Australia's National
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Understanding the risks to Australia from global climate tipping points

Workshop report

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Contents

Figures

Tables

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Executive summary

This Report summarises the outcomes of a Workshop on the topic of climate tipping points. While it contains a limited number of key references and points from the wider literature, it is primarily a discussion document based on discussions during the Workshop and is not a comprehensive review or assessment of the topic for Australia. It provides what is hopefully a useful starting point to summarise the science in this area. It also identifies current gaps areas where further work is needed.

Global climate tipping points were the focus of the large international review[1] released at the United Nations Climate Change Conference, COP28, in December 2023. This review represents the scientific consensus on this topic globally. However, the literature and therefore scientific reviews have little focus on the Southern Hemisphere and Australia.

The Workshop, held in in November 2023, brought together Australian climate researchers to discuss climate tipping points and their potential effect on Australia. There was a special focus on the Southern Hemisphere, including Antarctic ice sheets, sea ice and ocean, as well as land, vegetation, and ecosystems.

Background

- Paleoclimate records and other lines of evidence demonstrate that there are several important 'tipping elements' in the climate system that can reach a 'tipping point' where change becomes self-perpetuating. Change is often abrupt and irreversible on long timescales.
    - Examples of global climate tipping points include the thawing of Boreal permafrost and 'collapse' of the main overturning ocean circulation in the north Atlantic Ocean.
- Reaching a tipping point can trigger cascades of abrupt changes, trigger other tipping points, and produce impacts that are widespread and significant. There are far-reaching implications for our climate change mitigation strategies and adaptation responses from the presence of tipping points in the Earth systems.
- Increasing global warming increases the risk of triggering tipping points, with different thresholds for different tipping elements. It is possible that we have already passed some tipping points but haven't seen the consequences yet. Several tipping points may be triggered this century even with modest further warming, while others require higher levels of global warming. We cannot be precise about the conditions or timing of climate tipping points and in fact there are some 'deep uncertainties' around some processes.

[1] https://global-tipping-points.org/

- The consequences of passing a tipping point may be realised within decades (e.g., Amazon dieback, coral reef die-off). The consequences of passing other tipping points may be partially realised within decades (with notable societal consequences) but continue unfolding over 100s to even 1000s of years (e.g., loss of mass from Greenland and Antarctic ice sheets).

The main conclusions from the Workshop related to Australia were:

- The effects of tipping points on the global climate are generally not currently accounted for in projections based on climate models. This means that effects of tipping points are also not included in national climate projections and impact assessments for Australia and may represent significant risks on top of the changes that are generally included. Larger and more rapid warming and sea-level rise are the main possible consequences, but other effects may include abrupt changes to the El Niño Southern Oscillation, rainfall patterns, and rainfall variability that are not represented in climate model projections.
- The effect of some remote tipping points in Australia are likely small over any time scale (e.g., permafrost thaw, Amazon die-back), while others (e.g., sea-level rise resulting from rapid ice-sheet retreat) would have a measurable and material effect in Australia this century.
- Some changes from triggering tipping points set up a 'tug of war' with other influences, for example a 'collapse' of the Atlantic Meridional Overturning Circulation (AMOC) may result in substantial regional changes countering the general effect of climate warming (including regions of notable cooling in the northern hemisphere).
- Australian climate change impacts, adaptation and vulnerability analysis and policy should start to consider the presence of climate tipping points in two broad respects:
    - **Mitigation**: limiting further global warming limits the chances of triggering tipping points. Playing our role in the global effort to reduce emissions to net zero is required to minimise the chances of triggering tipping points.
    - **Adaptation**: we can consider where, when and how we may take prudent action to reduce the potential impacts of passing tipping points.

      We cannot be precise about the impacts of these tipping points on Australia, but we know passing tipping points would have considerable direct and indirect impacts.

      Although we have an incomplete understanding of the impacts of global tipping points on Australia, we need to consider the possible outcomes, because the impacts are so potentially great. This requires a risk management framework with an appropriate view of different types of uncertainty, likelihood and consequence, as well as an adequate view of complex, interconnected systems. Such a framework could use techniques such as the 'storylines' approach. Current planning projects could start to account for the 'low likelihood high impact' storylines that include climate tipping points. For example, construction plans for new critical infrastructure with a long lifetime and low tolerance for failure (e.g., nuclear waste storage and hospitals), could incorporate 'worst case' sea-level allowances that assume high-end Greenland and Antarctic ice-sheet contributions, of around ~2 m by 2100 into building specifications.

- To increase our understanding of tipping points, and how they may affect Australia and our region, we need increased attention and research. This includes paleoclimate records, theory and process understanding (including a hierarchy of models) and observations needed to scan for early warning signs. Australia's climate model, the Australian Community Climate and Earth System Simulator (ACCESS) is the only Earth System Model built in our hemisphere. It is essential and can be a useful tool in climate tipping points research of relevance to Australia, and related topics such as local ecosystem collapses.

  In general, greater research and modelling is needed to understand the regional impacts for Australia specifically, including physical, ecosystem and socio-economic aspects.

Introduction

The Earth's climate system has several large-scale components known as 'tipping elements' that are vulnerable to changing state. A 'tipping point' is where a system reaches a threshold, change becomes self-perpetuating and undergoes transformational change from one regime to another, or one state to another, into a qualitatively different mode of operation. The change is often abrupt and irreversible on the scale of decades to hundreds of years or longer.

We examine nine global climate tipping points that are of such a scale that they affect the Earth system functioning, and two of seven 'regional impact' tipping points that affect a large area but don't affect the entire Earth system function. The names of these, and the assessed level of global warming when they may be triggered, are found below (source: Armstrong McKay et al. 2022 review), noting that these warming estimates are not firm and subject to revision.

There are various similar or related concepts, such as socio-economic or ecological tipping points and regime shifts, that are not the focus here.

