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Review article
Climate Sciences

Permafrost and ice sheets: potential abrupt and/or irreversible changes

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Abstract. This short article presents a summary of a public lecture held at the Académie des Sciences in March, 2024 on continental tipping elements in the climate system. It first discusses some critical aspects of the tipping elements/tipping points concept as currently used in climate science. It is argued that using more clearly defined concepts such as abruptness and irreversibility instead of the "tipping element" framing, as done in the IPCC AR6 WGI report, can avoid confusion. The permafrost carbon reservoir and large continental ice sheets are then presented as prime examples of climate system elements possibly subject to abrupt and irreversible changes.

Keywords. Tipping elements, Irreversibility, Permafrost, Ice sheets.
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1. Introduction

The concept of abrupt and irreversible changes in the climate system as a consequence of human interference, in particular emissions of greenhouse gases, has been popularized under the expression "tipping" elements/points/events. In this context, the expression "tipping element" refers to the part of the climate system under scrutiny (e.g., the West Antarctic Ice Sheet), while the corresponding "tipping point" is usually a point in time at which the tipping event occurs—this can also sometimes be quantified as a deviation of global mean surface air temperature from a "preindustrial reference" value (which, under continuous warming, implicitly corresponds to a given point in time). The idea of possible tipping events in the climate system is tightly linked to the concept of bifurcations in complex system dynamics, but, in the context of the climate system, noise- and rate-induced "tipping" has also been studied (Ashwin et al., 2012). Related concepts such as regime shifts and critical transitions have been the focus of numerous studies in past decades. However, since the 2000s, the "tipping element/point/event" concept has been dominant, both in scientific and public discourse, at least in relation to the topic of climate change (Milkoreit et al., 2018).

Over the years, many potential tipping elements in the climate system have been proposed and discussed (e.g., Lenton, Held, et al., 2008; Schellnhuber, 2009; Lenton, Armstrong McKay, et al., 2023; McKay et al., 2022; Wang et al., 2023), such as loss of Amazon rainforest, loss of the West Antarctic Ice Sheet, loss of summer Arctic sea ice, or a slowdown of the Atlantic Meridional Overturning Circulation (AMOC). In is notable that many of the proposed tipping elements are situated in the high latitudes, and that the ensemble of tipping elements discussed in the literature is quite variable, depending in part on whether one considers only the climate system element per se (e.g., sea ice), or potential ecological or social impacts of large changes in that physical element (e.g., species extinctions linked to potentially reversible, temporary sea-ice decline). In addition to the study of individual tipping elements in isolation, several authors have drawn attention to potential interactions between tipping elements, subject to particularly large uncertainties (e.g., Wunderling et al., 2024).

The purpose of this short article is in no way to provide a full synthesis of past and ongoing research about continental tipping points in the climate system. Rather, this modest article will first issue a short caveat on the tipping element concept, based on the author's personal thoughts and published critiques of the concept. Subsequent sections will then discuss the potential for abrupt and irreversible changes linked to the physics and biogeochemistry of the permafrost carbon reservoir and large continental ice sheets, both of which can be considered as prime examples of the multitude of proposed "tipping elements" in the climate system. Tipping elements in the socio-economic system, linked to climate change impacts, adaptation to climate change, and its mitigation, are increasingly discussed in the literature (e.g., Otto et al., 2020; Lenton, Armstrong McKay, et al., 2023), but are not treated here.

2. A note on the concept of tipping points in the climate system

Definitions of "tipping" vary somewhat in the scientific literature. Following Milkoreit et al. (2018) and McKay et al. (2022), the recent "Global Tipping Points" report (Lenton, Armstrong McKay, et al., 2023) defines a tipping point as occurring when change in part of a system becomes self-perpetuating beyond a threshold, leading to substantial, widespread, frequently abrupt and often irreversible impacts. It is notable that in this definition, abruptness and irreversibility—the latter referring to characteristics of the change itself, as well as its impacts—are not strictly speaking necessary conditions for the existence of a tipping point. In any case, the existence of positive feedbacks, and their dominance during the phase of transition between two states, is a common feature of hypothetical or real tipping mechanisms in the climate system (Lenton, Held, et al., 2008). The somewhat unclear definitions of what a tipping element in the climate system really is, such as the definition cited above, reflect the difficulties the scientific community has in treating the concept. In such cases, it is often useful to take one step back. In the case of tipping elements in the physical climate system, taking this step back means concentrating on more clearly defined characteristics of the relevant elements of the climate system. This is why the IPCC AR6 Working Group I report (IPCC, 2021), while acknowledging the concept and referring to it, neither provides a detailed assessment of the existence of tipping elements in the climate system, nor quantifies tipping points as such. Rather, the report assesses the potential of abrupt changes and the irreversibility of these changes (in case the initial forcing leading to these changes is reversed), as can be seen in Table 1.

