RESEARCH ARTICLE SUMMARY

CLIMATE CHANGE

Exceeding 1.5°C global warming could trigger multiple climate tipping points

David I. Armstrong McKay*, Arie Staal, Jesse F. Abrams, Ricarda Winkelmann, Boris Sakschewski, Sina Loriani, Ingo Fetzer, Sarah E. Cornell, Johan Rockström, Timothy M. Lenton*

INTRODUCTION: Climate tipping points (CTPs) are a source of growing scientific, policy, and public concern. They occur when change in large parts of the climate system—known as tipping elements—become self-perpetuating beyond a warming threshold. Triggering CTPs leads to significant, policy-relevant impacts, including substantial sea level rise from collapsing ice sheets, dieback of biodiverse biomes such as the Amazon rainforest or warm-water corals, and carbon release from thawing permafrost. Nine policy-relevant tipping elements and their CTPs were originally identified by Lenton *et al.* (2008). We carry out the first comprehensive reassessment of all suggested tipping elements, their CTPs, and the timescales and impacts of tipping. We also highlight steps to further improve understanding of CTPs, including an expert elicitation, a model intercomparison project, and early warning systems leveraging deep learning and remotely sensed data.

RATIONALE: Since the original identification of tipping elements there have been substantial advances in scientific understanding from paleoclimate, observational, and model-based studies. Additional tipping elements have been proposed (e.g., parts of the East Antarctic ice sheet) and the status of others (e.g., Arctic summer sea ice) has been questioned. Observations have revealed that parts of the West Antarctic ice sheet may have already passed a tipping point. Potential early warning signals of the Greenland ice sheet, Atlantic Meridional Overturning Circulation, and Amazon rainforest destabilization have been detected. Multiple abrupt shifts have been found in climate models. Recent work has suggested that up to 15 tipping elements are now active (Lenton *et al.*, 2019). Hence it is timely to synthesize this new knowledge to provide a revised shortlist of potential tipping elements and their CTP thresholds.

RESULTS: We identify nine global "core" tipping elements which contribute substantially to Earth system functioning and seven regional "impact" tipping elements which contribute substantially to human welfare or have great value as unique features of the Earth system (see figure). Their estimated CTP thresholds have significant implications for climate policy: Current global warming of ~1.1°C above pre-industrial already lies within the lower end of five CTP uncertainty ranges. Six CTPs become likely (with a further four possible) within the Paris Agreement range of 1.5 to <2°C warming, including collapse of the Greenland and West Antarctic ice sheets, die-off of low-latitude coral reefs, and widespread abrupt permafrost thaw. An additional CTP becomes likely and another three possible at the ~2.6°C of warming expected under current policies.

CONCLUSION: Our assessment provides strong scientific evidence for urgent action to mitigate climate change. We show that even the Paris Agreement goal of limiting warming to well below 2°C and preferably 1.5°C is not safe as 1.5°C and above risks crossing multiple tipping points. Crossing these CTPs can generate positive feedbacks that increase the likelihood of crossing other CTPs. Currently the world is heading toward ~2 to 3°C of global warming; at best, if all net-zero pledges and nationally determined contributions are implemented it could reach just below 2°C. This would lower tipping point risks somewhat but would still be dangerous as it could trigger multiple climate tipping points. ■

The list of author affiliations is available in the full article online.
*Corresponding author. Email: d.mckay@exeter.ac.uk (D.I.A.M.); t.m.lenton@exeter.ac.uk (T.M.L.)
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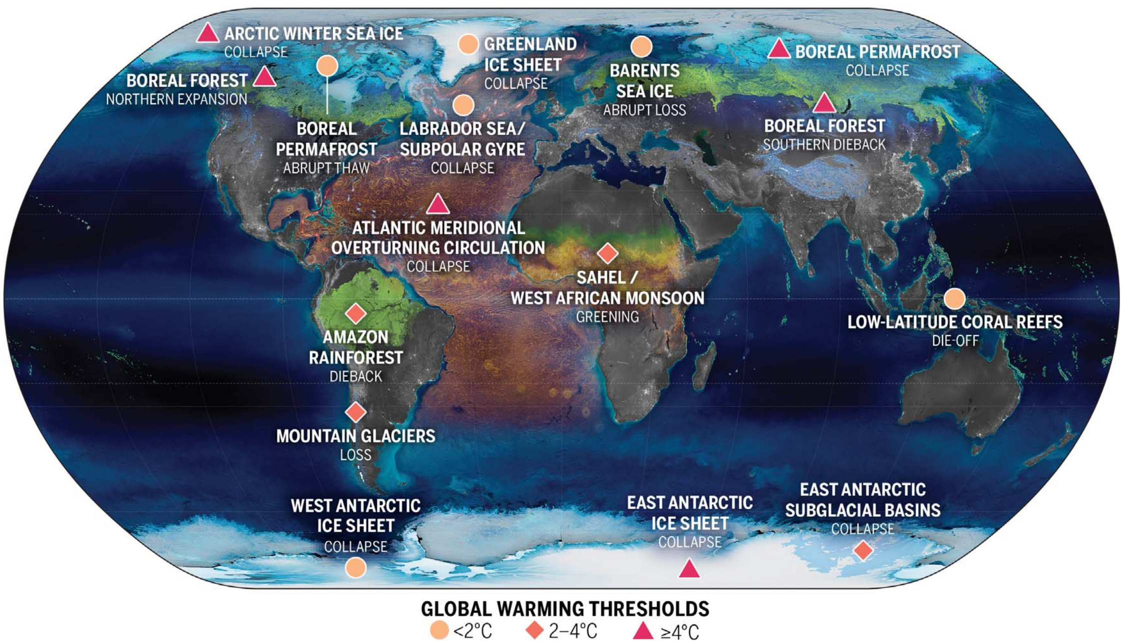

The location of climate tipping elements in the cryosphere (blue), biosphere (green), and ocean/atmosphere (orange), and global warming levels at which their tipping points will likely be triggered. Pins are colored according to our central global warming threshold estimate being below 2°C, i.e., within the Paris Agreement range (light orange, circles); between 2 and 4°C, i.e., accessible with current policies (orange, diamonds); and 4°C and above (red, triangles).

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Exceeding 1.5°C global warming could trigger multiple climate tipping points

David I. Armstrong McKay[1,2,3,4]*, Arie Staal[1,2,5], Jesse F. Abrams[3], Ricarda Winkelmann[6,7], Boris Sakschewski[6], Sina Loriani[6], Ingo Fetzer[1,2], Sarah E. Cornell[1,2], Johan Rockström[1,6], Timothy M. Lenton[3]*

Climate tipping points occur when change in a part of the climate system becomes self-perpetuating beyond a warming threshold, leading to substantial Earth system impacts. Synthesizing paleoclimate, observational, and model-based studies, we provide a revised shortlist of global "core" tipping elements and regional "impact" tipping elements and their temperature thresholds. Current global warming of ~1.1°C above preindustrial temperatures already lies within the lower end of some tipping point uncertainty ranges. Several tipping points may be triggered in the Paris Agreement range of 1.5 to <2°C global warming, with many more likely at the 2 to 3°C of warming expected on current policy trajectories. This strengthens the evidence base for urgent action to mitigate climate change and to develop improved tipping point risk assessment, early warning capability, and adaptation strategies.