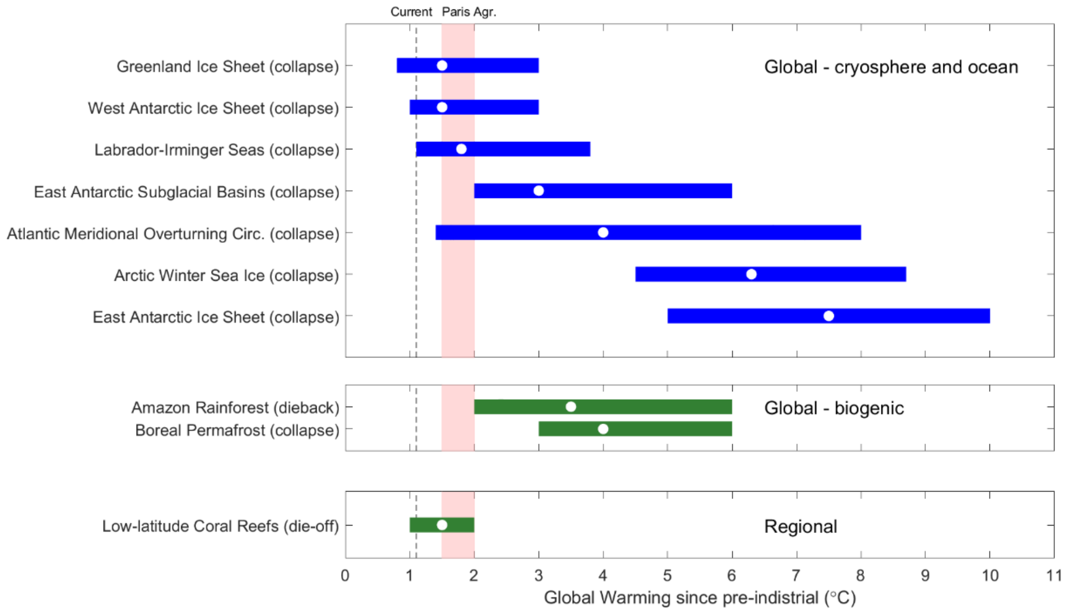

Figure 1 The nine global climate tipping points and the one most relevant regional tipping point of seven listed in Armstrong McKay et al. (2022) review, and their assessed ranges of global warming where the tipping may be triggered (note, some other evidence or studies may differ from these ranges).

International and Australian scene

There is a growing focus on tipping elements in the international research community, including the major review launched in December 2023. Attention is mainly in the areas of physical evidence such as paleoclimate records, theory and process understanding (including modelling) and observations of the climate system to monitor for early warning signs of tipping. Tipping elements are now prominently covered in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), and a special session at the recent World Climate Research Programme (WCRP) Open Science Conference and part of the Kigali Declaration[2] (Kigali, 23-27/10/2023). However, the current consensus is that there are insufficient observations, understanding and modelling studies to assign high confidence in the details of irreversible changes or surprises in the climate system. It is important to note that this is not a statement saying they are unlikely to happen, but rather that we lack the evidence to assign a statement of confidence about how likely they are over a given time.

Up to now, Australian climate change assessments have not included tipping points, and there has only been minimal research work in the area focussed on this region.

The Workshop noted that we should initiate more research and assessment in this area given the potential for high impact outcomes. Only one previous Australian Workshop was held ‘Tipping points and abrupt change in Earth System Risk Assessment for Australia’ (Meissner et al. 2020).

[2] https://wcrp-osc2023.org/images/documents/Kigali_Declaration_SupplementFinalVER.pdf

Tipping points and their impacts

Here we present a summary and synthesis of the discussions at the Workshop, together with some key points taken from the literature, primarily the Armstrong McKay et al. (2022) review, the Global Tipping Points review of OECD (2021) and other literature as cited.

1.1 Ice sheets and sea-level tipping points

The Greenland and the Antarctic ice sheets will continue to lose mass throughout this century under all scenarios, contributing to sea-level rise (IPCC 2021). On top of this, instabilities in the ice sheets could contribute significantly to ice loss and sea-level rise that would take a very long time to reverse, and potentially represent a tipping element in the system.

The tipping element in the Greenland ice sheet is mainly driven by an ice-sheet instability related to increases in air temperature, through a process known as the ‘melt-elevation feedback’. The predictable response to increasing air temperature can be described using standard measures of uncertainty. Reaching a threshold of tipping behaviour appears likely to be a response to extended time in an even slightly warmer state (‘time integrated forcing’) rather than a particular warming level for a short time. That is, tipping may be related to the volume of the ice sheet rather than a particular temperature. In contrast, Antarctic ice-sheet tipping depends more strongly on marine-ice instabilities that arise under increasing ocean temperatures. Because the dynamic processes involved in these instabilities are not well-observed, they are associated with deep uncertainty. In some cases, such as the hydro-fracture of ice shelves due to surface melt ponding, instabilities may be triggered if warming reaches a peak warming threshold (even if the climate then cools). Other processes, however, depend on the time-integrated forcing.

It is not possible to identify a single tipping point for either the Greenland or Antarctic ice sheets. However, paleoclimate records suggest that mass loss does become 'committed’ past a certain point. For Antarctic ice shelves, reaching a critical threshold may or may not be expressed as an increase in the rate of mass loss, but it would represent a point of irreversibility at long timescales. Also, the role of climate variability must be carefully considered when assessing changes and the reaching of thresholds or irreversibility.

Table 1 Global climate tipping points associated with ice sheets and sea level

Tipping element	Trigger definition	Notes on trigger conditions - timeframe, scenario, Global warming level, CO_2	Timescale to play out after trigger	Reversibility notes	Extra global warming	Direct climate impacts on Australia by 2100	Possible impact to Australia beyond 2100	Sources of evidence, science maturity
Greenland ice sheet collapse	Self-perpetuating loss of mass, but varies in space and no one clear tipping point	Defined by time integrated forcing of warmer conditions. Tipping possible from now (some evidence already triggered), possible under all scenarios, but more likely under higher.	Initial sea-level rise in decades, fully play out in 1,000-15,000 years	Very long timescales to reverse, collapse could be slowed through limiting of further warming	+0.13 °C (0.5 to 3 °C regionally)	Sea level rise at a rate of up to 0.5 m per century (global average, could be more/less in Aus, could be uneven in time) meaning more coastal inundation and coastal erosion	Major sea level rise (up to 7m eventually), added warming	Paleo, models. Measurable uncertainty
West Antarctic ice sheet collapse	Self-perpetuating loss of mass, but varies in space and no one clear tipping point	Instability may occur close to 1.5 – 2 °C warming. Tipping uncertain but possible from now (literature disagrees and currently rapidly developing), more likely under higher scenarios	Initial sea-level rise in decades, fully play out in 2,000-13,000 years	Very long timescales to reverse, collapse could be slowed through limiting of further warming	+0.05 °C (up to 1 °C regionally)	As above, but ongoing rise of up to 1 m per century (and may include notable rise over just a few decades)	Major sea level rise (3.3 m eventually)	Some measurable and some deep uncertainty
East Antarctic ice sheet collapse	Self-perpetuating loss of mass, but varies in space and no one clear tipping point	Considered likely under higher warming and scenarios only (but open questions remain).	Initial sea level rise unclear, fully play out in 10,000 years+	Very long timescales to reverse, collapse could be slowed through limiting of further warming	+0.6 °C (up to 2 °C regionally)	Unlikely to be major unless extreme worst-case scenario	Major sea-level rise under high scenarios (58 m if it all melted)	Some measurable and some deep uncertainty
Sea level - total			Special note: tipping points may be 'committed' before the tip is detectable	1000s of years-beyond policy horizons, effects on coastlines effectively irreversible		Together with other sources, a 'worst case' of 2 m is possible	Under extreme cases 5 m by 2150 is possible	Combination of likely sea-level rise, measurable uncertainty and estimate of deep uncertainties

