier and greater impacts on polar ecosystems and organisms; with even more, some potentially irreversible, occurring at higher temperatures and atmospheric CO_2 concentrations. This increased acidification also comes at the same time that polar species face other threats from climate change such as warming waters, ice-loss and freshening due to increased river run-off and ice melt. There is no doubt that intense acidification in the gradient between CO_2 levels today, through 1.5°C and beyond 2°C risks severe negative impacts for a range of polar marine organisms, from the smallest plankton to the largest fish, with severe consequences for polar ecosystems, fisheries and aquaculture. The only known way to slow the process of polar ocean acidification is through cutting the amount of CO_2 entering the atmosphere, aiming to hold levels within the 450 ppm range associated with warming of 1.5°C.

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LITERATURE

AMAP (2013) AMAP Assessment 2013: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. viii + 99 pp.

Baumann H, Talmage SC, Gobler CJ (2012) Reduced early life growth and survival in a fish in direct response to increased carbon dioxide. Nature Climate Change, 2: 38–41, doi:10.1038/nclimate1291

Bednaršek N, Tarling GA, Bakker DCE, Fielding S, Feely RA (2014) Dissolution dominating calcification process in polar pteropods close to the point of aragonite undersaturation. PLoS ONE, 9: e109183, doi:10.1371/journal.pone.0109183

Bednaršek N, Feely RA, Reum JCP, Peterson B, Menkel J, Alin SR, Hales B (2014) Limacina helicina shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. Proceedints of the Royal Society B: Biological Sciences, 281: 20140123, doi:10.1098/rspb.2014.0123

Cummings V et al. (2011) Ocean acidification at high latitudes: potential effects on functioning of the Antarctic bivalve *Laternula elliptica*. PLoS ONE, 6.1: e16069, doi:10.1371/journal.pone.0016069

Dupont S & Pörtner H (2013) Get ready for ocean acidification. Nature, 498: 429, doi:10.1038/498429a

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.* Marine Ecology Progress Series, 373: 285-294, doi: 10.3354/meps07800

Gattuso JP, Magnan A, Billé R, Cheung WWL, Howes EL, Joos F, Allemand D, Bopp L, Cooley SR, Eakin CM, Hoegh-Guldberg O, Kelly RP, Pörtner HO, Rogers AD, Baxter JM, Laffoley D, Osborn D, Rankovic A, Rochette J, Sumaila UR, Treyer S & Turley C (2015) Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. Science, 349: aac4722, doi:10.1126/science.aac4722.

IAP (2009) IAP Statement on Ocean Acidification. Retrieved from: http://www.interacademies.net/File.aspx?id=9075

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.

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.

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

Mathis JT, Cross JN, Evans W & Doney SC (2015) Ocean acidification in the surface waters of the Pacific-Arctic boundary regions. Oceanography, 28(2):122–135, doi:10.5670/oceanog.2015.36

McNeil BI, Matear RJ (2008) Southern Ocean acidification: A tipping point at 450-ppm atmospheric CO2. Proceedings of the National Academy of Sciences, 105(48): 18860-18864, doi:10.1073/pnas.0806318105

Riebesell,U. & Gattuso JP (2015) Lessons learned from ocean acidification research. Nature Climate Change, 5: 12–14, doi:10.1038/nclimate2456

Sasse TP, McNeil BI, Matear RJ, Lenton A (2015) Quantifying the influence of CO2 seasonality on future aragonite undersaturation onset. Biogeosciences, 12: 6017-6031, doi:10.5194/bg-12-6017-2015

Wittmann AC & Pörtner HO (2013) Sensitivities of extant animal taxa to ocean acidification. Nature Climate Change, 3: 995-1001, doi:10.1038/nclimate1982

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