Climate tipping points (CTPs) have emerged as a growing research topic and source of public concern (*1*–*3*). Tipping points are defined as "a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system" (*1*). Several large-scale Earth system components, termed tipping elements, were identified with evidence for tipping points that could be triggered by human activities this century. The initial shortlist constituted Arctic summer sea ice, the Greenland ice sheet (GrIS), the West Antarctic ice sheet (WAIS), Atlantic Meridional Overturning Circulation (now AMOC, previously THC), the El Niño Southern Oscillation, the Indian Summer monsoon, the Sahara/Sahel and West African Monsoon, the Amazon rainforest (AMAZ), and boreal forest. A literature review (*1*) and corresponding expert elicitation (*4*) provided early estimates of the temperature thresholds and potential interactions of these tipping elements. Subsequent work showed how recognition of CTPs considerably affects risk analysis and supports measures to minimize global warming to the Paris target of 1.5°C (*5*, *6*).

Since these early estimates (*1*), there have been considerable advances in our knowledge of CTPs including observations of nonlinear changes in the climate system, statistical early warning methods, paleoclimate evidence, upgraded Earth system models (ESMs), and improved offline models of particular elements (e.g., ice sheets and vegetation). Notably, observations and models suggest that parts of the WAIS may be approaching (*7*, *8*) or have even passed a tipping point (*9*, *10*). Early warning indicators have revealed potential destabilization of the GrIS, AMOC, and AMAZ (*11*–*13*). However, many ESMs still lack processes important for resolving potential tipping behavior—e.g., bias toward AMOC stability (*14*)—or underestimating current tropical carbon sink declines (*15*). Potential causal interactions among tipping elements (*4*) are such that overall tipping of one element increases the likelihood of tipping others (*16*), possibly risking a "tipping cascade" of impacts that may further amplify global warming (*2*, *3*). In the worst case scenario, interactions might produce a global CTP (*3*).

The list of tipping elements has evolved over time (*1*–*3*, *5*) (table S1). Different studies have proposed potential additions including southwest North America, the Yedoma permafrost region, the North Atlantic subpolar gyre (*17*), low-latitude coral reefs, the East Antarctic Ice Sheet (EAIS), Arctic winter sea ice (AWSI), Alpine glaciers (*5*), the northern polar jet stream (*3*), the Congo rainforest (*18*), and the Wilkes and Aurora subglacial basins in East Antarctica (*2*). A range of abrupt shifts have been identified in CMIP5 models (*19*), some of which are not in elements on the original shortlist such as boreal tundra or Antarctic sea ice. Conversely, arguments have been made that Arctic summer sea ice (*20*, *21*), El Niño–Southern Oscillation (ENSO) (*22*, *23*), and monsoons (*24*) should not be classified as CTPs. Numerous temperature threshold estimates have been made since (*1*) with some being revised markedly downward—notably WAIS (*2*, *25*). The recent the Intergovernmental Panel on Climate Change (IPCC) AR6 WG1 report identifies up to 15 candidates [table 4.10 in (*23*)] but was not explicit about their temperature thresholds (*23*).

Here we reassess the climate tipping elements based on the substantial literature published since (*1*), focusing on those triggerable by global warming. We clarify the definition of tipping elements and points and propose a new categorization separating global "core" and regional "impact" tipping elements. We then provide an updated list and assessment of the global mean surface temperature (GMST) range at which each candidate CTP could occur as well as their timescales and climate impacts. Finally we combine this information to assess the likelihood of triggering CTPs at successive global warming levels.

Defining tipping points and tipping elements

Given multiple inconsistent definitions of a CTP in the literature, we anchor on the technical definition provided by (*1*): A tipping point is a threshold in a (forcing) "control parameter" at which a small additional perturbation (within natural variability of ~0.2°C) causes a qualitative change [significantly larger than the standard deviation of natural variability in (*1*)] in the future state of a system [see (*1*) and SM for the full definition]. Here, our specific definition is as follows: Tipping points occur when change in part of the climate system becomes (i) self-perpetuating beyond (ii) a warming threshold as a result of asymmetry in the relevant feedbacks, leading to (iii) substantial and widespread Earth system impacts. We now explain key aspects of this definition in more detail.

Self-perpetuating change

Self-perpetuation mechanisms are critical to the existence of a tipping point in a system, beyond which they propel qualitative change such that even if forcing of the system ceases the qualitative change usually continues to unfold regardless (*20*). IPCC AR6 sometimes uses tipping point to refer to a class of abrupt change in which the subsequent rate of change is independent of the forcing [1.4.4.3 of (*26*)], although this is not part of AR6's core CTP definition [4.7.2 of (*23*)]. Self-perpetuation is usually due to positive feedback within a system attaining sufficient strength to overcome stabilizing negative feedbacks and (temporarily) reach a "runaway" condition (in which an initial change propagating around a feedback loop gives rise to an additional change that is at least as large as the initial change and so on). Most positive feedbacks never attain this condition and instead simply amplify the original driver in a constrained way. Notably, Arctic summer sea ice loss involves the positive ice-albedo feedback, but unlike year-round sea ice loss, that feedback alone is not strong enough to produce a clear threshold

[1]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden. [2]Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden. [3]Global Systems Institute, University of Exeter, Exeter, UK. [4]Georesilience Analytics, Leatherhead, UK. [5]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, Netherlands. [6]Potsdam Institute for Climate Impact Research, Potsdam, Germany. [7]Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany.
*Corresponding author. Email: d.mckay@exeter.ac.uk (D.I.A.M.); t.m.lenton@exeter.ac.uk (T.M.L.)

beyond which loss would continue even if global warming stopped (20, 21). Consequently, we describe such feedbacks as "threshold-free".

(Ir)reversibility

Tipping points usually lead to irreversible qualitative change but reversible tipping points are possible as a special case (1). Many tipping points result from crossing bifurcation points or attraction basin boundaries in bistable systems, with the resulting hysteresis making tipping effectively irreversible on human timescales. However, self-perpetuating change can also occur across noncatastrophic thresholds in unistable systems (27) (supplementary text S1). Other definitions of CTPs are more restrictive and require irreversibility, for example: "a system reorganizes… and does not return to the initial state even if the drivers of the change are abated" [6.1.1 of (22)]. The IPCC AR6 does not require irreversibility as this is difficult to prove for long timescales given model limitations: "A tipping point is a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly" [4.7.2 of (23)]. AR6 uses abruptness and irreversibility as proxies for tipping dynamics but does not specify criteria for system reorganization and sometimes does not clearly differentiate which abrupt and/or irreversible changes are considered tipping points (e.g., irreversible ocean temperature change is listed alongside potential tipping points in table 4.10 of (23) and box 12.1 in table 1 of (28) but has no clear critical threshold).

Timescale and abruptness

We allow for CTPs (e.g., in ice sheets) in which the resulting qualitative change is slower than the anthropogenic forcing causing it—i.e., not abrupt in the sense defined as faster than the cause (29). We only require that the transition to a new state occurs at a rate determined by the climate (sub)system itself (29). The resulting committed (often irreversible) qualitative changes can unfold over centuries to millennia [here we relax the ethical time horizon of (1) from ~1 thousand years (ky) to ~10 ky], but crucially they can increase short-term impacts (e.g., rate of sea level rise). Other authors require a tipping point to produce abrupt change (30) thereby excluding events such as ice sheet collapse. The IPCC defines abrupt change as "substantially faster than the rate of change in recent history" in AR6 [1.4.4.3 of (26)], which could allow for slower changes than anthropogenic forcing. However, AR6 also gave a more restrictive timescale-based definition for abrupt climate change as taking place over a few decades or less (i.e., as fast as anthropogenic forcing) and persisting for at least a few decades [4.7.2 of (23)]. More than a dozen abrupt changes have been found in CMIP5 model output (19) (table S2) but such changes could simply be the result of an abrupt change in forcing without involving CTPs. Below we assess which abrupt changes indicate potential tipping elements and which do not involve self-perpetuating feedback.

