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Only halving emissions by 2030 can minimise risks of crossing cryosphere thresholds

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Considering cryosphere and warming uncertainties together implies drastically increased risks of crossing thresholds in the cryosphere even under lower emission pathways and underscores the need for halving emissions by 2030 in line with the Paris Agreement 1.5°C limit.

A key risk of climate change is the potential crossing of abrupt and/or irreversible thresholds, often called tipping points *(e.g., ref.* [1]*)*. The need for improved understanding of such risks as well as what is required to minimise them is now also explicitly acknowledged by climate policy[2]. "Abrupt" means a much faster change than usual for that system, while "irreversible" on a given timescale means that the system will not be able to recover to its initial state on a similar timescale[3]. Some changes may be reversible on human timescales, after decades or centuries, while others may take millennia. For the cryosphere, which is not only particularly vulnerable to climate change but also a key driver of sea level rise, the latest Intergovernmental Panel on Climate Change (IPCC) assessment confirms again that several of its elements are susceptible to such threshold behaviour[3]. Examples of these are potential melting of the Greenland and Antarctic ice sheets or permafrost thaw *(e.g., refs.* [1,4,5]*)*.

Already at current warming of more than 1.1°C, the IPCC assesses that risks of exceeding thresholds in the Earth system are *moderate*, and could become *high* above 1.5°C[6]. Limiting warming in line with the Paris Agreement might still suffice to avoid passing multiple thresholds. The precise nature of the Earth system thresholds, however, is subject to considerable uncertainties[3]. While these are usually accounted for, the range of possible temperature responses to emissions pathways as assessed by the IPCC[7] is often less explicitly considered. In the following sections, we discuss both dimensions of uncertainty and implications for risk assessments of crossing cryospheric thresholds under different emissions pathways.

Threshold risks increase with every bit of warming

Arctic sea ice, glaciers across the world, ice sheets in Greenland and Antarctica, and permafrost have experienced losses over at least the last several decades[3]. The accelerated warming of the Arctic appears to be as fast as four times the global average[8]. The excess CO_2 in the atmosphere also directly affects the Arctic and Southern Oceans, which have taken up much of it – slowing global warming but rapidly increasing ocean acidification, harming polar species and ecosystems[9].

With further warming, the ice sheets could be at risk of crossing thresholds which lead to accelerated melting rates that cannot be stopped even by halting global warming. This would commit us to rising sea levels for millennia[3,10], with severe consequences for vulnerable coastal regions and small islands[6]. Global mean sea level rise could, however, be halved on millennial timescales by limiting peak warming to 1.5°C compared to 2°C[3].

The IPCC assesses that for Greenland there is limited evidence of complete ice sheet loss between 1.5-2°C; however, it cannot be ruled out that already a sustained warming of 1°C could cause a complete loss. Above 3°C, near-complete loss will be irreversible over multiple millennia. For Antarctica, there is large uncertainty around potential instabilities, which could trigger significant losses. The threshold for instability of the West Antarctic Ice Sheet (WAIS) might be between 1.5-2°C. Only parts would be lost below 2°C, with complete or near-complete loss at 2-3°C peak warming. Above 3°C the WAIS will be completely and the East Antarctic Wilkes Subglacial Basin substantially or completely lost over multiple millennia. Large losses from East Antarctica could occur above 5°C[3,11].

Arctic sea ice as well as global glacier and permafrost loss will continue, and possibly accelerate through feedback mechanisms, with increasing global warming, while potential threshold behaviour is dependent on the season or region. Adverse impacts to people and ecosystems and much of the losses in the cryosphere will be irreversible at human time scales[3].

For example, continued warming could result in abrupt loss of Arctic winter sea ice *(e.g.,* [3]*)*, a process which may be irreversible for several centuries as a result of changes in ocean stratification that inhibit winter ice formation.