To show how this high-impact scenario may plausibly play out, compare two results from the IPCC Sixth Assessment on global average sea level under the extreme high Shared Socio-economic Pathway (SSP) of SSP5-8.5 (now considered unlikely). The median projection within the range of likely change (excluding tipping points) results in up to ~1 m sea level rise by 2100 relative to the late 19th Century. But if a tipping point is reached and the West Antarctic Ice Sheet collapses more rapidly, we may switch to something like the low likelihood high impact projection of >1.5 m by 2100, nominally reported as 2 m by 2100.

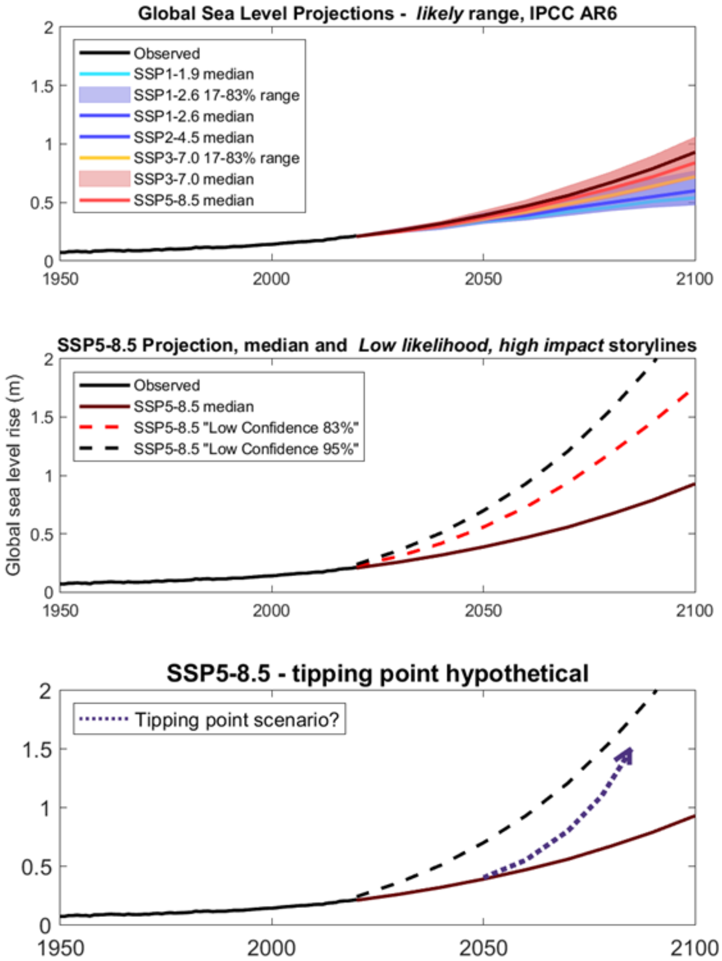

Figure 2 Projected sea level rise from the IPCC Sixth Assessment Report, including the high storyline scenarios that include triggering Antarctic ice sheet tipping points, and a schematic of a hypothetical way that the world could enter this scenario.

The 'low likelihood high impact' storylines of very large and rapid sea-level rise can be very confronting and confusing for stakeholders when considering climate change adaptations and resilience. Considering the direct effects in Australia, given limited adaptation budgets it is clear we can't build defences (e.g., sea walls) to the worst-case scenarios for all infrastructure. But it may be possible and appropriate to manage risk from the worst-case scenarios for some applications like the construction of new critical infrastructure such as nuclear power plants, the storage of nuclear waste, building of large bridges, hospitals, or airports. These facilities could plan for high warming levels and sea level futures (e.g., use sea-level allowances of several metres) as a "no-regrets" strategy.

Consideration of the indirect effects, including the policy settings, is also needed. Rapid and significant sea-level rise would have enormous implications for the in excess of 200 million people worldwide who live within 1 m of current sea level, including low-lying atolls in Australia's Pacific neighbour counties, and nations such as Bangladesh. The climate migration, political strife and conflict caused by rapid sea-level rise would present immense challenges for the world, including Australia.

Future work needed

All glacial ice processes require improvements of our understanding and numerical models to better understand the range of plausible changes, but some issues are of higher priority. In particular, the marine-ice cliff instability hypothesis introduces ambiguity into the ice-sheet trajectories being modelled, leading to deep uncertainty in future sea levels. Observing and understanding the relevant processes in ice cliffs and being able to model them (including improvements on the initialisation and resolution of models, as well as the dynamics of the processes) is likely to improve with more effort. Specialised models with high spatial resolution in the important areas (e.g., the grounding lines of marine ice sheets) as well as the ability to simulate the relevant processes (e.g., the 'hydrofracturing' of ice shelves, topographic pinning, isostatic rebound) is needed. In Australia, coupling an ice-sheet model into our ACCESS climate model is a high research priority that is underway.

1.1.1 Sea-ice tipping points

Satellite data show that Arctic sea-ice extent has been decreasing since regular global observations began in 1979. Despite global warming, Antarctic sea-ice extent slowly but steadily increased from 1979, reaching its all-time maximum in September 2014. However, since 2016, significantly reduced Antarctic sea-ice extent has been observed, with record low summer minima in early 2017, 2022 and again in 2023. Critically, for most of 2023 Antarctic sea-ice extent was significantly lower than for any other year on record.

These recent dramatic changes are very notable and important, however there is debate about whether sea-ice decline in either the Arctic or Antarctic may be described as a self-perpetuating and/or irreversible tipping point. In general, sea-ice decline is regarded as being more likely to be reversible, and with less lag than the other tipping points. Importantly, however, downstream impacts may not be reversible.