Spatial scale

Tipping elements are defined as components of the Earth system that are at least subcontinental in scale (of the order of 1000 km, i.e., ~1 M km_2) and could pass a tipping point as a result of actions this century (1). If self-perpetuating change (and a corresponding tipping point) occurs at a subcontinental scale then this qualifies as a global core tipping element. However, there are many examples of runaway feedback and associated tipping points at smaller spatial scales. Where a change in forcing (e.g., temperature) is fairly uniform across a large spatial scale, such that a smaller-scale tipping point is crossed near-synchronously in many locations that span a subcontinental scale (e.g., coral bleaching across the Great Barrier Reef or committed loss of Himalayan glaciers), then these are considered potential regional impact tipping elements. However, where systems exhibit localized tipping points (1 m to 1 km) at different forcing levels such that change does not self-perpetuate beyond a clear shared threshold (e.g., methane hydrates), these are classed as threshold-free feedbacks because the accumulated global consequences of multiple localized tipping events remain roughly proportional to the forcing.

Impacts

Climate tipping elements in (1) either (i) contribute significantly to the overall mode of operation of the Earth system (such that tipping them modifies the overall state of the whole system), (ii) contribute significantly to human welfare (such that tipping them affects >~100 million people), or (iii) have great value in themselves as a unique feature of the Earth system [expanded from the biosphere used in (1)]. Global core tipping elements must meet criterion (i) whereas regional impact tipping elements must meet criterion (ii) or (iii) but not (i). Regarding (i), crossing a tipping point need not involve feedback to global atmospheric composition or temperature—self-perpetuating feedback can exist entirely within a tipping element (1)—but there is usually causal coupling to other tipping elements such as through heat, salt, water, carbon, or momentum fluxes (4). Often there is feedback to global warming and where this exceeds ±0.1°C (i.e., natural variability and the triggering perturbation) we consider this to meet criterion (i). Thus, near-synchronous, large-scale crossing of smaller-scale tipping points can qualify as a global core tipping element if it changes warming by >0.1°C.

The climate tipping elements

Based on current observations, paleorecords, and model runs subsequent to (1), we draw up a longlist of proposed climate tipping elements. Together with expert judgment for each proposed element, we summarize the evidence and confidence levels for self-perpetuation, temperature thresholds, hysteresis or irreversibility, transition timescales, and global or regional impacts on climate (Materials and Methods, table S3, and supplementary text S2). Based on this evidence and the definitions in the preceding section, we shortlist global core and regional impact climate tipping elements (Table 1 and Fig. 1). Other candidate tipping elements that we consider uncertain, unlikely, or that have threshold-free feedbacks are discussed in the supplementary text along with differences with past assessments (table S4).

Cryosphere

Arctic sea ice (AWSI/BARI)

An abrupt collapse in AWSI (31) is observed in some CMIP5 models beyond ~4.5°C (19, 32), which arises either from asymmetry in ice formation and loss timescales creating a threshold response or from local positive feedback cycles. Hence we class AWSI as a global core tipping element (medium confidence), with a best estimate threshold of ~6.3°C (4.5 to 8.7°C, based on CMIP5) (high confidence), timescales of 20 years (10 to 100 years) (high confidence), and GMST feedback of ~+0.6°C (high confidence) [~+0.25°C when free of summer ice; regional ~+0.6 to 1.2°C (low confidence)]. A subcase is abrupt loss of Barents Sea winter ice (BARI), which occurs at ~1.6°C in two CMIP5 models (19), is self-reinforced by an increased inflow of warm Atlantic waters (33), and has substantial impacts on atmospheric circulation, European climate, and potentially the AMOC (34). We consider BARI a probable regional impact tipping element (medium confidence) with a threshold of 1.6°C (1.5 to 1.7°C) (low confidence), a timescale of ~25 years (low confidence), and regional warming (high confidence). By contrast Arctic summer sea ice (ASSI)—despite declining rapidly since the 1970s and outpacing previous IPCC projections since the 1990s—is responding linearly to cumulative emissions (35). This decline is amplified by the ice-albedo feedback and possibly feedbacks to cloud cover but damped by negative heat loss feedbacks (20). CMIP6 models better capture historical ASSI decline and project that ice-free Septembers will occur occasionally above 1.5°C GMST, become common beyond 2°C, and remain permanent at ~3°C (36). However, the linear modeled and observed responses suggest that ASSI is unlikely to feature a tipping point beyond which loss would self-perpetuate (21, 36). Hence, we recategorize ASSI as a threshold-free feedback.

Greenland ice sheet (GrIS)

The GrIS is shrinking at an accelerated rate as a result of both net surface melt and accelerated

Table 1. Table showing our literature-based threshold, timescale, and impact estimates for the tipping elements we categorize as global core or regional impact. Element acronym colors indicate Earth system domain (blue, cryosphere; green, biosphere; orange, ocean-atmosphere), and element name and estimate colors indicate subjective confidence levels (green, high; yellow, medium; red, low). Bolded element names indicate elements featured in previous climate tipping element characterizations.

Category		Proposed climate tipping element (and tipping point)	Threshold (°C)			Timescale (years)			Maximum impact* (°C)	
			Est.	Min	Max	Est.	Min	Max	Global	Region
Global core tipping elements	GrIS	**Greenland Ice Sheet (collapse)**	1.5	0.8	3.0	10k	1k	15k	0.13	0.5 to 3.0
	WAIS	**West Antarctic Ice Sheet (collapse)**	1.5	1.0	3.0	2k	500	13k	0.05	1.0
	LABC	Labrador-Irminger Seas / SPG Convection (collapse)	1.8	1.1	3.8	10	5	50	-0.50	-3.0
	EASB	East Antarctic Subglacial Basins (collapse)	3.0	2.0	6.0	2k	500	10k	0.05	?
	AMAZ	**Amazon Rainforest (dieback)**	3.5	2.0	6.0	100	50	200	Partial: 30 GtC / 0.1°C Total: 75 GtC / 0.2°C	0.4 to 2.0
	PFTP	**Boreal Permafrost (collapse)**	4.0	3.0	6.0	50	10	300	125-250 GtC / 175-350 GtCe / 0.2-0.4°C	~
	AMOC	**Atlantic M.O. Circulation (collapse)**	4.0	1.4	8.0	50	15	300	-0.50	-4 to -10
	AWSI	**Arctic Winter Sea Ice (collapse)**	6.3	4.5	8.7	20	10	100	0.60	0.6 to 1.2
	EAIS	**East Antarctic Ice Sheet (collapse)**	7.5	5.0	10.0	?	10k	?	0.60	2.0
Regional impact tipping elements	REEF	**Low -latitude Coral Reefs (die-off)**	1.5	1.0	2.0	10	~	~	~	~
	PFAT	**Boreal Permafrost (abrupt thaw)**	1.5	1.0	2.3	200	100	300	Abrupt thaw adds 50% to gradual: 10 GtC/14 GtCe/ .04°C per °C @2100; 25 GtC/35 GtCe/ .11°C per °C @2300	~
	BARI	Barents Sea Ice (abrupt loss)	1.6	1.5	1.7	25	?	?	~	+
	GLCR	**Mountain Glaciers (loss)**	2.0	1.5	3.0	200	50	1k	0.08	+
	SAHL	**Sahel and W. African Monsoon (greening)**	2.8	2.0	3.5	50	10	500	~	+
	BORF	**Boreal Forest (southern dieback)**	4.0	1.4	5.0	100	50	?	+52GtC / net -0.18°C	-0.5 to -2
	TUND	**Boreal Forest (northern expansion)**	4.0	1.5	7.2	100	40	?	-6 GtC / net +0.14°C	0.5-1.0

