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

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Short title: *Reassessment of climate tipping points*

Keywords:

Climate change; climate tipping elements; tipping points; climate feedbacks; abrupt change; nonlinear dynamics

This paper is a revised preprint resubmitted to *Science* following peer review – not to be uploaded to a preprint server until accepted (publisher rules) or shared further.

Abstract: 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 pre-industrial already lies within the lower end of some tipping point uncertainty ranges. Several more tipping points may be triggered in the Paris Agreement range of 1.5-<2°C global warming, with many more likely at the 2-3°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.

One-sentence summary: Reassessment of climate tipping point estimates strengthens evidence for limiting global warming to 1.5°C.

Climate tipping points (CTPs) have emerged as a growing research topic and source of public concern (*1*–*3*). Tipping points were 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 comprised: Arctic summer sea-ice, Greenland ice sheet (GrIS), West Antarctic ice sheet (WAIS), Atlantic Meridional Overturning Circulation (AMOC; then labelled THC), El Niño Southern Oscillation, Indian Summer monsoon, Sahara/Sahel and West African Monsoon, Amazon rainforest, and boreal forest. Literature review (*1*) and a corresponding expert elicitation (*4*) provided early estimates of their temperature thresholds and potential interactions. Subsequent work showed how recognition of CTPs significantly affects risk analysis and supports measures to minimize global warming to the Paris Target of 1.5°C (*5*, *6*).

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

The list of tipping elements has evolved over time (*1–3*, *5*) (Supplementary 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 sub-glacial basins in East Antarctica (*2*). A range of abrupt shifts have been identified in CMIP5 models (*19*), some in elements not on the original shortlist, such as boreal tundra or Antarctic sea-ice. Conversely, Arctic summer sea-ice (*20*, *21*), ENSO (*22*, *23*), and monsoons (*24*) have been argued not to be CTPs. Numerous temperature threshold estimates have been made since (*1*), with some being revised markedly downwards – notably WAIS (*2*, *25*). The recent IPCC AR6 WG1 report identified up to 15 candidates (Table 4.10), 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. Then we 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 full definition). Specifically, here: tipping points occur when change in part of the climate system becomes a) self-perpetuating beyond b) a warming threshold, due to asymmetry in the relevant feedbacks, leading to c) significant 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 usually even if forcing of the system ceases the qualitative change continues to unfold regardless (*20*). IPCC AR6 sometimes uses ‘tipping point’ to refer to a class of abrupt change where: “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 getting sufficiently strong to overcome stabilizing negative feedbacks and (temporarily) reach a ‘runaway’ condition (where 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 is not strong enough alone to produce a clear threshold 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 non-catastrophic thresholds in unistable systems (*27*) (Supplementary Text S1). Other definitions of CTPs are more restrictive, requiring irreversibility, e.g.: "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 Table 1 of (*28*) but has no clear critical threshold).

Timescale and abruptness. We allow for CTPs (e.g. in ice sheets) where 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*). Resulting committed (often irreversible) qualitative changes can unfold over centuries to millennia (here we relax the 'ethical' time horizon of (*1*) from ~1ky to ~10ky), but crucially they can increase short-term impacts (e.g. rate of sea level rise). Others require a tipping point to produce abrupt change (*30*), thereby excluding e.g. ice sheet collapse. The IPCC defined abrupt change as "substantially faster than the rate of change in the 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*)). Over a dozen abrupt changes have been found in CMIP5 model output (*19*) (Supplementary Table S2), but such changes could simply be due to an abrupt change in forcing without involving CTPs. Below we assess which are potential tipping elements (and which do not involve self-perpetuating feedback).

Spatial scale. Tipping elements are defined as at least sub-continental scale (of the order of 1000km, i.e. ~1M km^2) components of the Earth system that could pass a tipping point due to actions this century (*1*). If self-perpetuating change (and a corresponding tipping point) occurs at sub-continental 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 sub-continental scale (e.g. coral bleaching across the Great Barrier Reef, or melt of Himalayan glaciers), then these are considered potential regional 'impact' tipping elements. Where systems exhibit localized tipping points (1m-1km) 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 remains roughly proportional to the forcing.