Moreover, the triggering of abrupt changes, such as a rapid ice sheet decay, may in many cases require not only exceeding a given threshold (in most cases, a certain temperature level), but also a certain amount of time during which that exceedance takes place (e.g., Schleussner et al., 2024). Therefore focusing on "tipping points" in terms of a single threshold in public discourse can lead to misconceptions such as the imaginary existence of a single global temperature level which would be a sharp divide between a safe world and the global catastrophe. Therefore the IPCC, in its most recent synthesis report (H. Lee et al., 2023a), took great care to reduce the use of the word "tipping point" to a minimum. A more detailed discussion of these aspects can be found in Kopp et al. (2025).

In many cases, an assessment of the risk of tipping, and associated tipping points, cannot be made based on evidence delivered by climate models alone, for several reasons. First, as will be discussed for specific cases in later sections of this text, critical processes are in some case simply not represented in complex climate models. For example, abrupt thaw processes, which can lean to strong local acceleration of permafrost decay, are not represented in current-generation comprehensive (CMIP-type) climate models. This is sometimes because these processes take place at very small scales. Another source of difficulty is that tipping of major elements of the climate system has not been observed in the recent past. Therefore, calibration of models in this respect would need to rely on information from past climates, which is subject to multiple sources of uncertainty (e.g., limited spatial coverage, limited temporal resolution, or difficulties in interpreting the proxy record).

The IPCC nevertheless provides an assessment of the global risk level ("Reasons for Concern") associated with "large scale singular events" (see Figure 1),

Table 1. Continental tipping elements, potential abruptness and irreversibility of future changes, projected change over the 21st century as assessed in the IPCC AR6 Working Group I report (excerpt from Table 4.10, Chapter 4 (J.-Y. Lee et al., 2021)

Earth system component/tipping element	Potential abrupt climate change?	Irreversibility if forcing reversed (time scales indicated)	Projected 21st century change under continued warming
Tropical Forest	Yes, *low confidence*	Irreversible for multi-decades, *medium confidence*	*Medium confidence* in increasing vegetation carbon storage depending on human disturbance
Boreal Forest	Yes, *low confidence*	Irreversible for multi-decades, *medium confidence*	*Medium confidence* in offsetting lower latitude dieback and poleward extension depending on human disturbance
Permafrost Carbon	Yes, *high confidence*	Irreversible for centuries, *high confidence*	*Virtually certain* decline in frozen carbon; *low confidence* in net carbon change
Greenland Ice Sheet	No, *high confidence*	Irreversible for millennia, *high confidence*	*Virtually certain* mass loss under all scenarios
West Antarctic Ice Sheet and shelves	Yes, *high confidence*	Irreversible for decades to millennia, *high confidence*	*Likely* mass loss under all scenarios; deep uncertainty in projections for above 3 °C

The continental tipping elements mentioned in this table are tropical forests, boreal forests, permafrost carbon, the Greenland Ice Sheet, and the West Antarctic Ice Sheet with its large ice shelves.

based on structured expert elicitation. The tipping of a major element of the climate system, for example the irreversible destabilisation and, at least partial, loss of the West Antarctic Ice Sheet, would be such a "large scale singular event". The ensemble of these "large scale singular events" give rise to a global risk level that AR6 assessed to be moderate for a sustained warming of 1.5 °C with respect to the reference period 1850–1900, transitioning to high at about 2 °C warming.

In the following, the permafrost carbon reservoir and the large continental ice sheets, as prime examples of potentially unstable major elements of the global climate system, will be discussed in terms of how abruptly they might change in the future and inhowfar the changes might be irreversible.

3. Permafrost

Permafrost is perennially frozen soil. In high latitudes and mountainous regions, permafrost is ubiquitous: the total area of the northern circumpolar permafrost region is about 17.8×10^6 km^2 (Schuur et al., 2022). Carbon has accumulated in these soils for millennia, because the cold soil temperatures inhibit microbial decomposition of organic matter. Estimates of the total quantity of carbon in permafrost soil are variable but in the order of about 1500 PgC (ibid.). Under a warming climate, it is very plausible that high-latitude soils at a given depth will remain seasonally unfrozen for a longer time, leading to more efficient microbial decomposition of the available organic matter; in areas close to the southern limit of the permafrost area, permafrost might be replaced by seasonally frozen soil. The decomposition of organic matter that has been locked away in perennially or almost perennially frozen soil for decades to millennia would thus lead to additional greenhouse gas emissions (CO_2 or CH_4, depending primarily on the moisture of the soil). This positive feedback to climate change—warming leading to additional greenhouse gas emissions, leading to enhanced