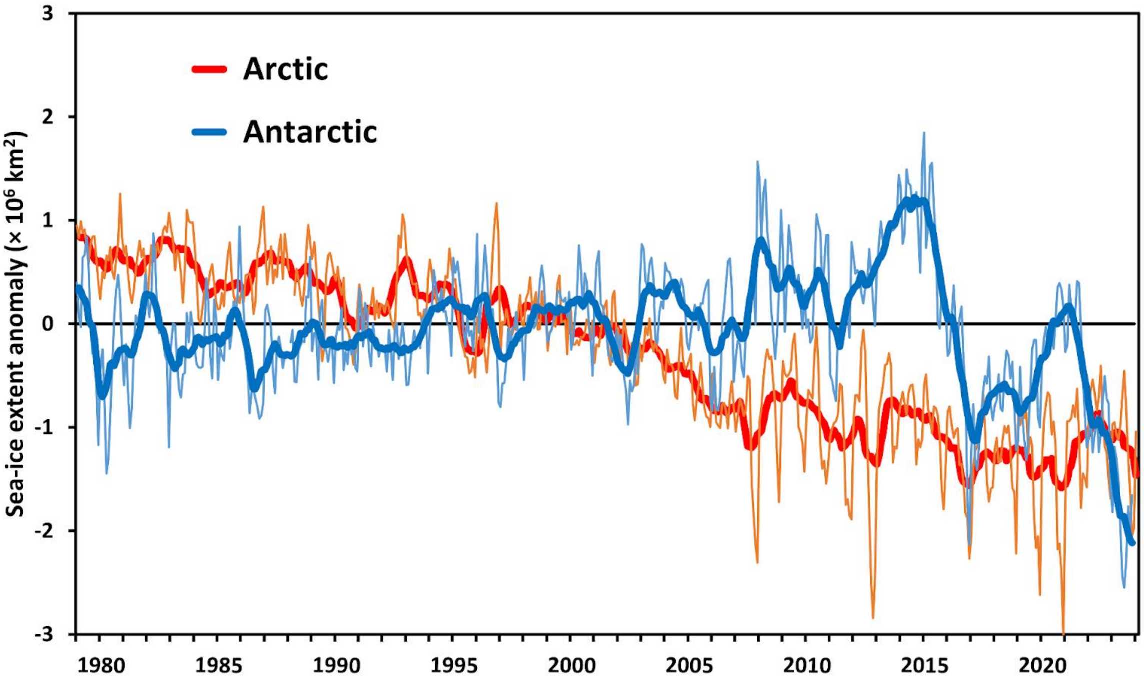

Figure 3 Observed Arctic and Antarctic sea-ice extent: 1979 to November 2023. Updated from Turner and Comiso (2017).

1.1.2 Arctic winter sea ice

Although net Arctic sea-ice extent is currently showing its greatest negative trends during the summer (Parkinson and DiGirolamo 2021), the IPCC Sixth Assessment Report concluded that "there is no tipping point or critical threshold in global mean temperature beyond which the loss of summer sea ice becomes self-accelerating and irreversible” (Fox-Kemper et al. 2021). However, the potential rapid decline of winter-time sea-ice extent in the Arctic is regarded by Armstrong McKay et al. (2022) as a tipping point. This is not universally accepted though, and recent research emphasises the uncertainty in whether there is a potential tipping point in Arctic sea ice (Johannessen et al. 2023; Hankel et al. 2023). While some global coupled models show an irreversible tipping point, others do not.

A key process thought to be responsible for a potential Arctic winter sea-ice tipping point is the ice-albedo feedback. As the Arctic warms, the sea ice melts, and less incoming solar radiation is reflected back into space and thus more energy is absorbed by the less reflective exposed ocean surface. This accelerates the warming effect and the reduction in ice extent. Other relevant processes relate to interactions between sea ice, atmospheric moisture, cloud cover and surface heat fluxes and, in the Barents Sea, a feedback between sea-ice and ocean circulation.

Our understanding of the Arctic ice-albedo feedback and other self-perpetuating mechanisms is incomplete and as a consequence there is uncertainty in the level of global warming required to trigger an Arctic winter sea-ice tipping point. Estimates of the level of global warming required to trigger such a tipping point include the range from 4.5 to 8.7°C, based on CMIP5 climate modelling (Armstrong McKay et al. 2022). This is above the 2.5 to 3.0°C warming anticipated by the end of the century for current emissions reductions policies (not accounting for triggering of tipping points) and well above the 1.5 and 2°C warming limits of the Paris Agreement. Although an Arctic winter sea-ice tipping point would significantly amplify global warming, and hence accelerate climate change in Australia, global warming in the range 4.5 to 8.7°C would have massive detrimental impacts on global society irrespective of additional climate change due to the triggering of the tipping point. Hence, the tipping point may only be relevant to risk assessments if it eventuates that the global warming level for triggering is less than the range suggested by the CMIP5 climate models. Given the limitations of the models, this cannot be ruled out.

1.1.3 Antarctic sea ice

Historically, the matter of whether Antarctic sea ice could undergo an irreversible tipping point has received less scientific attention than the Arctic and, to date, modelling studies focussing on Antarctic sea ice have not targeted the identification of irreversible tipping points. Leaving aside the issue of irreversibility, the possibility of an abrupt Antarctic sea-ice loss has been recognised as a theoretical possibility for some time (Ferreira et al. 2015; Kostov et al. 2016). There is also recent evidence from statistical analysis of sea-ice observations that suggest Antarctic sea ice shifted into a new low-extent state in about 2016. It is possible that the behaviour of the sea ice has fundamentally changed. Historically, atmosphere forcing has been a strong driver of the annual cycle of Antarctic sea-ice growth and melt, and hence dominated variability in sea-ice extent. Based on the recent collapse of Antarctic sea ice, there are suggestions that the ocean is now playing an important role in driving the sea-ice state. However, there is no scientific consensus on whether the recent observed Antarctic sea-ice decline constitutes an abrupt (or permanent) transition. Model projections for the next few decades show a steady decline in sea ice and it is possible observed recent changes could be part of this. More definitive information is unavailable due to a lack of understanding of the mechanisms behind these changes and the uncertainties associated with model projections. Further observations and research are needed to understand whether this new low sea-ice state represents a new regime in Antarctic sea ice and, if so, whether this regime has tipping point behaviour (Purich and Doddridge 2023).