Impacts. Climate tipping elements 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 impacts on >~100 million people), or; (iii) have great value in themselves as a unique feature of the Earth system (expanded from 'biosphere' in (*1*)). Global 'core' tipping elements must meet criterion (i), whereas regional 'impact' tipping elements 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 be purely within a tipping element (*1*) – but there is usually causal coupling to other tipping elements – e.g. via 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, palaeo-records, and model runs subsequent to (*1*), we draw up a longlist of proposed climate tipping elements. Together with expert judgment for each, we summarize the evidence and confidence levels for self-perpetuation, temperature thresholds, hysteresis / irreversibility, transition timescales, and global / regional impacts on climate (Materials and Methods, Supplementary Table S3 & Text S2). Based on this evidence and the definitions in Section 2, we shortlist Global ‘Core’ and Regional ‘Impact’ climate tipping elements (Table 1;

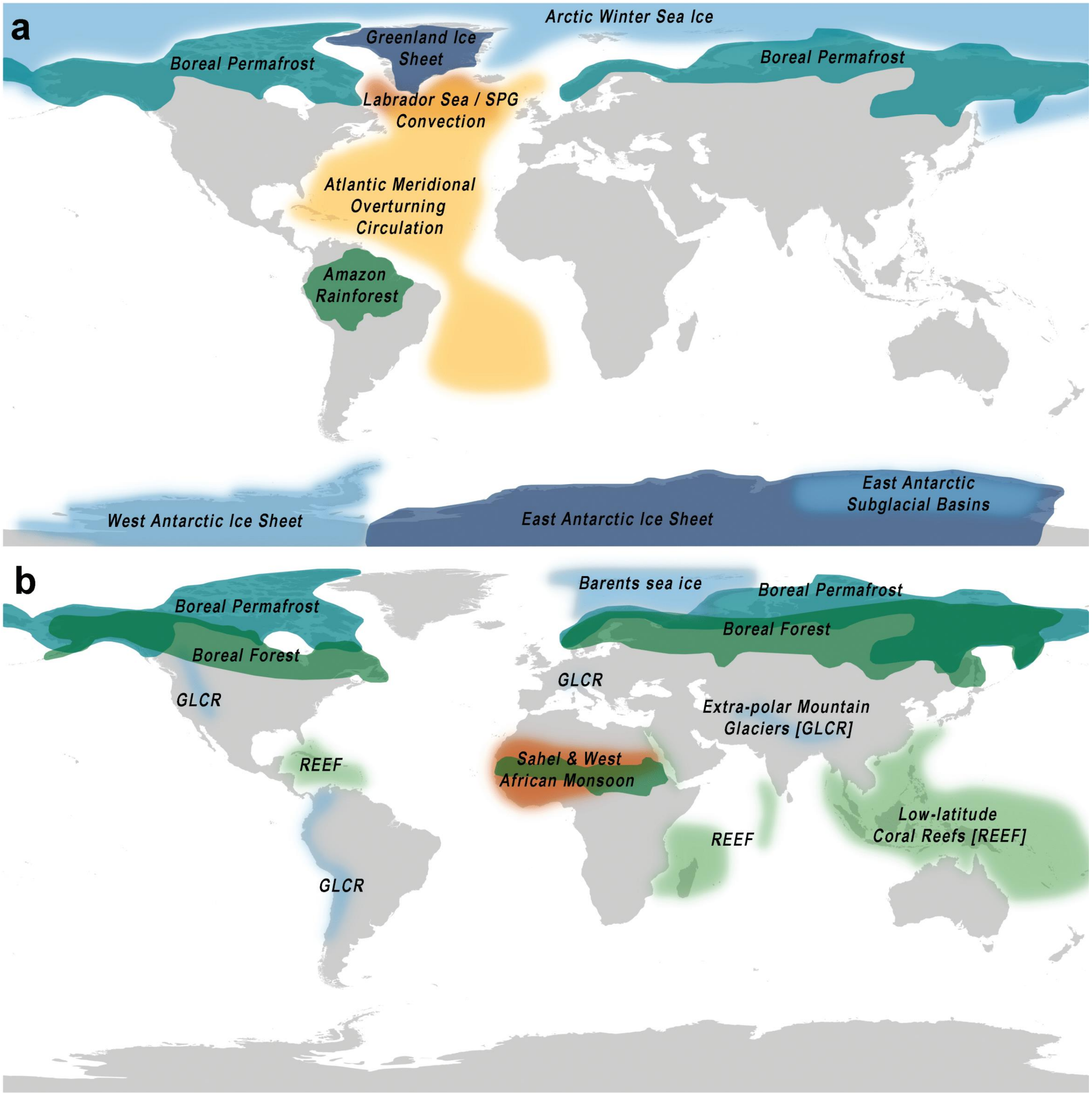


Fig. *1*). Other candidate tipping elements that we consider uncertain, unlikely, or threshold-free feedbacks are discussed in the Supplementary Text, together with differences to past assessments (Supplementary Table S4).