*Feedback strength in °C per °C for abrupt permafrost thaw is calculated relative to preindustrial and declines with further degrees of warming (by ~21% per °C).

calving (37, 38) and shows early warning signals consistent with approaching a tipping point in west Greenland (11). Both ice sheet modeling and paleoclimate data indicate that a GrIS tipping point can occur when the melt-elevation feedback gets strong enough to support self-propelling melt (as an ice sheet surface loses height, it enters warmer air and thus melts faster) (1). Different models give a critical threshold of ~1.6°C (0.8 to 3.2°C) (39), ~1.5°C (40), or 2.7±0.2°C (41). Paleoclimate and model evidence shows that ice only reaches full coverage below ~0.3 to 0.5°C [~300 parts per million (ppm) CO_2] (39, 42). Hysteresis allows GrIS to exist above this growth threshold once formed (39) but paleorecords indicate that GrIS partially retreats above this threshold (42) and likely collapsed during the long MIS-11 interglacial which was considerably warmer (>1.5°C) (43). A coupled ice sheet–atmosphere model found no collapse threshold (44), leading AR6 to state that there is limited evidence for irreversible GrIS loss below 3°C (21). However, some irreversible loss occurs beyond 3.5 m sea level equivalent (equivalent to ~2 to 2.5°C) (44), indicating self-perpetuating feedback. GrIS collapse would shift the Earth system to a unipolar icehouse state and affect other tipping elements (particularly the AMOC), hence qualifying as a global core tipping element (high confidence). Our best estimates for GrIS include a threshold of ~1.5°C (0.8 to 3°C) (high confidence), timescales of 10 ky (1 to 15 ky) (medium confidence), and GMST feedback of ~+0.13°C (regional ~+0.5 to 3°C) (low confidence). The timescale of ice sheet meltdown gets shorter the greater the temperature threshold is exceeded (40), with a minimum of ~1000 years.

West Antarctic ice sheet (WAIS)

Large parts of the WAIS are grounded below sea level; if the grounding line in these marine ice sheet basins reaches retrograde slopes, this may lead to the onset of marine ice sheet instability (MISI) and crossing of a tipping point (7, 8, 45). MISI is based on a feedback between the grounding line retreat and ice flux across the grounding line as it reaches thicker ice. This can lead to self-sustaining retreat and is hypothesized to have driven past collapses of the WAIS during previous warmer interglacial periods with high sea levels (21, 46). Some glaciers in the Amundsen Sea Embayment are already close to this threshold and experiencing substantial grounding line retreat (9). The grounding line of Thwaites glacier is only ~30 km away from the subglacial ridge and retreating at ~1 km per year (47); eventual collapse may already be inevitable (10, 45). Models support irreversible retreat being underway for present levels of ocean warming (25, 48) and suggest that losing Thwaites glacier may destabilize much of WAIS (7). Under sustained

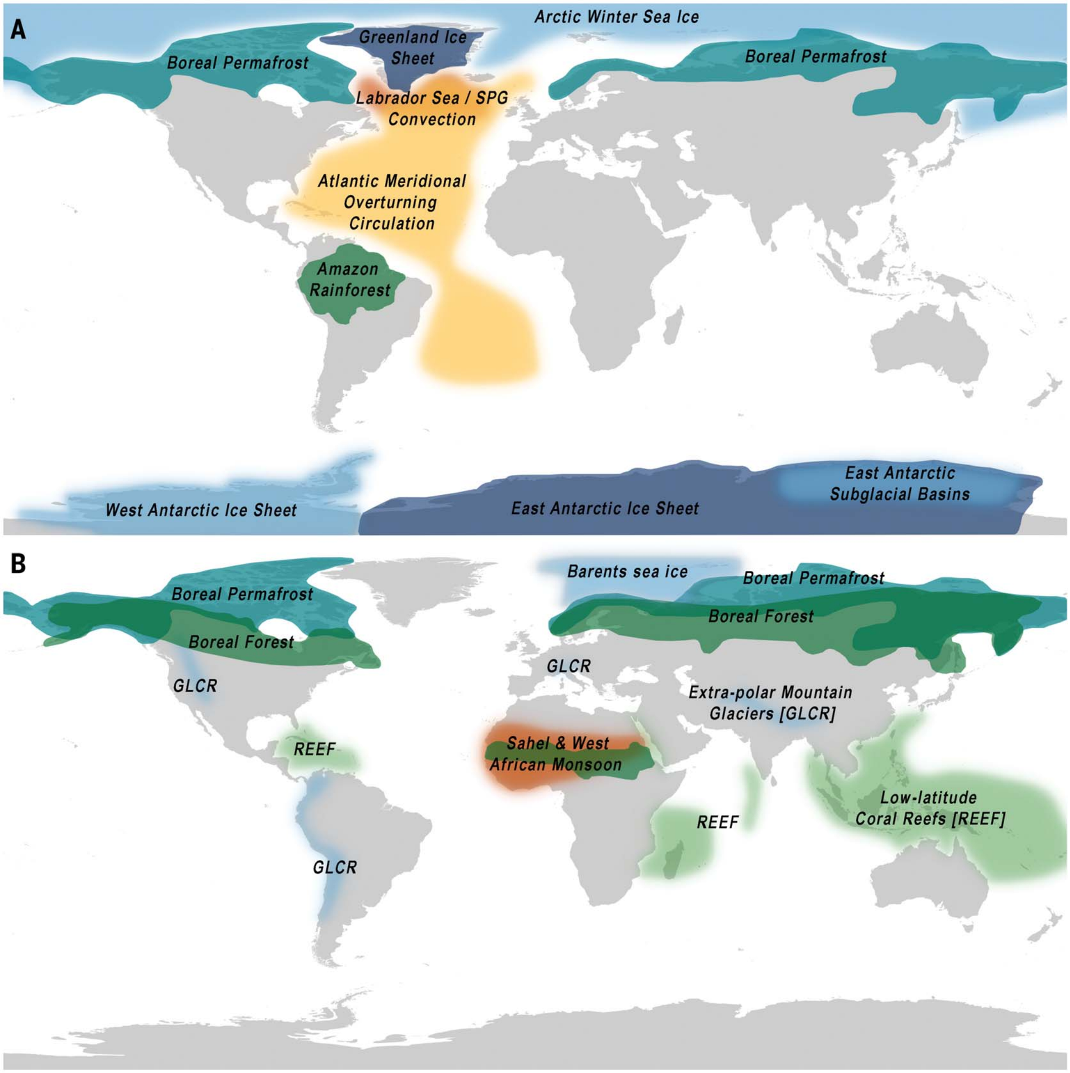

Fig. 1. Maps showing the global core (**A**) and regional impact (**B**) climate tipping elements identified in this study. Blue, green, and orange areas represent cryosphere, biosphere, and ocean-atmosphere elements, respectively.

1°C warming one model shows partial WAIS collapse with mass loss peaking at ~2°C warming (*25*). Hence we retain WAIS as a core global tipping element (high confidence) with a best estimate threshold of ~1.5°C [1 to 3°C, down from 3.5 to 5.5°C in (*1*)] (high confidence), timescales of 2 ky (500 years to 13 ky) (medium confidence), and GMST feedback of ~+0.05°C (regional ~+1°C) (low confidence). Higher threshold exceedance reduces the transition timescale to a minimum of ~500 years (*40*).