Armstrong McKay et al. (2022), who published before the most recent observed record low Antarctic sea ice, do not regard sea-ice decline in the Antarctic as a tipping point. This is primarily because of uncertainty in the CMIP5 climate model ensemble on which their review largely is based. There is uncertainty in Antarctic sea-ice projections and possibly tipping points primarily due to the deficiencies in sea-ice processes within climate models (Holmes et al 2022, Lin et al 2023). Some sea-ice processes are explicitly represented in the models, but the processes are not adequately represented for the models to be able to reproduce key characteristics of Antarctic sea ice (including fundamental characteristics, such as annual average sea-ice concentrations, and the northernmost extent of sea ice). Characteristics vary significantly between different models and, as a consequence, the IPCC Sixth Assessment Report assigned low confidence to Antarctic sea-ice projections from the CMIP6 models (Fox-Kemper et al. 2021).

Table 2 Global climate tipping points possibly associated with sea ice

Tipping element	Trigger definition	Notes on trigger conditions - timeframe, scenario Global warming level, CO_2	Timescale to play out after trigger (years)	Reversibility notes	Extra global warming	Direct climate impacts on Australia by 2100	Possible impact beyond 2100	Sources of evidence, science maturity
Arctic winter sea ice	Change of state to ice free (possibly not a true tipping point), may only apply to winter	Unclear. If it is a tipping point then one estimate gives 4.5-8.7 °C of global warming (low confidence)	10-100 years	Potentially reversible, but with irreversible downstream impacts	0.6 °C (0.6 to 1.2 °C regionally)	Unclear	Additional global warming (though ice albedo feedback)	Process understanding insufficient to definitively identify a tipping point. Models (limited confidence). Statistical analysis of observational data.
Antarctic sea ice	Unknown (possibly not a true tipping point)	Unknown	Unknown, possibly similar to Arctic (10-100 years) Likely shorter than Arctic sea ice.	Unknown (possibly similar to Arctic)	Unknown	Unclear but could include increased warming and changes to rainfall and storms	Additional warming Changes in Southern Ocean ecosystems. Possible weakening of and/or a northward shift of the storm track, changes to ENSO, change in precipitation patterns over southern Australia	Process understanding insufficient to identify a tipping point or explain recent changes. Models (limited confidence). Statistical analysis of observational data.

Irrespective of whether Antarctic sea-ice decline is technically a tipping point, changes in net- and regional sea-ice extent are highly likely to have a large impact on global and Australian climate. Antarctic sea ice covers a vast area of the Southern Ocean. Dramatic sea-ice loss could accelerate changes in Antarctic ice shelves and sheets (see above); significantly change the circulation of the atmosphere and ocean (including the Antarctic overturning, see below); and impact the biogeochemistry and ecosystems of the Southern Ocean. The ice-albedo changes from Antarctic sea-ice decline are expected to amplify global average temperature increases. However, climate changes would be especially significant in the Southern Hemisphere, with greater warming here and a possible weakening of and/or northward shift of the Southern Hemisphere storm track and jet (e.g., Ayres et al. 2022). Although more research is needed to build confidence in their results, some modelling studies have suggested that the effects in Australia of Antarctic sea-ice decline could include enhanced warming and changed precipitation patterns over southern Australia and, potentially, changes in the behaviour of the El Niño-Southern Oscillation (England et al. 2020). The effect of reduced sea ice and flow-on effects to temperature, winds and circulation likely includes a reduction in the Southern Ocean carbon sink (Choudhury et al. 2022).

Future work needed

There are significant gaps in our understanding of sea ice that limit our ability to even establish with confidence that there are tipping points in Arctic and Antarctic sea ice. These extend to the processes responsible for recent Antarctic summer sea ice minima in 2022 and 2023 and the 2023 Antarctic winter sea-ice deficit. There is an urgent need for further research into sea-ice tipping points. To support risk assessments, this needs to extend to whether dramatic changes in Antarctic sea ice promote hemispheric to global-scale warming and acceleration or triggering of other climate and Earth system tipping points related, for example, to ocean circulation, ice shelves, or elements of the biosphere. Improved coupled models would facilitate greater understanding. At present, there is low confidence in results from the models as they have significant limitations. For example, some models drastically underestimate the maximum extent of Antarctic sea ice. while other models overestimate it. Modelling challenges include improving the simulation of cloud processes over the Southern Ocean and running models at sufficiently high resolution to represent ocean eddies. Aside from modelling, a longer record of sea-ice characteristics from before the (post-1978) satellite observations could provide a valuable longer-term perspective on changes in sea ice.

Progress is expected on modelling issues over the next few years. However, beyond modelling, there are important gaps in our fundamental understanding of the mechanisms associated with sea-ice formation, redistribution and decay of sea ice that mean that tipping point processes cannot be identified with confidence. There is also little information on how sea ice or its absence impacts the mid- and low-latitudes, including Australia, either directly or via teleconnections. Dedicated long-term observations and detailed process studies are urgently required to add to our understanding of sea-ice processes and interactions between sea ice and the broader Earth system.

1.2 Ocean circulation tipping points

Changes to ocean circulation, particularly the 'overturning' circulations, represent tipping elements in the climate system, and are subject to abrupt, irreversible, and self-perpetuating change. Much of the literature on tipping elements in ocean circulation have focused on changes in the north Atlantic basin, mainly the Atlantic Meridional Overturning Circulation (AMOC), while the meridional overturning in the Southern Ocean has received comparatively little attention. However, changes in the ocean properties and ocean circulation around the Antarctic continental shelf may have important implications for the climate of the southern hemisphere, and therefore the climate of Australia. Aside from feedback with ice-shelf melting, the deep ocean circulation around Antarctica also has important implications for nutrient upwelling and carbon uptake.

One reason for the focus on AMOC is that the heat carried in the North Atlantic overturning is much greater than that carried in the Southern Ocean overturning cell, and therefore any changes in the Atlantic overturning would likely have far greater impact, including to Australia. Regardless, it is now understood that changes in the Southern Ocean overturning are likely already underway (Gunn et al. 2023), and these may occur on timescales of decades rather than centuries (Li et al. 2023), and in turn have implications for AMOC.

Circumpolar Deep Water in the Antarctic region has warmed by around 0.36 °C per decade since 1950 (Herraiz Borreguero et al. 2022). Pritchard et al. (2012) found that the changes in the West Antarctic ice shelf over the period 2003 to 2008 coincided with greatest warming of Circumpolar Deep Water. Whether the East Antarctic seas will become like the West Antarctic seas in future is currently unknown. However, the evidence described here suggests that the changes in ocean circulation, sea ice and continental ice shelves are all interconnected.