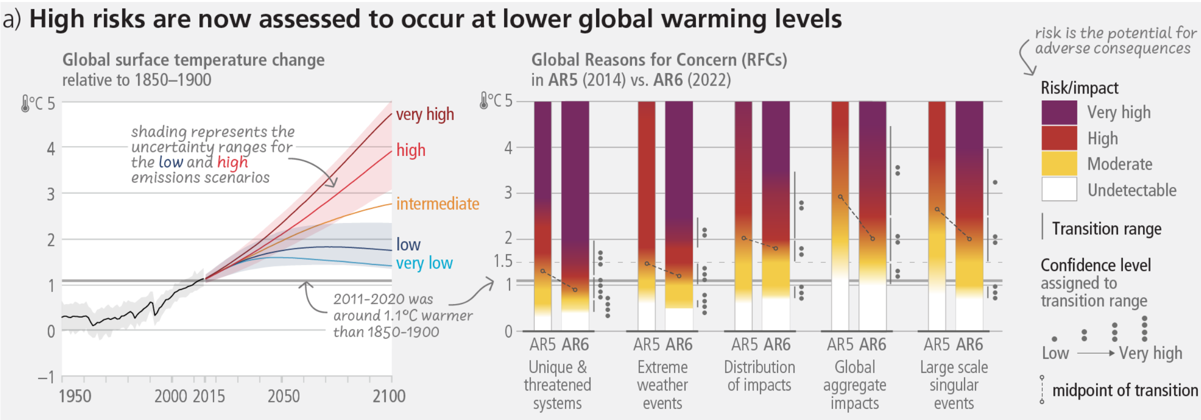

Figure 1. "Reasons for Concern" reproduced from the IPCC AR6 Synthesis Report Figure SPM4a (H. Lee et al., 2023b), containing, on the right, a "burning ember" diagram that shows the assessed risk level associated to "large-scale singular events" as a function of the Global Warming Level (global mean surface air temperature increase above the 1850–1900 level). The figure compares the assessed risk levels for AR5 and AR6, showing that, for a given global mean temperature change, the risk level linked to "large-scale singular events" is estimated higher in AR6 than in AR5.

warming—has been recognized for decades, but its quantification has been difficult, for many reasons. First, there have been large uncertainties about the total quantity of organic carbon in permafrost soils (e.g., Zimov et al., 2006). Second, there is a large spatial heterogeneity in northern permafrost soils (e.g., Olefeldt et al., 2016; Nitzbon et al., 2020; Mishra et al., 2021), strongly influencing estimates of future thaw. Third, and in part due to the strong spatial heterogeneity, the quality of the organic matter has not been well quantified until relatively recently (e.g., Schädel, Schuur, et al., 2014). Fourth, many climate models do not represent a substantial permafrost carbon reservoir in the high-latitude soils, or simply do not well represent permafrost-related soil processes (Schädel, Rogers, et al., 2024). The consequence is that when the climate warms, the models cannot simulate greenhouse gas emissions from permafrost regions, yielding an unphysical total carbon reservoir increase in northern high latitudes (see Figure 2).

In spite of these difficulties, a consensus has nevertheless emerged over the last decade or so, based on availability of new data, better process understanding and improved modeling. This now allows to provide more consolidated estimates of future greenhouse gas emissions from thawing permafrost in a warming world, with admittedly still large uncertainty ranges (see Figure 3). The emerging consensus suggests weaker future permafrost carbon losses than earlier estimates. In the IPCC AR6 Working Group I report, the permafrost CO_2 feedback per °C of global warming is thus estimated to be 18 (3.1–41, 5–95% range) PgC·°C^{-1} (Canadell et al., 2021).

However, these assessments are partly based on models that neglect abrupt thaw processes. Thawing of ice-rich permafrost leads to local land subsidence, a process called thermokarst formation. These distinctive landforms, with local depressions often filled with water ("thermokarst lakes"), can lead to increased thaw rates along the newly formed local slopes, often accelerated by increased erosion rates. Model studies taking into account abrupt thaw processes (Turetsky et al., 2020; Nitzbon et al., 2020) consistently suggest higher future permafrost thaw rates for a given global warming trajectory, and therefore a stronger permafrost carbon feedback. This is recognized in the most recent IPCC assessment that only attributes *low confidence* to its estimate of future greenhouse gas emissions from permafrost thaw (Canadell et al., 2021).