East Antarctic subglacial basins (EASB)

Recent data and models have shown that several subglacial basins of the EAIS—particularly the Wilkes, Aurora, and Recovery Basins—are also affected by MISI (*21*, *25*, *49*–*51*). These basins may also be subject to marine ice cliff instability in which the collapse of floating ice shelves creates unstable ice cliffs at the marine edge of the ice sheet which can retreat faster, but the importance of this process is disputed (*49*, *51*). One model indicates that Wilkes collapse may be committed by 3 to 4°C (*25*). Paleoclimate evidence for a higher mid-Pliocene sea level (+5 to 25 m) indicates that parts of the EASB (together with the GrIS and WAIS) were likely absent when the world was ~2.5 to 4°C warmer (*21*, *42*, *52*). By contrast sea levels of +6 to 13 m at 1.1 to 2.1°C in MIS-11 do not require substantial EASB contribution (assuming WAIS and GrIS were lost) (*50*). Hence we class EASB as a core global tipping element (high confidence) with best estimates for a tipping threshold of 3°C (2 to 6°C) (medium confidence), timescales of 2 ky (500 y to 10 ky) (medium confidence), and an uncertain GMST feedback provisionally assumed to be similar to WAIS (i.e., ~+0.05°C) (low confidence).

East Antarctic ice sheet (EAIS)

The land-grounded bulk of the EAIS is the world's largest ice sheet, containing the equivalent of ~50 m of sea level potential (*25*). Paleorecords indicate that growth occurred once atmospheric CO_2 fell below ~650 to 1000 ppm (~6 to 9°C) (*42*). Modeled ice sheets often exhibit alternative ice-covered or ice-free stable states for a range of global boundary conditions (*53*). As a result of this hysteresis the EAIS is expected to remain stable at CO_2 levels well beyond 650 ppm, helping it to survive through the warm mid-Miocene Climatic Optimum ~16 Mya (~2 to 4°C) (*42*). However, long-term stabilization at >1000 ppm CO_2 and ~8 to 10°C warming could cause total disintegration (*25*). Once past this threshold, self-perpetuating feedbacks amplify ice loss (*39*). The loss of EAIS would have global effects and hence is categorized as a global core tipping element (medium confidence). Although unlikely, under high emissions [e.g., Representative Concentration Pathway (RCP) 8.5] and high climate sensitivity it might conceivably be committed to during this century or thereafter. Our best estimates for the EAIS are a tipping threshold of ~7.5°C (5 to 10°C) (medium confidence), timescales of >10 ky (medium confidence), and GMST feedback of ~+0.6°C (regional ~+2°C) (low confidence).

Boreal permafrost (PFTP/PFAT)

Permanently frozen soils and sediments in boreal regions contain ~1035 gigatonnes of carbon (GtC) that can be partly released as CO_2 and methane upon thawing (*54*). Although initially lacking evidence for a synchronous large-scale threshold (*1*), subsequent assessments recognized that part(s) of the permafrost could be considered a tipping element (*3*, *17*). Here we separate permafrost into three components with different dynamics: gradual thaw [PFGT; a threshold-free feedback (high confidence)] (*54*–*56*) (see SM); abrupt thaw [PFAT; a regional impact tipping element (medium confidence)], and collapse [PFTP: a global core tipping element (low confidence)]. Abrupt thaw processes (PFAT) such as slope slumping and thermokarst lake formation (*54*) could increase emissions by 50 to 100% relative to gradual thaw (*57*), involve localized tipping dynamics (e.g., continued thaw subsidence after initiation) and could occur near-synchronously on a subcontinental scale. Our best estimates for PFAT include a tipping threshold of 1.5°C (1 to 2.3°C) (medium confidence), a timescale of 200 years (100 to 300<years) (medium confidence), and an additional ~50% emissions beyond gradual thaw (~10 to 25 GtC per °C) (medium confidence). Finally, abrupt permafrost drying at ~4°C (*58*) and/or sufficiently rapid regional warming (>9°C) corresponding to ~5°C globally (*17*, *59*) could act as a trigger for permafrost collapse (PFTP) driven by internal heat production in carbon-rich permafrost—"the compost bomb" instability (*60*, *61*). The Yedoma deep ice- and carbon-rich permafrost (containing ~115 GtC in Yedoma deposits, ~400 GtC across the Yedoma domain) is particularly vulnerable as fast thaw processes can expose previously isolated deep deposits (*54*, *59*). This and other carbon-rich regions vulnerable to abrupt drying at >4°C (*58*) could have considerable feedback to global temperatures. Our best estimates for PFTP include a threshold of 4°C (3 to 6°C) (low confidence), a timescale of 50 years (10 to 300 years) (medium confidence), and emissions on the order of ~125 to 250 GtC (ΔGMST ~+0.2 to 0.4°C) (low confidence).

Mountain glaciers (GLCR)

Alpine glaciers outside Greenland and Antarctica have individual mass balance thresholds and elevation feedbacks yet large-scale synchronous losses are projected in several key regions at specific global warming levels. In transient simulations, peak water from European glacier melt is expected at ~1°C (*62*) with near-total loss expected to be committed at ~2°C (*20*). Global peak water occurs at ~2°C but committed eventual loss is expected at lower temperatures (*63*). Long model integrations show that global warming of 1.5 to 2°C is sufficient to lead to the eventual loss of most extra-polar glaciers (and possibly even polar glaciers) (*40*, *64*). RCP4.5 (>2°C by 2100) puts most lower-latitude glaciers on a path to significant losses beyond 2100 (*21*). Glaciers in High Mountain Asia last longer than elsewhere but reach peak water at ~2°C with significant social impacts for South Asia (*62*). Given the considerable human impacts of glacier loss (*63*) we categorize mountain glaciers as a regional impact tipping element (medium confidence). Our best estimate includes a threshold of ~2°C (1.5 to 3°C) (medium confidence), a timescale of 200 years (50 years to 1 ky) (medium confidence), and GMST feedback of ~+0.08°C (regionally greater) (low confidence).

Southern Ocean sea ice features abrupt events in some climate models (*19*) but because of uncertain dynamics and low confidence in projections it is classed as an uncertain tipping element (see SM). Marine methane hydrates are classed as a threshold-free feedback and Tibetan plateau snow is classed as uncertain (see SM).

Ocean-Atmosphere (circulation)

North Atlantic subpolar gyre / Labrador-Irminger Sea convection (LABC)

Convection in the Labrador and Irminger Seas in the North Atlantic—part of the subpolar gyre (SPG)—abruptly collapses in some models as a result of warming-induced stratification, a state which is then maintained by self-reinforcing convection feedbacks (*19*, *65*) giving two alternative stable states with or without deep convection. Abrupt future SPG collapse occurs in nine runs across five CMIP5 models at 1.1 to 2.0°C, in one additional model run at 3.8°C (*19*, *65*), and in four CMIP6 models in the 2040s (~1 to 2°C) (*66*). In some models SPG collapse affects AMOC strength but SPG and AMOC have distinct feedback dynamics and patterns of impacts, and SPG collapse can occur much faster than AMOC collapse. The North Atlantic cooling trend (i.e., the "warming hole") is centered over the SPG and in models is often closely linked to SPG weakening (*65*, *66*), although others have associated it with AMOC slowdown (*67*). SPG collapse causes a concentrated North Atlantic regional cooling of ~2 to 3°C, potential global cooling of up to ~0.5°C, a northward-shifted jet stream, weather extremes in Europe, and southward shift of the intertropical convergence zone (ITCZ) (*65*, *66*). Given clear tipping dynamics and global impact we class SPG as a global core tipping element (medium confidence), with a best estimate threshold of ~1.8°C (1.1 to 3.8°C) (high confidence), a timescale of 10 years (5 to 50 years) (high confidence), and GMST feedback of ~0.5°C (regional ~–3°C) (low confidence).