While it is known that the changes in Antarctic abyssal overturning circulation are important, it has been shown that state-of-the-art climate models used for climate projections from the Coupled Model Intercomparison Project (CMIP) do not capture this important feature of the Southern Ocean (Purich and England 2021). Similarly, CMIP models have limitations in the simulation of AMOC dynamics and may tend towards showing 'monostable' behaviour (Liu et al. 2014), which is a barrier in modelling transitions in state and the chances of reaching tipping points. Other ocean models are being developed to better represent the relevant processes in the ocean. Apart from a meltwater-induced slowdown of the Antarctic overturning (Li et al. 2023), preliminary experiments have found that the projected slowdown in winds around the Antarctic margin (Neme et al. 2022) can also trigger a slowdown in the ocean overturning around Antarctica. The assessed likelihood of AMOC collapse increases with global warming and is thought to be "as likely as not" under high emissions scenarios by 2300 in IPCC (2021).

Table 3 Global climate tipping points associated with the main overturning ocean circulations

Tipping element	Trigger definition	Notes on trigger conditions - timeframe, scenario Global warming level, CO_2	Timescale to play out after trigger (years)	Reversibility notes	Extra global warming	Direct climate impacts on Australia by 2100	Possible impact beyond 2100	Sources of evidence, science maturity
AMOC slowdown/ collapse	Extended stop or reversal of water mass movement (no precise threshold)	Unclear and open question, assessed as possible at 1.4 - 8 °C global warming range, may be path-dependent		Has reversed in geological past, would take a long time to reverse	-0.5 °C (-4 to -10 °C regionally in northern hemisphere)	Unclear (could affect warming, rainfall and extremes)	Unclear	Paleo records, Limited model studies
Antarctic Overturning slowdown	Collapse in in the overturning of dense shelf water (DSW) around Antarctica.	Unclear	Decades to multi-decades	Evidence exists in the paleo record of past slowdown epochs	Model experiments suggest delayed warming of ~a decade (Bronsalear et al. 2018 Nature)	In the absence of other changes, results in a drier cooler Southern Hemisphere	Possible impacts on nutrient upwelling from the abyssal ocean	Paleo records, Limited model studies

Although the changes in the AMOC are remote to Australia it does have implications for the Australian climate through atmospheric and oceanic teleconnections and a weakening of the interhemispheric temperature gradient (OECD 2021, Orihuela-Pinto et al. 2022; see Figure below). The direct effects of AMOC shutdown on Australia's climate may be to enhance, counter, offset or otherwise modify changes driven by other aspects of greenhouse forcing. The effect may also be felt in the variability and extremes as well as the mean trends. AMOC collapse would likely enhance the regional warming experienced in the Southern Hemisphere including for Australia, in contrast to the confident projection that it would cool much of the northern hemisphere. But this is not a confident projection, and AMOC collapse causing an offset of Australian warming can't be ruled out. AMOC collapse may offset drying in parts of the Southern Hemisphere mid-latitudes (OECD 2021), and could indirectly induce a wetting effect over northern Australia. A schematic illustration of the effect of AMOC shutdown on a typical projections time series plot is shown below.

Given the extreme impacts likely in the northern hemisphere from AMOC collapse, Australia would likely experience significant indirect impacts from disruptions to trade, migration and so on. There is relatively little literature or discussion about policy or adaptation responses to AMOC or other ocean circulation tipping points. There is also a less clear and direct set of implications and implied adaptation options compared to sea level rise from ice sheet collapse.

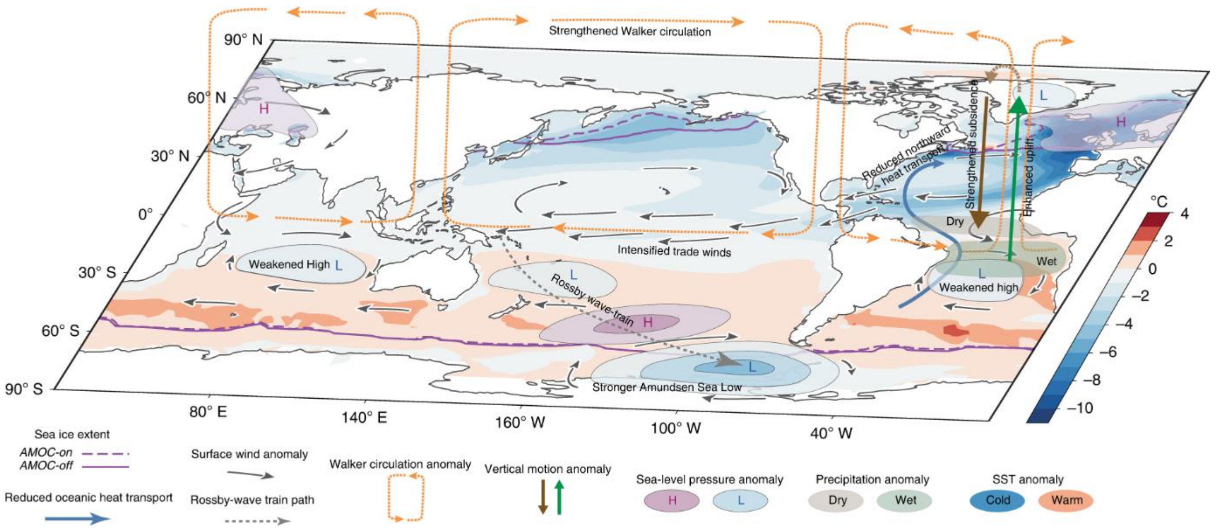

Figure 4 A schematic of the hypothesised circulation and teleconnections affected by an AMOC shutdown (source: Orihuela-Pinto et al. 2022).