If we define a perturbed state of a dynamical system as "irreversible on a given time scale if the recovery from this state due to natural processes takes substantially longer than the time scale of

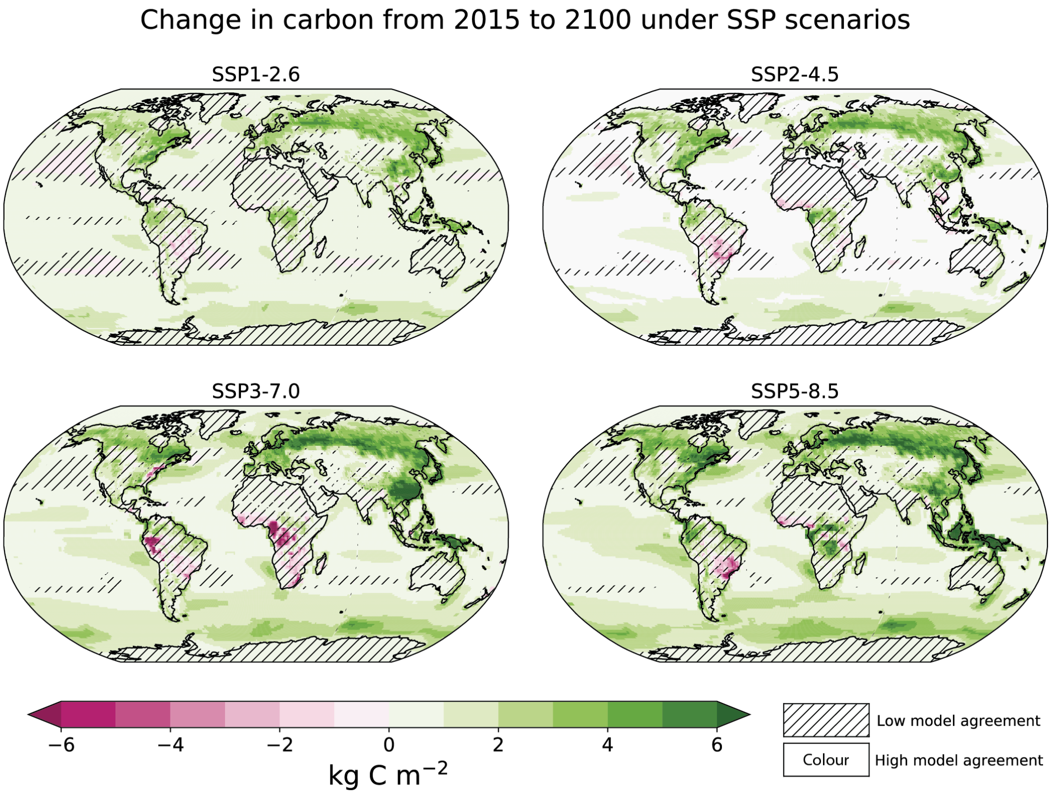

Figure 2. Net carbon changes under four Shared Socio-economic Pathway (SSP) scenarios, as evaluated from nine CMIP6 Earth system models (IPCC AR6 Working Group I, Figure 5.26 (Canadell et al., 2021)). It is noteworthy that the total carbon stored in northern high latitudes is projected to increase in these models, due to increased storage of carbon in vegetation and soils, while there is no or only little loss of permafrost carbon simulated because relevant processes are not represented in the models.

interest" (see the IPCC AR6 Working Group I glossary (Matthews et al., 2021)), then permafrost carbon release in a warming world will clearly be irreversible. But is permafrost really a tipping element in the global climate system? The definition of tipping elements, as stated before, requires the change to become self-perpetuating. It is clear that abrupt thaw, once locally initiated, is a process that tends to reinforce itself—this is precisely why it is called abrupt thaw. However, although permafrost carbon release is a positive feedback to climate change, and would therefore sensu stricto be self-amplifying, it is not obvious why permafrost thaw should be a coherent global tipping element of the Earth system with a single abrupt threshold, as sometimes suggested (e.g., Drijfhout et al., 2015). Rather, abrupt thaw is a local process, although it is often initiated by a coherent large-scale driver (global warming), and in particular by extreme events such as fires (Gibson et al., 2018) or heavy precipitation events (Magnússon et al., 2022), the frequency and amplitude of which is linked to long-term warming. There is no known process by which thermokarst formation at one place would spur thermokarst formation in its surroundings. Moreover, the large spatial heterogeneity of permafrost landscapes (Mishra et al., 2021) can lead to a large range of temperature thresholds for triggering abrupt thaw at rather small spatial scales. Therefore, aggregated across the pan-Arctic region, there is very probably no single "tipping point" (i.e., global warming level) beyond which the entire northern permafrost reservoir would more or less suddenly start collapsing. There is no known mechanism that would initiate a large-scale chain reaction of abrupt