Atlantic meridional overturning circulation (AMOC)

The AMOC is self-sustaining due to salt-advection feedback (northward movement of warm water increases its density as a result of cooling and evaporation supporting the deep convection that drives the circulation). Import of salt at the southern boundary of the Atlantic also supports alternative strong and weak AMOC stable states with multiple abrupt switches between them observed in the past (*68*). Global warming increases Arctic precipitation, freshwater runoff from Greenland, and sea surface temperatures, which together slow down the AMOC by inhibiting deep convection. The AMOC is inferred from some reconstructions to have weakened by ~15% over the past ~50 years (*67*) and early warning signals in indirect AMOC footprints are consistent with the current AMOC "strong" state losing stability (*12*). However, the IPCC gives low confidence on historical AMOC trends (*21*). The Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (*22*) assessed AMOC collapse occurring during the 21st century to be very unlikely but physically plausible; however, this was increased to unlikely (medium confidence) in AR6 (*21*). AMOC collapse is triggered in three runs of one CMIP5 model at 1.4 to 1.9°C and in two runs of an additional model at 2.2 to 2.5°C (*19*, *65*) in contrast to gradual declines in other CMIP5 and CMIP6 models (*21*). However, AR6 assessed CMIP models as generally tending toward "unrealistic stability" with respect to observational constraints (*14*, *21*). They also neglect meltwater forcing from rapid GrIS melt (*21*, *69*). Both factors make the AMOC more vulnerable to collapse. AMOC collapse would have global impacts on temperature and precipitation patterns including North Atlantic cooling, Southern Hemisphere warming, southward-shifted ITCZ, monsoon weakening in Africa and Asia, monsoon strengthening in the Southern Hemisphere leading to drying in the Sahel and parts of Amazonia, and reduced natural carbon sinks (*70*–*73*). Hence AMOC is retained as a core global tipping element (medium confidence) with a best estimate threshold of ~4°C [1.4 to 8°C versus 3.5 to 5.5°C in (*1*)] (low confidence), timescales of ~50 years (15 to 300 years) (medium confidence), and a GMST feedback of –0.5°C (low confidence) [regional –4 to –10°C, highly heterogeneous global pattern (medium confidence)].

The Indian summer monsoon (and other monsoon systems) have been reclassified as uncertain climate tipping elements because of a lack of evidence for a warming-related threshold behavior. Equatorial stratocumulus cloud breakup and Indian Ocean upwelling are uncertain as a result of limited evidence. Global ocean anoxia is uncertain because the global warming level required for weathering-induced anoxia is unclear. ENSO is reclassified as an unlikely tipping element as it lacks a clear self-perpetuation threshold. Arctic ozone hole expansion is reclassified as unlikely as it is now improbable that it would be triggerable as a result of climate change. The Northern Polar Jet stream is classed unlikely because instability as a result of climate change remains uncertain and no threshold has been proposed. (All of the above elements are discussed in more detail in the supplementary materials.)

Biosphere

Amazon rainforest (AMAZ)

The Amazon forest biome stores ~150 to 200 GtC (*3*, *74*, *75*) and historically has been a important sink for human CO_2 emissions (*15*). However, in intact forests this sink has declined since the 1990s (*15*) and ~17% of the Amazon forest has been lost to deforestation since the 1970s, a rate that has accelerated since 2019 (*75*). A combination of a climate change-induced drying trend, unprecedented droughts, and anthropogenic degradation in the south and east has led to the biome as a whole becoming a net carbon source (*74*). It has also lost resilience across ~76% of its area (*13*). Rainfall is projected to further decline and the dry season is expected to lengthen in southern and eastern areas of the forest in response to further warming, likely worsening this trend (*75*). The Amazon forest recycles around a third of the Amazon basin's rainfall on average (*76*) and up to ~70% in parts of the basin (*77*), particularly during the critical dry season as the forest maintains transpiration fluxes (*76*). This and localized fire feedbacks mean that ~40% of the Amazon forest is estimated to currently be in a bistable state, increasing to ~66% on an RCP8.5 trajectory (*18*, *77*), and rainforest loss could initiate self-reinforcing drying that tips this portion into a degraded or savanna-like state. Widespread Amazon dieback was originally projected at either 3 to 4°C of warming or ~40% deforestation (*78*) but uncertain synergistic interaction might lower the deforestation threshold to only ~20 to 25% (*79*). More recent ESMs tend not to simulate climate-induced Amazon dieback and emergent constraints indicate lower rainforest sensitivity to warming (*80*). However, two CMIP5 models exhibit dieback at 2.5 and 6.2°C (*19*). Additionally, CMIP5 ESMs underestimate observed tree mortality (*15*) and likely overestimate CO_2 fertilization (*81*), potentially making these models undersensitive to dieback. Given the size of the region affected by even partial dieback and its global impacts we categorize the Amazon forest as a global core tipping element (medium confidence). Our best estimates for AMAZ are a threshold of ~3.5°C (2 to 6°C) independent of deforestation (likely lower with deforestation) (low confidence), timescales of 100 years (50 to 200 years) (low confidence), and partial dieback of 40% (i.e., current bistable area) leading to emissions of ~30 GtC along with biogeophysical feedbacks (see SM) to a GMST feedback of ~+0.1° (regional +0.4 to 2°C) (medium confidence).

Boreal forest (BORF/TUND)

The boreal forest (or taiga) encircling the Arctic region features multiple stable states of tree cover as a result of feedbacks including albedo and fire (*82*, *83*). We classify it as a regional impact tipping element with two potential CTPs associated with abrupt dieback at its southern edge (BORF) (medium confidence) and abrupt expansion at its northern edge (tundra greening) (TUND) (medium confidence). Warming is projected to destabilize the southern edge, where factors such as hydrological changes, increased fire frequency, and bark beetle outbreaks can lead to self-reinforcing feedbacks driving regionally synchronized forest dieback (on the order of 100 km) to a grass-dominated steppe or prairie state (*83*). Models project that regime shifts may start in this area at ~1.5°C and become widespread by >3.5°C (*84*, *85*). Dieback may also be rate-dependent (*85*). Our best estimates for BORF is a threshold of ~4°C (1.4 to 5°C) (low confidence), timescales of 100 years (50+ years) (low confidence), and partial (~50%) dieback leading to emissions of ~52 GtC, which—along with countervailing biogeophysical feedbacks such as increased albedo and reduced evapotranspiration—leads to a net GMST feedback of ~−0.18°C (medium confidence) [regional ~−0.5 to 2°C (low confidence)]. Northward expansion of the forest into the current tundra biome may also feature self-perpetuation dynamics (e.g., by causing further local warming through albedo feedback). Models suggest that regime shifts may begin in this northern area at ~1.5°C and become widespread by ~3.5°C (*84*), with abrupt high latitude forest expansion occurring in one CMIP5 model at 7.2°C (*19*). For TUND our best estimates are for a threshold at ~4°C (1.5 to 7.2°C) (low confidence), timescales of 100 years (40+ years) (low confidence), and partial (~50%) uptake of ~6 GtC which along with countervailing biogeophysical feedbacks (decreased albedo, increased evapotranspiration) leads to a net GMST feedback of +0.14°C per °C (regional ~+0.5 to 1°C) (low confidence).