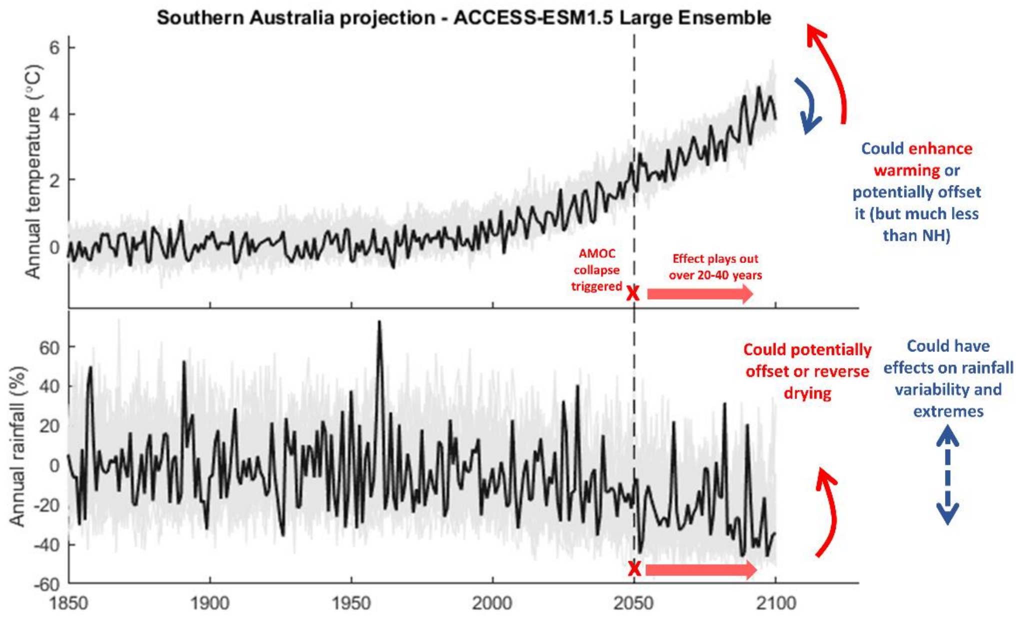

Figure 5 Projection of the 40 member ACCESS-ESM1.5 large ensemble for Southern Australia under the high SSP3-7.0, and notes about the potential effect of a hypothetical AMOC collapse triggered in 2050 could affect this projection.

Future work needed

Australia has an important role in the further understanding and projection of changes in ocean circulation around Antarctica. This means enhancing efforts to observe Antarctic continental marginal seas, including the regions where warm water access the Antarctic ice shelves, and the formation and overflows of Antarctic Bottom Water (especially in the Australian Antarctic Basin). The establishment of long-term ocean observations tracks the pace of ocean warming (and so climate) and challenges our climate models to perform at their best. Enhancements to our ACCESS climate model needed to address questions of overturning circulation tipping points include the inclusion of cryosphere processes and ocean-ice shelf coupling, as well as the inclusion of ice-shelf cavities.

1.3 Biosphere and carbon cycle tipping points

There are numerous tipping elements in the biosphere, and some represent tipping elements for the global climate system mainly through affecting the carbon cycle, including permafrost thaw, Amazon and boreal forests die-back. The global climate tipping points in the biosphere are outside Australia, and most likely only affect the Australian climate indirectly via changes in greenhouse gas concentrations in the atmosphere.

Permafrost thaw may contribute to climate feedback through localised abrupt thaw (e.g., thermokarst taliks) and regional scale collapses such as in the 'compost bomb' hypothesis. The CO_2 and methane climate feedback from permafrost thaw is estimated to be up to 0.2 W m-2 C-1, but a huge uncertainty exists (IPCC 2021). IPCC estimated 18 (3.1 - 41) PgC per C-1 to 2100 from permafrost thaw, which is equivalent to adding 0.003-0.094 °C to global mean surface temperature based on assessed Transient Climate Response to cumulative Emissions of carbon dioxide (TCRE). The possible abrupt changes in permafrost would offset the net ecosystem carbon uptake under most moderate scenarios (Turetsky et al. 2020), and the 'compost bomb' hypothesis of an irreversible and dramatic positive feedback and marked extra global warming from permafrost thaw has not gained support. One barrier to understanding this tipping point is that most current generations of ESMs lack the representation of thermokarst (uneven terrain produced by ice-rich permafrost thaws) or fire-permafrost-carbon interactions.

Amazon dieback essentially means the broadscale change from wet forest to savannah. There is a low confidence in our understanding of crossing a tipping point in the Amazon basin this century. This does not mean it is unlikely, rather that we can't assess the likelihood, and it is unequivocal that human influence and further warming is adding to the risk. It has long been known that around 25-35% of precipitation within the Amazon basin is internally recycled leading to enough rainfall to support the Amazon ecosystem. Deforestation reduces the scale of the Amazon and reduces rainfall recycling, but for the Amazon rainforest to collapse (i.e., become more like savannah) it would require deforestation of more than 40%, precipitation reduction of 30-40% and global warming of 3-4 °C. Canadell et al. (2021; Ch5 IPCC WGI) estimated that if two-thirds of the Amazonia turned to savannah (implying a net source of 47-67 GtC to the atmosphere) that would lead to an additional global warming of 0.05 C-0.15 °C based on assessed TCRE. Without human intervention, it would be difficult to revert to moist tropical forests if the Amazon Forest collapse occured. It is unlikely that a collapse of the Amazon would have a large direct climate impact on Australia (this is not known with certainty) but it would have an indirect effect via increases in atmospheric greenhouse gas concentrations. Amazon dieback would have indirect impacts to Australia via major disruptions in the South American region.

Ecosystem collapse is happening across Australia, and 19 ecosystems from the Antarctic to the tropics have been identified with a clear collapse profile (Bergstrom et al. 2021). The most significant ecosystems at risk of collapse in Australia are alpine ecosystems, coastal ecosystems, and temperate forests. Coral reef die-off, including of the Great Barrier Reef, is considered a climate tipping point, and has implications for Australian regional climate as well as for ecosystems, industry and our society. Other ecosystem collapses are not considered climate tipping points but have important implications for Australia. For example, temperate forests observed a massive fire regime change, with fire return intervals becoming shorter in recent decades. Local and regional ecosystem collapses are a massive issue, and worthy of attention beyond what we cover here.

Table 4 Global and regional climate tipping elements associated with ecosystem carbon cycle

Tipping element	Trigger definition	Notes on trigger conditions - timeframe, scenario Global warming level, CO_2	Timescale to play out after trigger	Reversibility notes	Extra global warming	Direct climate impact on Australia by 2100	Possible impacts beyond 2100	Sources of evidence, science maturity
Permafrost collapse	Significant area of thaw (no precise area/time threshold)	1 to 2.3 °C for 'abrupt thaw', 3 to 6 °C for 'collapse'	Decades to centuries			Extra warming (possibly small)	Extra warming	Observations and modelling offer insights, need further development (similar for all elements)
Coral reef die off	Significant change from hard coral to other system	1 to 2 °C, possible some already triggered	Decades	Very slow to reverse, will not come back to original state	N/A	Regional climate near reefs possibly affected	Climate, ecosystem and carbon cycle changes in relevant regions	
Boreal forest dieback	Change of state in extent, southern edge and greenness of tundra, steppe and taiga zones	3 - 6 °C for 'collapse'	50-100 years (but low confidence)		0.2 - 0.4 °C	Unclear	Unclear	
Amazon dieback	Change from rainforest to savannah (no precise threshold)	2 to 6 °C	50 – 200 years (but could contain abrupt changes)	Ecosystem would never return to original state	Depends on partial (~0.1 °C) or total (~0.2 °C), more regionally	Likely small, but not clear	Unclear	

2 Considering risks to Australia

When considering and assessing climate risk, there is rapidly growing interest and focus around the world on a wider framework of physical climate hazards: 1) extreme weather events such as heatwaves, droughts, and floods; 2) slow onset events such as sea level rise, ocean acidification and deoxygenation; and 3) tipping points. All three must be considered to get a complete picture of future climate impacts we may face under different future scenarios. Tipping points are not typically included in standard model projections of future climate, and this needs to change.