Polar ocean acidification is approaching a chemical threshold within the coming decades. At 1.5-2°C warming, Arctic waters will be corrosive for organisms that use the important mineral aragonite to build shells and skeletons for several months of the year, with the Southern Ocean following at 2-3°C warming. It will take tens of thousands of years to reverse due to the very slow ocean processes involved; limiting warming to 1.5°C can avoid the worst of it[9].

Glaciers are committed to losing mass for decades even without further warming. Potential thresholds and timescales for recovery of glaciers vary across the world, such that glaciers in all regions with little glacier area, for instance the European Alps, Scandinavia, and Western North America, could lose nearly all mass between 3-5°C of global warming[3]. Adverse impacts on people and ecosystems include severely limited water resources above 1.5°C of warming for those dependent on glaciers and snowmelt[6].

Permafrost thaw has threshold behaviour at the local scale, which may scale to regions[9]. Permafrost greenhouse gas (GHG) emissions in the form of carbon dioxide and methane will be irreversible at millennial timescales and will decrease the carbon budget further, by 50-250 Pg C-CO_2 equivalents by the end of century depending on the level of human-caused warming and the response of Arctic ecosystems[3,12,13].

Climate response uncertainties overlap with thresholds

Assessing the probabilities of crossing cryospheric thresholds by warming levels is a critical step, but not sufficient to understand the full risks for different GHG emissions pathways. The uncertainties in how exactly the climate system will respond to increasing atmospheric GHG emissions remain substantial and high warming outcomes of more than 0.5°C above the median projection cannot be ruled out[7]. Only linking categories of GHG emissions pathways to specific warming levels (i.e., 1.5°C or 2°C) gives a false sense of certainty in that regard. In fact, due to the uncertainties in the temperature response to emissions, emissions pathways that aim to limit warming to 1.5°C and to "well below 2°C" as per the Paris Agreement overlap in terms of their associated likelihoods to limit warming[14]. When assessing the risks of crossing irreversible thresholds in the cryosphere, climate response uncertainties in the warming outcomes of emissions scenarios need to be considered alongside threshold uncertainties.

This joint uncertainty perspective reveals that even Paris Agreement-compatible emissions pathways have a chance of reaching warming levels within the range of potential cryosphere temperature thresholds (compare Fig. 1). If emissions until 2030 follow current NDCs, there is a *likely* chance that 1.5°C will be exceeded. Under the assumption that action is delayed and current NDCs are superseded by very stringent emission reductions post 2030, median peak warming is projected at 1.8°C, but warming of up to 2.7°C (95% range) cannot be ruled out[7,15]. Under pathways that continue with ambition levels implied by current NDCs beyond 2030, warming could reach up to 4.3°C (95% range) or more. The combined risk arising from uncertainties in the warming outcomes of emissions pathways and threshold uncertainty implies a significantly higher chance of crossing thresholds under emissions pathways than looking at both in isolation.

1.5°C action to safeguard against crossing thresholds

It is important to highlight that IPCC threshold assessments refer to sustained warming levels, not just peak warming outcomes. For how long temperature levels would need to be reached to trigger abrupt and/or irreversible changes also depends on the system in question[16]. Specifically, there are risks under overshoot pathways, where temperatures peak above a certain level, for example 1.5°C, and then decline again, which are a major research gap[17]. The fact that emissions scenarios following current NDCs until 2030, even if significantly strengthened after 2030, could reach warming levels under which crossing thresholds is not just a risk but the most probable outcome, clearly calls for a precautionary approach. Following the IPCC AR6, risks rapidly escalate above 1.5°C and even more so if 2°C is exceeded. Exceeding 3°C, which is within uncertainties under an NDC scenario, would almost certainly trigger ice sheet stability threshold behaviour[3], as well as cause widespread ocean acidification resulting in conditions corroding carbonate minerals, to form seasonally in both the Arctic and Southern Ocean[9].