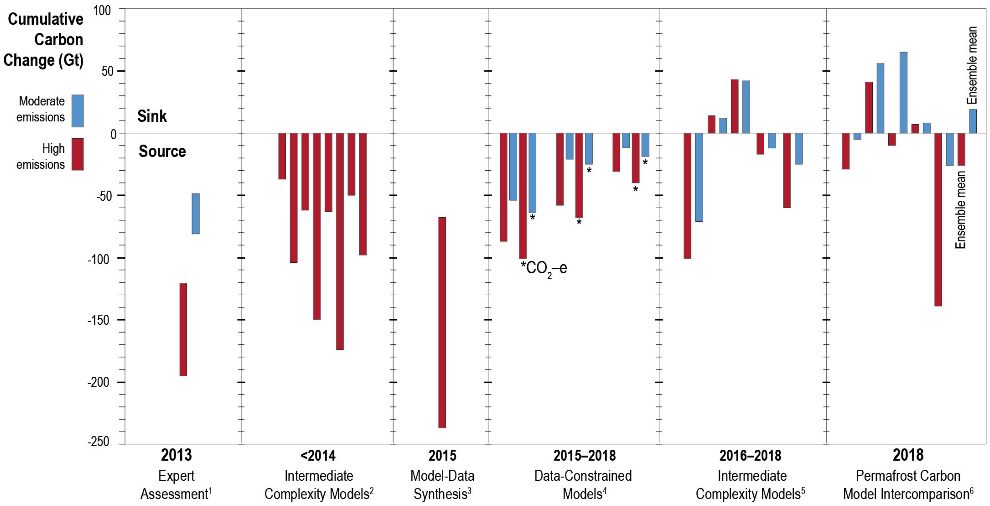

Figure 3. Evolution of the estimates of potential future carbon loss from northern circumpolar permafrost soils. Reproduced from Figure 3.11, IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (Meredith et al., 2019).

permafrost thaw once a specific global warming level is exceeded.

4. Continental ice sheets

The two existing large continental ice sheets in Greenland and Antarctica would raise the global sea level by about 7 m (Dowdeswell, 2006) and 58 m (Morlighem, Rignot, et al., 2020), respectively, if they melted completely. Although it is clear that there is no risk of a complete decay of these two ice sheets in the foreseeable future, concerns are real that large-scale instabilities of both ice sheets could be triggered by human-caused global warming, potentially leading to several meters of additional sea-level rise within a few centuries (Arias et al., 2021). Potential mechanisms of self-amplifying mass loss are of two kinds: The melting can be driven by oceanic or by atmospheric warming.

In the case of melting driven by atmospheric warming (Figure 4, right-hand side), the melt-induced lowering of the ice-sheet surface leads to warmer surface conditions, amplifying the mass loss. Surface melt rates on glaciers, driven by exceptionally warm summer temperatures, can be of the order of several meters per year (Cremona et al., 2023). This positive feedback can thus, in extreme cases of an ice sheet very far from equilibrium, lead to a rapid decay of an ice sheet. However, this feedback will not immediately be in full swing once an ice sheet starts to melt, as the additional disequilibrium induced by surface lowering is cumulative—it is, necessarily, zero at the beginning of the melting process. If the initial warming is modest and only leads to a weakly negative ice sheet mass balance, this ice-sheet altitude feedback will thus not be perceptible at the beginning, and the ice-sheet decay driven by atmospheric warming can in such cases, theoretically, go on for thousands of years before the amplifying ice-sheet altitude really “kicks in” (Robinson et al., 2012). Melting driven by air temperature is responsible for about 50% of the mass loss of the Greenland Ice Sheet between 1992 and 2018 (The IMBIE consortium, 2020), while the surface mass balance of the Antarctic Ice Sheet over the period 1992–2017 was close to equilibrium (The IMBIE consortium, 2018). Therefore, at least currently, the ice sheet altitude feedback, which involves substantial surface melting, is more relevant for Greenland than for Antarctica.

If height loss of the ice sheet is large enough to maintain further mass loss even in case the initial cause of the mass loss—an atmospheric warming—is reversed, then this is an irreversible process. However, if the cumulative mass loss is weak, the ice sheet can recover its initial surface height if the warming is