[Table 1]

[Fig. 1]

Cryosphere

Arctic sea-ice (AWSI/BARI). An abrupt collapse in Arctic winter sea ice (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 (4.5-8.7°C, based on CMIP5) [high confidence], timescales of 20y (10-100y) [high confidence], and GMST feedback of ~+0.6°C [high confidence] (~+0.25°C when summer ice-free; regional ~+0.6-1.2°C [low confidence]). A sub-case 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 significant 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 (1.5-1.7°C) [low confidence], timescale of ~25y [low confidence], and regional warming [high confidence]. In contrast, Arctic summer sea ice (ASSI) despite declining rapidly since the 1970s and outpacing past 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 ice-free Septembers will occur occasionally above 1.5°C GMST, become common beyond 2°C, and permanent around 3°C (*36*). However, the linear modelled and observed responses suggest ASSI is unlikely to feature a tipping point beyond which loss would self-perpetuate (*21*, *36*). Hence, we re-categorize ASSI as a threshold-free feedback.

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

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 can lead to the onset of the 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 past warmer interglacial periods with high sea levels (*21*, *46*). Some glaciers in the Amundsen Sea Embayment are already close to this threshold, and experiencing significant grounding line retreat (*9*). Thwaites glacier's grounding line is only ~30km away from the subglacial ridge and retreating at ~1km/year (*47*) and 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 can destabilize much of WAIS (*7*). Under sustained 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 (1-3°C, down from 3.5-5.5°C in (*1*)) [high confidence], timescales of 2ky (500y-13ky) [medium confidence], and GMST feedback of ~+0.05°C (regional ~+1°C) [low confidence]. Higher threshold exceedance reduces transition timescale to a minimum of ~500y (*40*).

East Antarctic sub-glacial basins (EASB). Recent data and models have shown that several subglacial basins of the East Antarctic ice sheet (EAIS) – in particular the Wilkes, Aurora, and Recovery Basins – are also affected by MISI (*21*, *25*, *49*–*51*). Likewise they may also be subject to 'marine ice cliff instability' (MICI) in which the collapse of floating ice shelves creates unstable ice cliffs at the marine edge of the ice sheet that can retreat faster, but the significance of this process is disputed (*49*, *51*). One model indicates that Wilkes collapse may be committed by 3-4°C (*25*). Palaeoclimate evidence for mid-Pliocene sea level being 5-25m higher indicates that parts of the EASB (together with the GrIS and WAIS), were likely absent in that ~2.5-4°C warmer world (*21*, *42*, *52*). In contrast, sea levels of +6-13m at 1.1-2.1°C in MIS-11 does not require significant 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 (2-6°C) [medium confidence], timescales of 2ky (500y-10ky) [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 ~50m of sea level potential (*25*). Palaeorecords indicate it grew once atmospheric CO_2 fell below ~650-1000 ppm (~6-9°C) (*42*). Modelled ice sheets often exhibit alternative ice-covered or ice-free stable states for a range of global boundary conditions (*53*). Due to this hysteresis, the EAIS is expected to remain stable some way beyond 650ppm, and survived through the warm mid-Miocene Climatic Optimum ~16 Mya (~2-4°C) (*42*). However, long-term stabilization at ~1000+ppm CO_2 and ~8-10°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, hence is categorized as a global core tipping element [medium confidence]. Although unlikely, under high emissions (e.g. RCP8.5) and high climate sensitivity it might conceivably be committed to this century or thereafter. Our best estimates for the EAIS are a tipping threshold of ~7.5°C (5-10°C) [medium confidence], timescales of >10ky [medium confidence], and GMST feedback of ~+0.6°C (regional ~+2°C) [low confidence].