Any given temperature level might be reached sooner than predicted, if the effects of accelerated Arctic warming on permafrost thaw emissions and wildfires are fully taken into account[13,18]. The consideration of potentially "catastrophic" climate change, which is understudied[19], further puts the need for action into perspective.

Only emissions pathways that are fully Paris Agreement-compatible (keeping 1.5°C within reach while holding warming to "well below 2°C") can reduce the risks of critical thresholds for ice sheets being crossed resulting in irreversible losses in the cryosphere. In such pathways, emissions until 2030 need to be about halved compared to today, with stronger reductions further reducing the risks of high warming outcomes. Every increment of avoided warming makes a difference for reducing the risks of crossing thresholds. The IPCC's mitigation report shows a multitude of options for the necessary system transformations across all sectors[7]. Achieving the goals of the Paris Agreement does not guarantee we avoid crossing thresholds – but it is our best chance. If the world fails to reduce emissions in this critical decade for climate action, the cryospheric legacy of this failure could reshape the face of this planet for millennia to come.

Fig. 1: Joint uncertainties of cryospheric thresholds and losses, sea level rise, and warming outcomes of emissions pathways.

a, Potential thresholds and losses of key cryosphere elements and the *likely* range of committed global mean sea level rise over 2000 years from all major drivers, associated with different sustained global warming levels. **b**, Median and *very likely* (5-95%) range of peak temperature outcomes over the 21st century relative to pre-industrial (1850-1900) levels, accounting for scenario and climate uncertainty of selected emissions pathway categories from the IPCC AR6 Working Group III contribution: limit warming to 1.5°C (>50%) with no or limited overshoot, with net zero GHGs (C1a), using only a subset of pathways that also limit warming to 2°C with a 90% likelihood; NDCs until 2030 with delayed action to limit warming to 2°C (>67%) (C3b); limit warming to 3°C (>50%), corresponding to implementation of NDCs as formulated in 2020 with some further strengthening (C6) *(data from* [20]*)*. In addition, for panel (a), key sources of information are indicated on the right-hand side; for panel (b), GHG emissions reductions in percent from 2019 are given for 2030 and 2050 (median with 5th-95th percentile in square brackets).