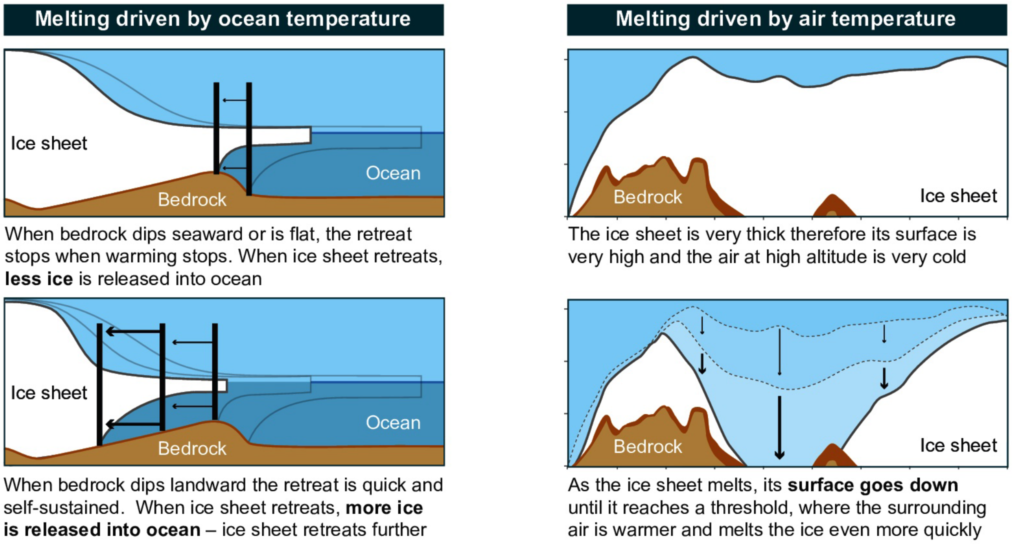

Figure 4. Mechanisms of self-amplifying ice sheet mass loss. Left: melting driven by ocean temperature; right: melting driven by air temperature. In both cases, initial ice sheet retreat can, under certain conditions, be amplified by positive feedbacks. Reproduced from FAQ9.1, IPCC AR6 Working Group I report (Fox-Kemper et al., 2021).

reversed. Therefore, ice-sheet melting driven by air temperature becomes an irreversible process only at a certain stage, and it is usually not abrupt except in its final phase, when the remainders of the almost-gone ice sheet are far from equilibrium with the new surface climate. Nevertheless, the conceptual framework of a "tipping element" still remains applicable to the Greenland Ice Sheet: Once it shrinks sufficiently after a certain global warming threshold has been exceeded, it will not come back even if temperature falls back below that threshold; at that stage, the process is clearly irreversible. However, this tipping point is difficult to quantify, and temperature needs to exceed the threshold for a sufficient amount of time, which is also difficult to quantify. It is essentially for these reasons that the IPCC AR6 Working Group I makes the somewhat fuzzy statement that "there is *limited evidence* that… the Greenland ice sheet will be lost almost completely and irreversibly over multiple millennia" at a "sustained" global warming level between 2 °C and 3 °C.

Another type of self-sustained ice-sheet decay is caused by the Marine Ice Sheet Instability (MISI) mechanism, depicted on the left-hand side of Figure 4. This mechanism requires the base of an ice sheet to be situated below the sea level, and the bedrock to be retrograde (i.e. sloping towards the interior of the continent). This is the case in particular for large parts of the West Antarctic Ice Sheet. The vulnerability of this part of the Antarctic Ice Sheet to ocean-driven melting has been recognized almost 50 years ago (Mercer, 1978). When, during ocean-driven melting of the immersed part of an ice sheet, the grounding line recedes behind a topographic maximum of the bedrock, the ice-sheet retreat becomes self-sustained (e.g., Ritz et al., 2015; Pattyn and Morlighem, 2020). The dominant process that can trigger these large and abrupt changes is the loss of the stabilizing effect of floating ice shelves on the inland ice sheet, called ice shelf buttressing (e.g., Fürst et al., 2016; Pattyn and Morlighem, 2020).

MISI can become irreversible within a few decades and unfold over a few centuries until the almost complete decay of the affected part of the ice sheet (e.g., Feldmann and Levermann, 2015; Rosier et al., 2021). Therefore MISI is probably as close as it gets to a tipping mechanism as it is commonly understood: a self-sustained, irreversible ice-sheet retreat that can take place sufficiently rapidly to be qualified as "abrupt", with obviously large consequences. Similarly to abrupt permafrost thaw, extreme events can, in certain cases, be the final trigger of the tipping