Significant extra sea-level rise, extra warming, changes to precipitation and droughts, changes to the fire regime, as well as changes to climate variability and extreme events are the main direct climate impacts of triggering tipping points. Some climate tipping points are themselves ecosystem collapses (e.g., coral reef die-off), while other climate tipping points may in fact trigger ecosystem collapses (e.g., southern forests and fire, Alpine ecosystems). For human systems, along with the implications of direct climate impacts to Australia, we would see significant indirect effects by being part of an interconnected global community. Disruptions to trade and supply chains, as well as an increase in climate migration, political strife and conflict are just some of the potential impacts. Direct and indirect impacts from triggering a tipping point may then trigger further tipping points, and lead to cascading impacts including ecosystem collapses and transformative changes in human systems. These changes would push various systems outside their adaptive capacity.

If, when and how climate tipping points may be triggered is often poorly understood, and the confidence around tipping points can often not be assigned due to a lack of understanding and adequate modelling. But because these effects are so consequential, the possible triggering of these tipping points and their effects must be acknowledged and considered when managing risk, despite the uncertainty. This is acknowledged in IPCC Sixth Assessment Report through 'low likelihood, high impact' outcomes. However, given deep uncertainties we propose that the term 'poorly understood likelihood, high impact' outcomes is perhaps more inclusive and appropriate.

We therefore need a suitable framework to consider risk. There is limited literature on considering tipping points as a 'poorly understood likelihood, high impact' possibility in a risk framework. In some cases, we may not have sufficient knowledge to characterise the epistemic (limited by understanding) and aleatoric uncertainties (intrinsic randomness) adequately. One way to partially address these issues is to apply a storylines approach to future climate projections (e.g., Shepherd et al. 2018). Based on a causal network towards an outcome or decision of interest, a storylines framework can provide a conditional view of risk.

3 Discussion points

3.1 Definition of tipping points and related concepts

There are several concepts that are similar to global climate tipping points and are also important. These include local or regional regime shifts, socio-economic or system tipping points, record shattering extremes, step-like changes and 'low likelihood high warming' futures. Also, while some ecosystem collapses are climate tipping points such as coral reef die-off dieback, there are many other potential ecosystem collapses that are not considered climate tipping points but nonetheless would have important regional effects. In Australia, regional effects of alpine ecosystem collapse, coastal ecosystem collapses (e.g., kelp forests), and southern forest-fire regime shifts are very important.

The Workshop identified the need for care around the definition of 'tipping points' and related terms (e.g., 'regime change', 'change of state', 'abrupt change'). It also identified the need to be clear about global climate tipping points distinct from other uses of the term 'tipping point' (including socio-economic). The Workshop also strongly urged for an increased focus on all aspects of potential change not currently included in climate projections (whether strictly tipping points or not), including all possible long-lasting and severe changes that may be outside the likely range of change.

A change in the nature of the El Niño Southern Oscillation and changes to monsoons are now not treated as true tipping points in some reviews, but the important effects of these potential changes are worth noting for our purposes. An abrupt shift in the amplitude, frequency or other behaviour of these remote drivers, or their teleconnection to Australia, would have profound influence on the mean climate and climate variability of Australia, including droughts and water availability.

3.2 Definition and timing of triggers

The triggers for tipping points are often difficult to precisely define. For example, permafrost collapse tipping is related to significant thawing but there is no defined area, depth or magnitude of thawing that is agreed as the threshold.

Also, if a trigger or threshold for a tipping point is reached it may not be immediately clear. The precise timing of reaching a trigger or threshold point may not be clear until after the fact. Also, there may be a period before the trigger where we are effectively 'committed' to crossing it due to inertia in emissions and climate systems. Temporary warming 'overshoot' over the trigger threshold may trigger some tipping points but may not trigger others. Further understanding of triggers, monitoring for early warning signs of reaching triggers, and understanding points of 'commitment' or 'lock in' are important.

3.3 Dependence on triggering on emissions scenarios

Each section above includes a column on the conditions required for triggering tipping points. As noted, some triggers are related to 'time integrated forcing', while others are related to a peak level of global warming, and numerous others are unclear. To inform our policy on both emissions mitigation and climate adaptation, we need information integrated under human emissions specifically – this will show under what conditions of our actions that we can control may trigger tipping points, and therefore what we can do to minimise the chances of triggering them. It will also show what we need to prepare for under any likely scenario of human action. Given that some tipping points involve carbon cycle feedbacks and some tipping points may trigger other tipping points, this means going beyond concentration pathways (e.g., the Shared Socio-economic Pathways or SSPs used in the latest IPCC Assessment Report), to truly emissions-driven scenarios with a full carbon cycle and feedbacks.

Some aspects of human emissions related to climate tipping points are clear – higher emissions mean higher chances of triggering tipping points, some tipping elements could tip from now (e.g., coral reef die off, Greenland ice sheet collapse) but others are only vulnerable under higher scenarios (e.g., east Antarctic ice sheet collapse). But the specific thresholds and timeframes for each tipping point need further attention.

3.4 Our responses

Related to the point above, it is helpful to have greater emphasis on appropriate responses by the global community to the risks posed by tipping points, to empower rather than disempower action. Climate tipping points can be confronting and a response to hearing about them can be paralysis or despair. While the seriousness of the potential consequences can't be ignored, it was noted that it is helpful to clearly outline what can be done (our agency) to avoid or deal with tipping points to prevent feelings of doom and helplessness. Professor Tim Lenton points out that there are 'positive tipping points' in human societies to tackling climate change, meaning that the 'tipping point' concept represents some of the greatest threats we face but also provide part of the solution.

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