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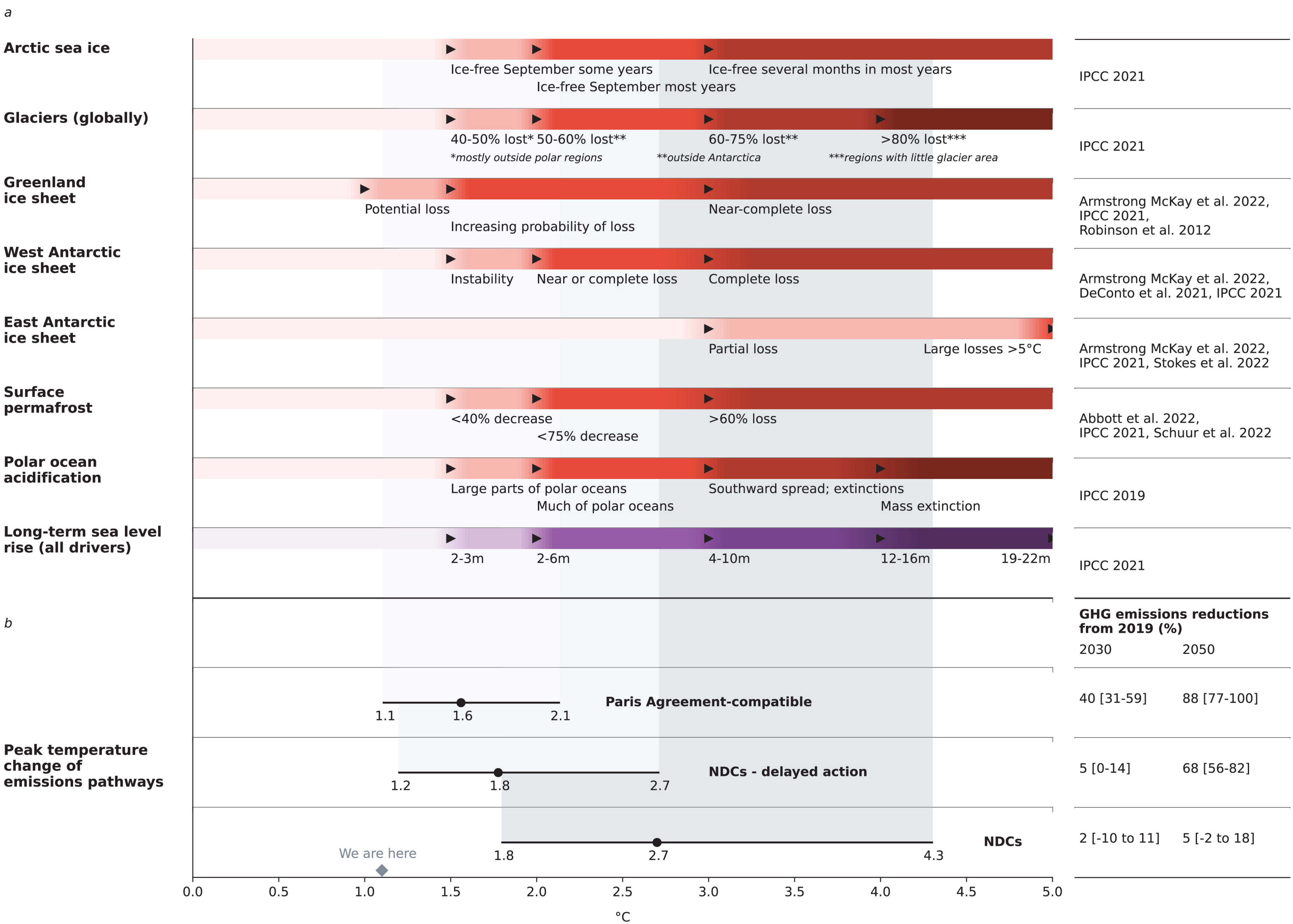
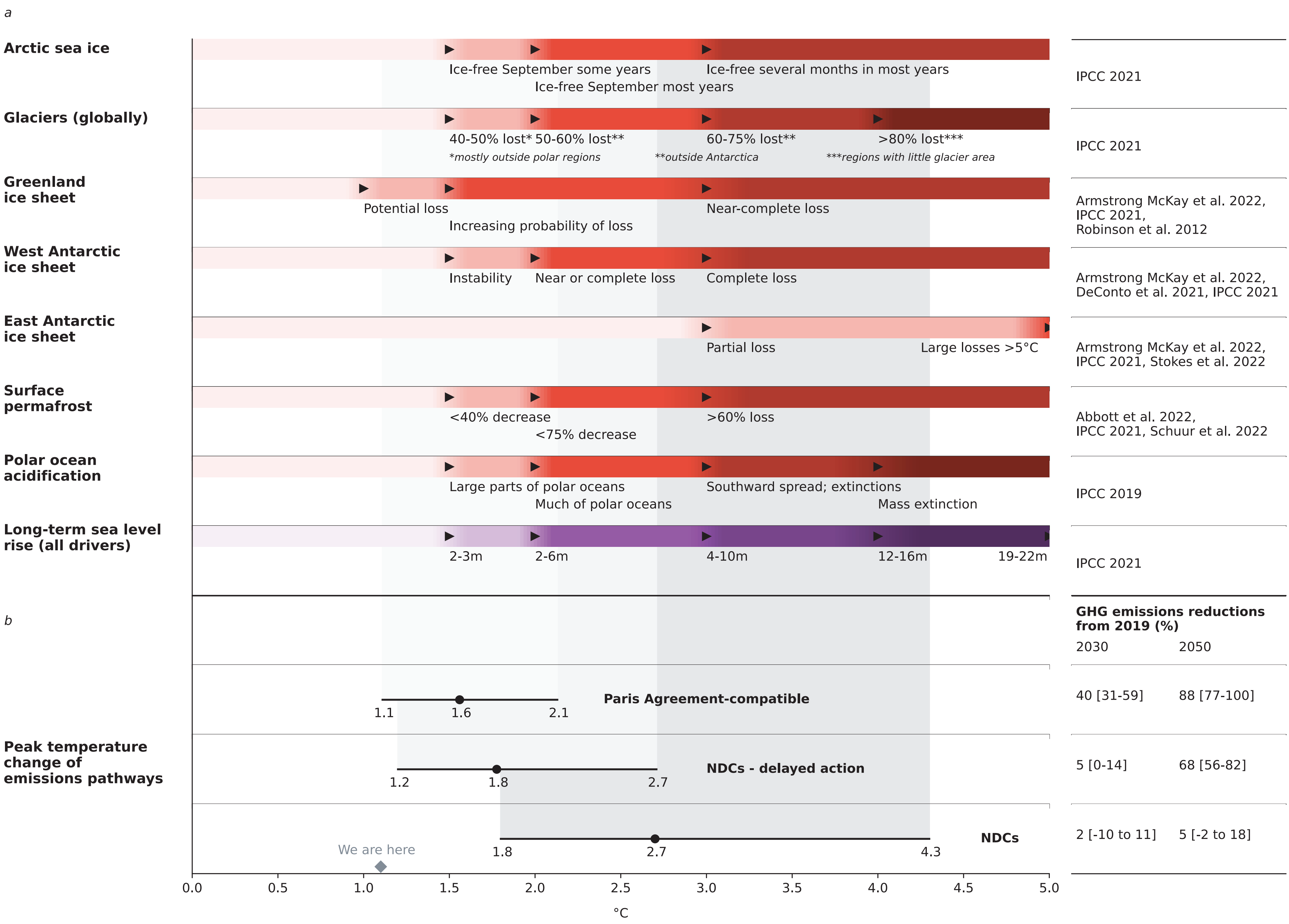