Boreal permafrost (PFTP/PFAT). Permanently frozen soils and sediments in the boreal region contain ~1035 GtC that can be partly released as CO_2 and methane upon thawing (*54*). Although initially lacking of evidence for a synchronous large-scale threshold (*1*), subsequent assessments recognized part(s) of the permafrost could be 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 50-100% relative to gradual thaw (*57*), involve localized tipping dynamics (e.g. continued thaw subsidence after initiation), and could occur near synchronously on a sub-continental scale. Our best estimates for PFAT are a tipping threshold of 1.5°C (1-2.3°C) [medium confidence], timescale of 200y (100-300<y) [medium confidence], and an additional ~50% emissions beyond gradual thaw (~10-25 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 Yedoma domain) is particularly vulnerable, as fast thaw processes can expose previously isolated deep deposits (*54*, *59*). This and other regions vulnerable to abrupt drying at >4°C (*58*) could have significant feedback to global temperature. Our best estimates for PFTP is a threshold of 4°C (3-6°C) [low confidence], timescale of 50y (10-300y) [medium confidence], and emissions on the order of ~125-250 GtC (ΔGMST ~+0.2-0.4°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 1.5-2°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 lower-latitude mountain glaciers as a regional impact tipping element [medium confidence]. Our best estimate is a threshold of ~2°C (1.5-3°C) [medium confidence], timescale of 200y (50y-1ky) [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 due to uncertain dynamics and low confidence in projections is classed as an uncertain tipping element (see SM). **Marine methane hydrates** are classed as a threshold-free feedback and **Tibetan plateau snow** as uncertain (see SM).

Ocean-Atmosphere (circulation)

North Atlantic sub-polar gyre / Labrador-Irminger Sea convection (LABC). Convection in the Labrador and Irminger Seas in the North Atlantic – part of the sub-polar 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 1.1-2.0°C, and in one additional model run at 3.8°C (*19*, *65*), and in four CMIP6 models in the 2040s (~1-2°C) (*66*). In some models SPG collapse affects AMOC strength, but SPG and AMOC have distinct feedback dynamics, 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 ~2-3°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 (1.1-3.8°C) [high confidence], timescale of 10y (5-50y) [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 due to 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, slowing down the AMOC by inhibiting deep convection. The AMOC is inferred from some reconstructions to have weakened by ~15% over the last ~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 SROCC (*22*) assessed AMOC collapse occurring during the 21st century to be “very unlikely, but physically plausible”, but this was increased to unlikely (medium confidence) in AR6 (*21*). AMOC collapse is triggered in three runs of one CMIP5 model at 1.4-1.9°C and in two runs of an additional model at 2.2-2.5°C (*19*, *65*) in contrast with gradual declines in other CMIP5 and CMIP6 models (*21*). However, AR6 assessed CMIP models as generally tending towards “unrealistic stability” with respect to observational constraints (*14, 21*). They also neglect meltwater forcing from rapid GrIS melt (*21*, *69*). Both factors make 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 and strengthening in Southern Hemisphere leading to drying in 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 best estimate threshold of ~4°C (1.4-8°C, vs. 3.5-5.5°C in (*1*)) [low confidence], timescales of ~50y (15-300y) [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) is reclassified as an uncertain climate tipping element because of a lack of evidence for a warming-related threshold behavior. **Equatorial stratocumulus cloud breakup** and **Indian Ocean upwelling** are uncertain, due to limited evidence. **Global ocean anoxia** is uncertain because the global warming level required for weathering-induced anoxia is unclear. The **El Nino Southern Oscillation** is reclassified as unlikely to be a tipping element, because it lacks a clear self-perpetuation threshold. **Arctic ozone hole expansion** is reclassified as unlikely because it is now unlikely to be triggerable due to 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 are discussed in the SM.)

Biosphere

Amazon rainforest (AMAZ). The Amazon forest biome stores ~150-200 GtC (*3*, *74*, *75*) and historically has been a strong sink for human CO_2 emissions (*15*). However, the sink in intact forests has declined since the 1990s (*15*), and ~17% of the Amazon forest has been lost to deforestation since the 1970s, accelerating 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 to lengthen in southern and eastern areas of the forest with 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 (80). This and localized fire feedbacks mean ~40% of the Amazon forest is estimated to currently be in a bi-stable state, increasing to ~66% on a RCP8.5 trajectory (*18*, *77*), and rainforest loss could initiate self-reinforcing drying that tip this portion into a degraded or savanna-like state. Widespread 'Amazon dieback' was originally projected at either 3-4°C of warming or ~40% deforestation (*78*), but uncertain synergistic interaction might lower the deforestation threshold to only ~20-25% (*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°C and 6.2°C (*19*). Additionally, CMIP5 ESMs underestimate observed tree mortality (*15*) and likely overestimate CO_2 fertilization (*81*), potentially making these models under-sensitive 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 (2-6°C) independent of deforestation (likely lower with deforestation) [low confidence], timescales of 100y (50-200y) [low confidence], and partial dieback (40%, i.e. currently bistable area) leading to emissions of ~30 GtC and along with biogeophysical feedbacks (see SM) to a GMST feedback of ~+0.1° (regional +0.4-2°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 like hydrological changes, increased fire frequency, and bark beetle outbreaks can lead to self-reinforcing feedbacks driving regionally synchronized forest dieback (of the order of 100km) to a grass-dominated steppe/prairie state (*83*). Models project regime shifts starting in this area at ~1.5°C and becoming 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 (1.4-5°C) [low confidence], timescales of 100y (50-?y) [low confidence], and partial (~50%) dieback leading to emissions of ~52 GtC, which along with countervailing biogeophysical feedbacks (increased albedo, reduced evapotranspiration) leads to a net GMST feedback of ~-0.18°C [medium confidence] (regional ~-0.5-2°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 via albedo feedback. Models suggest regime shifts 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 (1.5-7.2°C) [low confidence], timescales of 100y (40-?y) [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 ~+0.5-1°C) [low confidence].