Sahel vegetation and the West African monsoon (SAHL)

Paleoevidence indicates multiple abrupt shifts into and out of African Humid Periods with associated greening of the Sahara in response to gradual changes in orbital forcing (*86*). AMOC weakening and associated warming of the Equatorial East Atlantic also caused past collapses of the West African monsoon (WAM) (*70*, *86*, *87*). Dust aerosol-rainfall positive feedbacks amplify change alongside well-established vegetation-rainfall positive feedbacks but many models still underestimate self-amplifying feedbacks and cannot reproduce the extent of past rainfall and vegetation changes (*86*). By contrast, a model optimized against present observations and mid-Holocene reconstructions recently reproduced abrupt transitions in Saharan vegetation with potential tipping dynamics (*88*). In future projections with GHG forcing, global (CMIP5 and CMIP6) and some regional Coordinated Regional Climate Downscaling Experiment (CORDEX) climate models tend to predict strengthening of the WAM and wetting and northward expansion of the central and eastern Sahel (as well as drying in coastal west Africa) (*23*, *70*, *89*–*91*), which tend to green the Sahel (*86*). Abrupt increases in vegetation in the Eastern Sahel occur in three ESM runs at 2.1 to 3.5°C (*19*). In other global models more gradual WAM strengthening and vegetation shifts are predicted but in some regional climate models the WAM instead collapses (*89*). Clearly the existence of a future tipping threshold for the WAM and Sahel remains uncertain as does its sign but given multiple past abrupt shifts, known weaknesses in current models, and huge regional impacts but modest global climate feedback, we retain the Sahel/WAM as a potential regional impact tipping element (low confidence). We adopt the scenario of abrupt wetting and greening with a threshold of ~2.8°C (2 to 3.5°C) (low confidence), a timescale of 50 years (10 to 500 years) (low confidence), and uncertain Earth system impacts (regional warming) (medium confidence).

Low-latitude coral reefs (REEF)

Tropical and subtropical coral reefs are threatened by anthropogenic pressures including overfishing, direct damage, sedimentation, ocean acidification, and global warming (*92*). When water temperatures exceed a certain threshold coral irreversibly expel their symbiotic algae resulting in coral bleaching, thereby triggering coral death (*93*). Ocean acidification worsens warming-induced degradation. Coral collapse would remove one of the Earth's most biodiverse ecosystems, affecting the wider marine food web, ocean nutrient and carbon cycling, and livelihoods of millions of people worldwide (*92*). Although coral bleaching is a localized process synchronous bleaching can occur at the ~1000 km scale (as seen for the Great Barrier Reef), and further warming is expected to cause widespread bleaching (93). Adaptation may be possible with slower warming rates (92) but the IPCC has projected 70 to 90% tropical and subtropical coral reef loss at 1.5°C with near total loss by 2°C (90). Given regionally synchronized tipping dynamics with significant human but indirect climate impacts, we categorize warm-water coral reefs as a regional impact tipping element (high confidence). Our best estimates are for a threshold of ~1.5°C (1 to 2°C) (high confidence), timescales of ~10 years (medium confidence), and negligible GMST feedback (high confidence). Beyond the biosphere elements listed, the ocean biological pump and land/ocean carbon sink are unlikely to be tipping elements although they may feature nonlinearities (see SM).

Implications for climate policy and preventing dangerous levels of global warming

Figure 2A summarizes our temperature threshold estimates for each tipping element making the shortlists (others are summarized in the supplementary text). Here we define crossing a CTP as "possible" beyond its minimum temperature threshold and "likely" beyond its central estimate.

This revised assessment of CTPs has significant implications for climate policy by determining levels of global warming that prevent tipping to either committed changes in Earth system function or major damage to future societies. A risk minimization approach such as this seeks to avoid minimum estimated thresholds but this no longer appears possible for some tipping elements.

Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS and GrIS tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94). Setting aside achievability (and recognizing internal climate variability of ~±0.1°C), this suggests that ~1°C is a level of global warming that minimizes the likelihood of crossing CTPs. This is consistent with the <0.5 to 1°C range of Holocene temperature variability whereas past interglacials ≤1.5 to 2°C had up to 10 to 13 m higher sea level (21, 95).

The chance of triggering CTPs is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse, near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC collapse is crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESMs at 1.5 to 2°C (19). Although not tipping elements, ASSI loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C.

Recent net zero targets if implemented could limit peak warming to ~1.95°C (1.3 to 3°C), but as of November 2021 current policies are estimated to result in ~2.6 °C (1.9 °C to 3.7 °C) by 2100 (96). Therefore 2 to 3°C by 2100 is currently likely with matching of pledges with policies key to determining where warming ends up in this range. Going from 2 to 3°C, maximum estimated thresholds for abrupt permafrost thaw, GrIS, WAIS, and extra-polar glaciers are passed, suggesting that tipping them would become very likely. The likelihood of triggering EASB collapse, Amazon dieback, and West African monsoon shift (Sahel greening) becomes non-negligible at ~2°C and increases at ~3°C. Subpolar gyre collapse, boreal forest dieback, and AMOC collapse also become more likely. Although not tipping elements, above 2°C the Arctic would very likely become summer ice–free and land carbon sink-to-source transitions would become widespread.

If the moderate ambition of current policies is not improved and climate sensitivity or carbon cycle feedbacks turn out to be higher than the median assumption then warming of up to ~4°C is possible by 2100, and >4°C cannot be ruled out if future policy ambition declines and/or implementation falters. Going from 3 to 5°C, EASB collapse becomes very likely, Amazon dieback becomes likely >3.5°C, boreal forest shifts likely >4°C, and large-scale permafrost collapse becomes possible at >3°C and likely >4°C. AMOC collapse may become likely >4°C but with high uncertainty (1.4 to 8°C range) and AWSI collapse becomes possible >4.5°C. Warming of >5°C, although very unlikely this century, becomes plausible in the longer-term under higher climate sensitivities with current or reversed policies. This risks EAIS collapse and a commitment of ~55 m of sea level rise if warming stabilizes >5°C for multiple centuries. Other tipping elements, if not already triggered—e.g., Amazon dieback, widespread Permafrost collapse—would very likely be committed and AMOC collapse and AWSI collapse would become increasingly likely. Equatorial stratocumulus cloud breakup occurs in one model beyond ~6°C (97) and if plausible would represent a global CTP to a "hothouse" climate state (3).

Discussion

Tipping elements and their tipping points were treated independently in this assessment but there are multiple causal interactions between them with risks of triggering cascades among CTPs (2, 4, 16), some mediated through temperature. The strength and in some cases even the sign of identified interactions is uncertain (4). Nevertheless, their combined effect tends to lower CTP temperature thresholds (6, 16). The present assessment would likely amplify this effect, further strengthening the incentive for ambitious mitigation.

Some of the threshold and impact estimates are highly uncertain (e.g., AMOC, BORF/TUND, AMAZ, SAHL, PFTP) as are the transition timescales of many elements. Some proposed elements remain too uncertain to categorize (e.g., EQSC, ANOX, INSM, AABW, Congo rainforest), and others considered unlikely to feature tipping dynamics (e.g., ENSO, JETS) cannot yet be fully ruled out (see SM). Other tipping elements may yet be discovered. It may be possible to safely overshoot CTPs in slower elements such as ice sheets (94) but the allowable overshoot times need further research. Spatial pattern formation might allow some biosphere elements to evade direct tipping (98) but this needs to be assessed.

To further our understanding of the likelihood of crossing CTPs an updated expert elicitation [building on (4)] is overdue. A horizon-scanning exercise and systematic scanning of CMIP6 model output [following (19)] and a tipping point model intercomparison project could help identify more candidate tipping elements and refine assessment of their likelihood. Further model improvements and model-data intercomparison are essential. Early warning methods are starting to reveal whether tipping elements are destabilizing for parts of GrIS (11), AMOC (12), and the Amazon (13), and can reveal proximity to a CTP (11). These could be augmented with deep learning techniques (99). Systematic application to observational and remotely sensed data together with targeted new observing systems could begin to provide a CTP early warning system (100).