a
Arctic sea ice
Ice-free September some years
Ice-free several months in most years
Ice-free September most years
IPCC 2021
Glaciers (globally)
40-50% lost*
50-60% lost**
60-75% lost**
>80% lost***
*mostly outside polar regions
**outside Antarctica
***regions with little glacier area
IPCC 2021
Greenland ice sheet
Potential loss
Near-complete loss
Increasing probability of loss
Armstrong McKay et al. 2022, IPCC 2021, Robinson et al. 2012
West Antarctic ice sheet
Instability
Near or complete loss
Complete loss
Armstrong McKay et al. 2022, DeConto et al. 2021, IPCC 2021
East Antarctic ice sheet
Partial loss
Large losses >5°C
Armstrong McKay et al. 2022, IPCC 2021, Stokes et al. 2022
Surface permafrost
<40% decrease
>60% loss
<75% decrease
Abbott et al. 2022, IPCC 2021, Schuur et al. 2022
Polar ocean acidification
Large parts of polar oceans
Southward spread; extinctions
Much of polar oceans
Mass extinction
IPCC 2019
Long-term sea level rise (all drivers)
2-3m
2-6m
4-10m
12-16m
19-22m
IPCC 2021
b
GHG emissions reductions from 2019 (%)
2030
2050
Paris Agreement-compatible
1.1
1.6
2.1
40 [31-59]
88 [77-100]
Peak temperature change of emissions pathways
NDCs - delayed action
1.2
1.8
2.7
5 [0-14]
68 [56-82]
NDCs
We are here
1.8
2.7
4.3
2 [-10 to 11]
5 [-2 to 18]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
°C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1.2
1.8
2.7
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68 [56-82]
NDCs
1.8
2.7
4.3
2 [-10 to 11]
5 [-2 to 18]
We are here
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
°C