Sahel vegetation & the West African monsoon (SAHL). Palaeo-evidence 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*). In 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, CMIP6) and some regional (CORDEX) climate models tend to predict strengthening of the WAM, and wetting and northward expansion of the central and eastern Sahel (and 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 2.1-3.5°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, 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 (2-3.5°C) [low confidence], timescale of 50y (10-500y) [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, impacting the wider marine food web, ocean nutrient and carbon cycling, and livelihoods for millions of people worldwide (*92*). Although coral bleaching is a localized process, synchronous bleaching can occur at ~1000km 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 70-90% tropical/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 (1-2°C) [high confidence], timescales of ~10y [medium confidence], and negligible GMST feedback [high confidence].

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

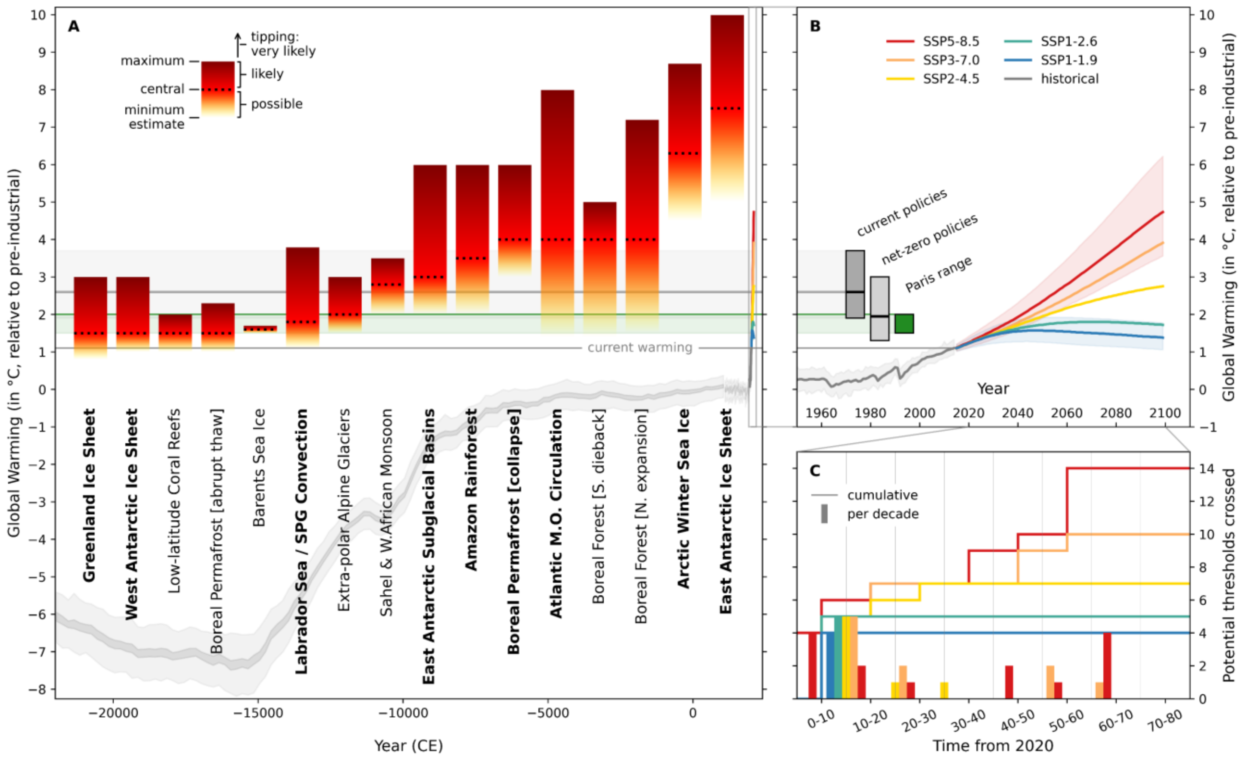


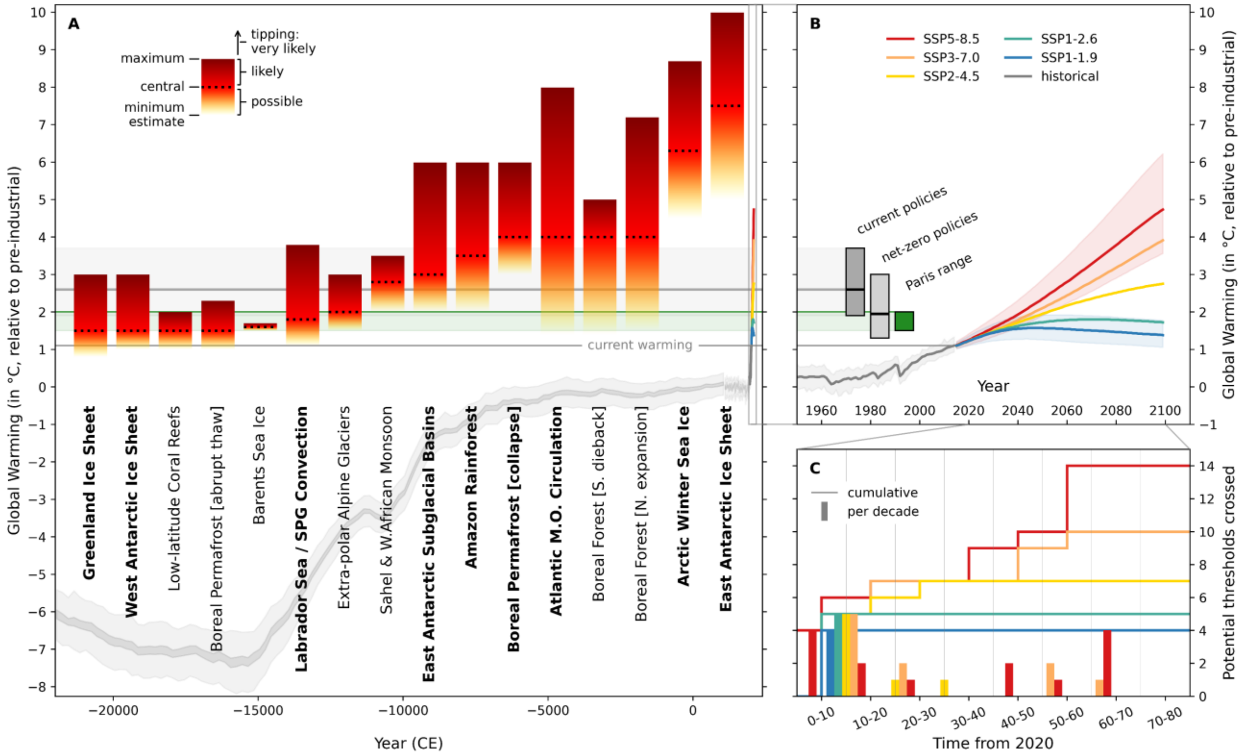
Fig. 2a summarizes our temperature threshold estimates for each tipping element making the shortlists (others are summarized in the Supplementary Text). Here we define crossing a CTP as 'possible' beyond its minimum temperature threshold and 'likely' beyond its central estimate.

[Fig. 2]

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 damages to future societies. Such a risk minimization approach 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 1.1-1.5°C range. Our best estimate thresholds for GrIS, WAIS, warm-water corals (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 ~1°C is a level of global warming that minimizes the likelihood of crossing CTPs. This is consistent with the <0.5-1°C range of Holocene temperature variability, whereas past interglacials ≤1.5-2°C had up to 10-13m 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. 2b & 2c). Nevertheless, achieving the Paris Agreement aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (*90*) (