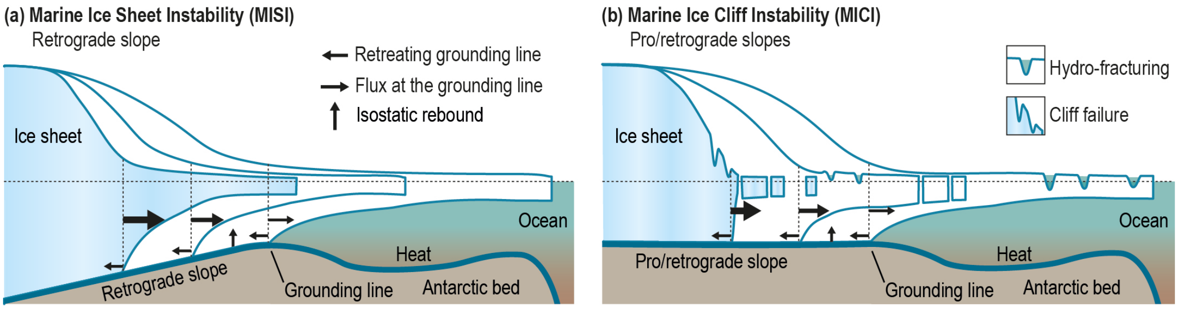

Figure 5. Schematic representation of Marine Ice Sheet Instability (MISI, a) and Marine Ice Cliff Instability (MICI, b). Reproduced from Figure CB8.1, IPCC Special Report on Ocean and Cryophere in a Changing Climate (Meredith et al., 2019).

event. Loss of buttressing ice shelves can be accelerated by massive surface melt events linked to heatwaves or even short events such as atmospheric rivers which advect large amounts of warm and moist air from lower latitudes (Wille, Favier, Dufour, et al., 2019; Wille, Favier, Jourdain, et al., 2022). However, these extreme events would only be the "final kick" leading to local and from there to potentially larger-scale instability, with long-term oceanic and atmospheric preconditioning as a necessary condition (Bassis et al., 2024). Therefore, such extreme events would determine the timing of the tipping—in other words, the tipping point—, but would they not be a critical element of the instability process as such.

A second potential ocean-driven ice sheet instability process is Marine Ice Cliff Instability (DeConto and Pollard, 2016). This process has never been observed at scale and has been proposed on theoretical grounds, linked to mechanical properties of ice which cannot support high, partially immersed cliff faces in excess of about ≈800 m thickness. Such a cliff face, initially generated by bottom melting and/or destabilization of ice shelves by strong surface melt and refreeze (hydro-fracturing), would theoretically be subject to repeated structural failure, leading to abrupt and irreversible ice sheet retreat (ibid.), as shown on the right-hand side of Figure 5 (the left part of the figure displays marine ice sheet instability, for comparison). However, a recent study (Morlighem, Goldberg, et al., 2024) has shown that rapid thinning and ice flow speed-up would rapidly stabilize such a cliff if it existed, suggesting reduced vulnerability of the West Antarctic Ice Sheet to this destabilizing process, at least during initial phases of ice sheet retreat (that is, at least during the 21st century). Moreover, the Marine Ice Cliff Instability process is not needed to explain reconstructed rapid mass losses of the Antarctic Ice Sheet in the past, neither for the mid-Pliocene epoch, nor for the last interglacial period, and certainly not for the recent period of mass loss since 1992 where MICI has not been observed (Edwards et al., 2019). Therefore, the principle of parsimony, also known as "Occam's razor", would lead us to discard this eventuality based on the available evidence.

The problem with climate change is that in addition to large uncertainties, values are in dispute, stakes are high and decisions are urgent—which is exactly the definition of "post-normal science" following Funtowicz and Ravetz (1991). In the specific case of MICI, which could cause very high sea-level rise rates over the next centuries and which cannot be excluded, this means that scientists, when they provide scientific expertise at the science-policy interface (for example, as IPCC authors), cannot neglect this eventuality. Therefore, MICI has been explicitly taken into account in the most recent IPCC assessment, as a specific "low-likelihood, high-impact" storyline building on processes that "[could] not be excluded", a wording that was used consistently starting from the underlying chapter 9 in the Working Group I report (Fox-Kemper et al., 2021) up to the Summary for Policymakers of the Synthesis Report (H. Lee et al., 2023b). Given the new, available evidence published since the literature cutoff date of the last IPCC Working Group I report in 2021, one can wonder whether MICI would still be taken into account if the report was written now. Speculation is moot, but it is worth noting that the fundamental underlying reasons for