Conclusion

The UNFCCC stipulates that all countries commit to avoid dangerous climate change, translated through the Paris climate agreement into keeping GMST well below 2°C and aiming for 1.5°C. Our assessment of climate tipping elements and their tipping points suggests that danger may be approached

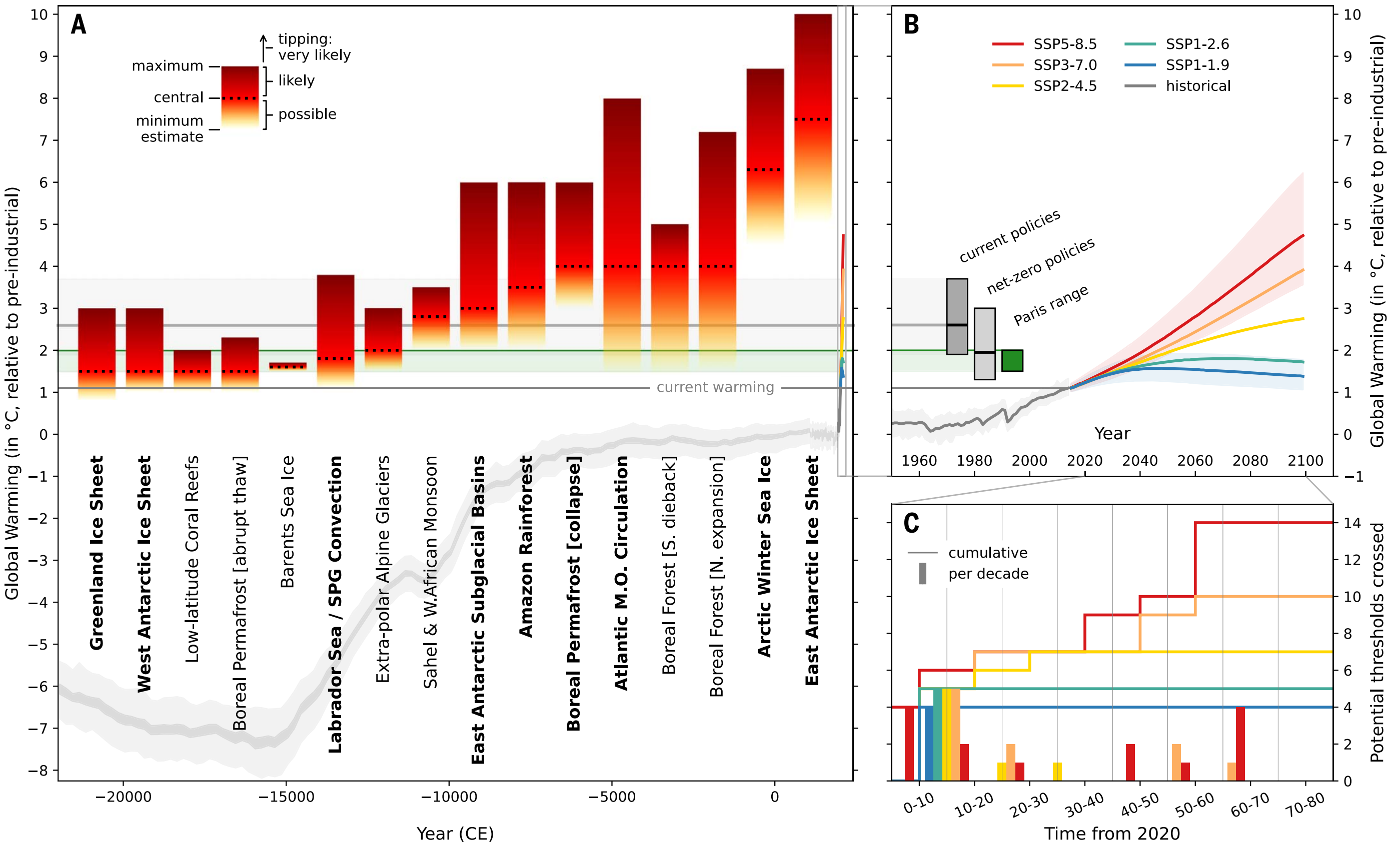

Fig. 2. Our global warming threshold estimates for global core and regional impact climate tipping elements. Tipping elements (**A**) relative to IPCC SSP projections and likely future scenarios given current policies and targets (**B**) and how many thresholds may be crossed per Shared Socioeconomic Pathways (SSP) projection (**C**). Bars in (A) show the minimum (base, yellow), central (line, red), and maximum (top, dark red) threshold estimates for each element (bold font, global core; regular font, regional impact), with a paleorecord of GMST over the past ~25 ky (*95*) and projections of future climate change (green, SSP1-1.9; yellow, SSP1-2.6; orange, SSP2-4.5; red, SSP3-7.0; purple, SSP5-8.5) from IPCC AR6 (*23*) shown for context. Future projections are shown in more detail in (B) along with estimated 21st century warming trajectories for current and net-zero policies (gray bars, extending into (A); horizontal lines show central estimates, bar height the uncertainty ranges) as of November 2021 (*96*) versus the Paris Agreement range of 1.5 to <2°C (green bar). The number of thresholds potentially passed in the coming decades depending on SSP trajectory in (C) is shown per decade (bars) and cumulatively (lines).

even earlier. The Earth may have left a safe climate state beyond 1°C global warming. A significant likelihood of passing multiple climate tipping points exists above ~1.5°C, particularly in major ice sheets. Tipping point likelihood increases further in the Paris range of 1.5 to <2°C warming. Current policies leading to ~2 to 3°C warming are unsafe because they would likely trigger multiple climate tipping points. Our updated assessment of climate tipping points provides strong scientific support for the Paris Agreement and associated efforts to limit global warming to 1.5°C.

Materials and Methods

We mined the literature subsequent to (*1*), including studies of paleoclimate change, observed change, early warning signals, future model projections, underlying theory, and existing assessments, to draw up a longlist of possible candidate tipping elements (table S3). For each we extracted information on evidence for self-perpetuation, temperature thresholds, hysteresis/irreversibility, transition timescales, and global/regional impacts on climate, on which we then use subjective expert judgment to determine our best estimates. From this evidence (or lack of it) we drew up shortlists (Table 1) of 'core' global tipping elements and regional 'impact' tipping elements (Fig. 1), for which we summarize the rationale in the main text and supplementary text S2 and S3. Candidates that did not make the shortlists (table S3) are classed as: (a) 'uncertain' tipping elements—due to limited evidence for self-perpetuating feedback and threshold behavior; (b) 'unlikely' tipping elements—possessing only localized tipping or nonfeedback response to climate change; and (c) 'threshold-free feedbacks'—where positive feedbacks exist but are not strong enough to self-perpetuate. Different parts or phenomena of some systems—notably permafrost—are assigned to different categories. We give (very low, low, medium, high, very high) confidence levels based on the IPCC's confidence rating system (as a product of the authors' judgements of both the robustness and the degree of agreement of the assessed literature) (*101*) for the estimates of central, minimum, and maximum temperature thresholds, timescales of transition, and global and local impacts on climate (supplementary text S2). We define crossing a CTP as 'possible' beyond its minimum temperature threshold and 'likely' beyond its best estimate. Differences with past lists of tipping elements are described in table S4.

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SUPPLEMENTARY MATERIALS

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