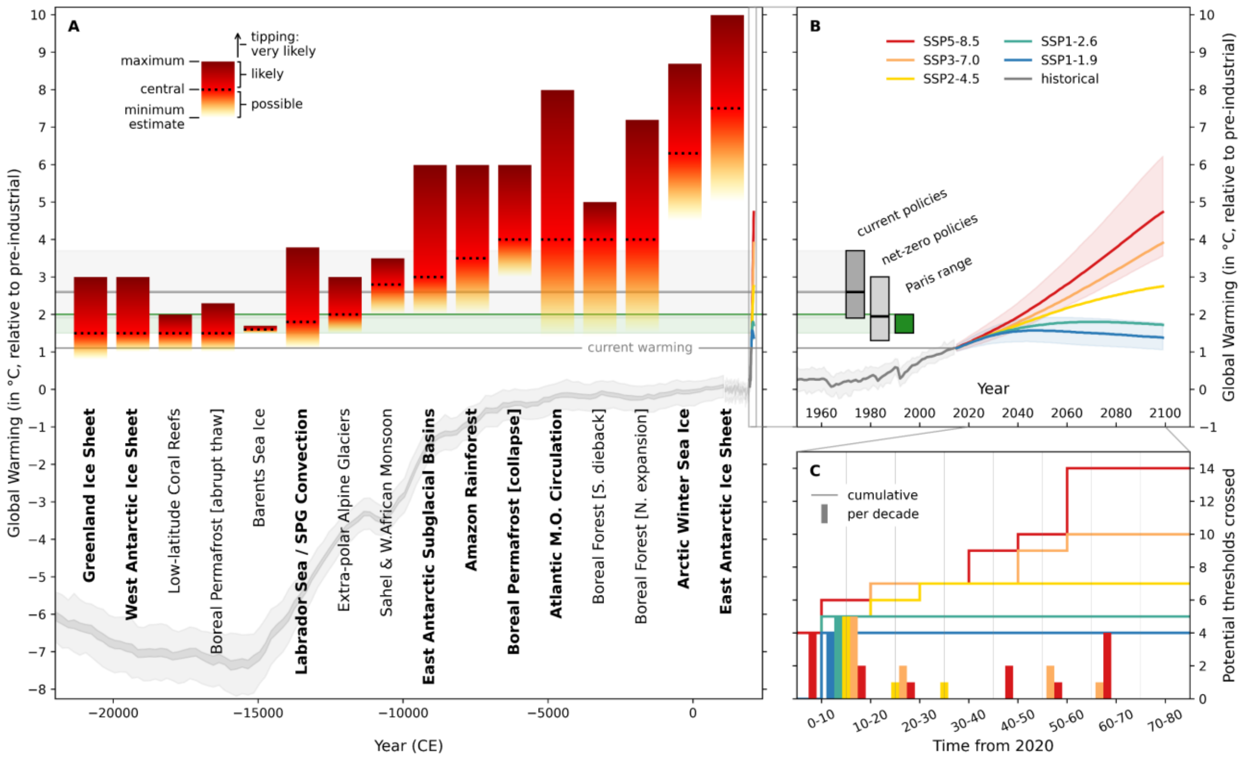


Fig. *2*). Going from 1.5 to 2°C, the likelihood of committing to WAIS and GrIS collapse, near complete warm-water coral reef die-off, and abrupt permafrost thaw increases, and the best estimate threshold for LABC collapse is also crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, 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 1.5-2°C (*19*). While 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 significant by 2°C.

Recent “Net Zero” targets if implemented could limit peak warming to ~1.95°C (1.3-3°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*). 2-3°C by 2100 is therefore 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 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. Sub-polar gyre collapse, boreal forest dieback, and AMOC collapse also become more likely. While 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 (1.4-8°C range), and Arctic winter sea ice collapse becomes possible >4.5°C. Warming of >5°C, whilst 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 ~55m 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 Arctic winter sea ice 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 via 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), and the transition timescale of many elements is uncertain. 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 like ice sheets (*94*), but the allowable overshoot times need further research. Spatial pattern formation might allow some biosphere elements to evade directly 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 inter-comparison project could help identify more candidate tipping elements and refine assessment of their likelihood. Further model improvements and model-data inter-comparison 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*). They 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 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-<2°C warming. Current policies leading to ~2-3°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.

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Acknowledgements:

Funding:

This work was initiated and supported by the European Research Council Advanced Investigator project "Earth Resilience in the Anthropocene" ERC-2016-ADG-743080 (DIAM, AS, SC, IF, JR)

This work is part of the Earth Commission which is hosted by Future Earth and is the science component of the Global Commons Alliance. The Global Commons Alliance is a sponsored project of Rockefeller Philanthropy Advisors, with support from Oak Foundation, MAVA, Porticus, Gordon and Betty Moore Foundation, Herlin Foundation and the Global Environment Facility. (DIAM, JFA, RW, BS, SL, JR)

Leverhulme Trust RPG-2018-046 (TML, DIAM)

Turing Fellowship (TML)

Author contributions:

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Investigation: DIAM

Validation: AS, JFA, RW, BS, IF, TML

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Writing – review & editing: DIAM, AS, JFA, RW, BS, SL, IF, SEC, JR, TML

Competing interests: The authors declare no competing financial interests.