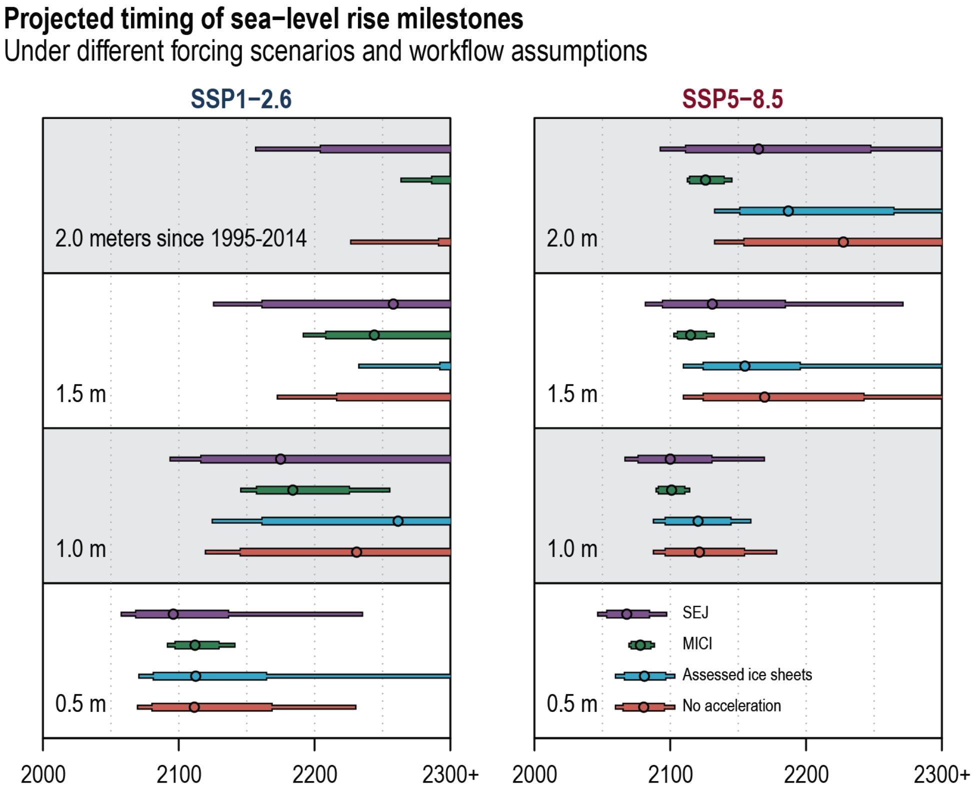

Figure 6. IPCC WR6 WGI assessment of the timing of when global mean sea level (GMSL) thresholds of 0.5, 1.0, 1.5 and 2.0 m are exceeded, based on four different ice-sheet projection methods informing post-2100 projections. Methods are labelled based on their treatment of ice sheets. "No acceleration" assumes constant rates of mass change after 2100. "Assessed ice sheet" models post-2100 ice-sheet losses using a parametric fit extending to 2300 based on a multi-model assessment of contributions under RCP2.6 and RCP8.5 at 2300. Structured expert judgement (SEJ) employs ice-sheet projections from Bamber et al. (2019). Marine ice-cliff instability (MICI) combines the parametric fit for Greenland with Antarctic projections based on DeConto, Pollard, Alley, et al. (2021). Circles, thick bars and thin bars represent the 50th, 17th–83rd and 5th–95th percentiles of the exceedance timing for the indicated projection method. Figure and caption (adapted) from IPCC AR6 Working Group I Figure 9.29 (Fox-Kemper et al., 2021).

taking MICI into account in the assessment of possible future sea-level rise still remain valid: large-scale occurrence of MICI cannot fully be excluded (yet), and the impacts would be very large.

In any case, it is important to keep in mind that concerning sea-level rise, the fundamental question humanity faces is less "how much?", but rather "when?", as can be seen in Figure 6. Under a strong emissions scenario (SPS5-8.5), for example, large-scale occurrence of marine ice cliff instability would make sea-level rise (relative to the 1995–2014 level) reach the 2 m milestone earlier than otherwise (that is, during the first half of the 22nd century in the corresponding "low-likelihood, high-impact" storyline), but even without MICI, that milestone would eventually be reached, and it would probably eventually even be reached in low-emissions pathways, only much later.

5. Conclusion

In the oral presentation this article is based on, and in this article itself, I have discussed in a little bit of detail two possible "tipping elements" in the climate system: permafrost carbon and large continental ice sheets. The purpose was not to provide a comprehensive review of continental tipping elements, but rather to help the public and the non-specialist reader better understand the underlying concepts and the current state of the science concerning the general concept of tipping element/points/events and these two specific possible tipping elements. However, instead of using the concept of "tipping" throughout, I preferred to analyse potential future permafrost carbon and ice sheet changes in terms of irreversibility and abruptness. Both permafrost and continental ice sheets can change irreversibly, and they will undergo irreversible changes if global warming continues. These changes can be abrupt, at least at the "local" scale (for example, for a specific outlet glacier of a large ice sheet, including parts of its drainage basin), but it is not obvious that they will be abrupt at the large scale (that is, the scale of an entire ice sheet or the entire northern circumpolar permafrost region). This article has been largely based on the IPCC's 6th assessment report, which remains relevant in its treatment of "tipping elements" in the light of new publications, even several years after its literature cutoff.

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Declaration of interests

The author does not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and has declared no affiliations other than their research organization.

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