Data and materials availability: All data are available in the manuscript or the supplementary materials

Supplementary Materials:

Materials and Methods

Supplementary Text

References (*101-#*)

Tables S1-S4

Data S1 (Climate Tipping Elements Database)

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Figures and Tables:

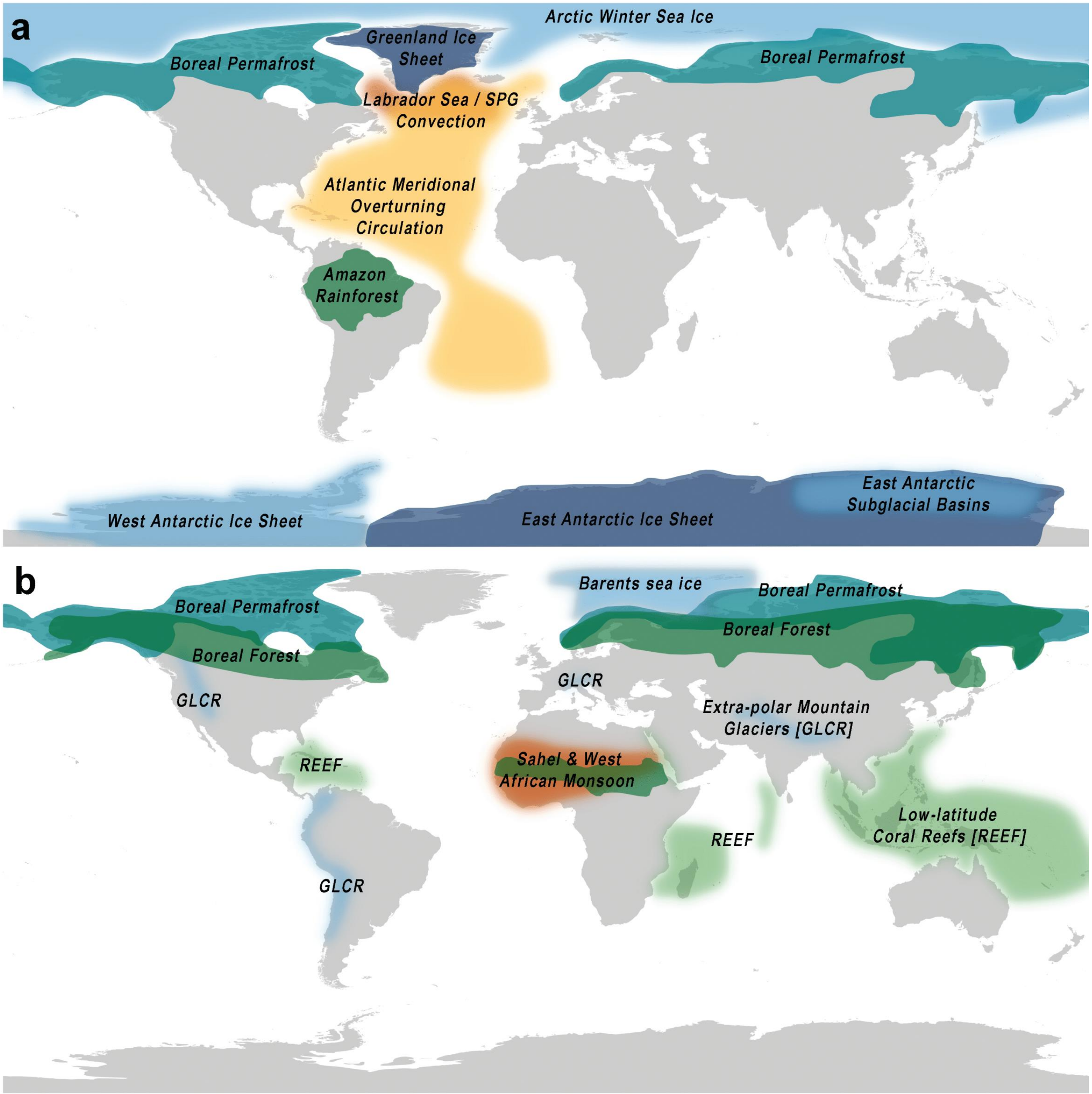

Fig. 1. Maps showing the global 'core' (a) and regional 'impact' (b) climate tipping elements identified in this study. Blue areas represent cryosphere elements, green biosphere, and orange ocean-atmosphere.

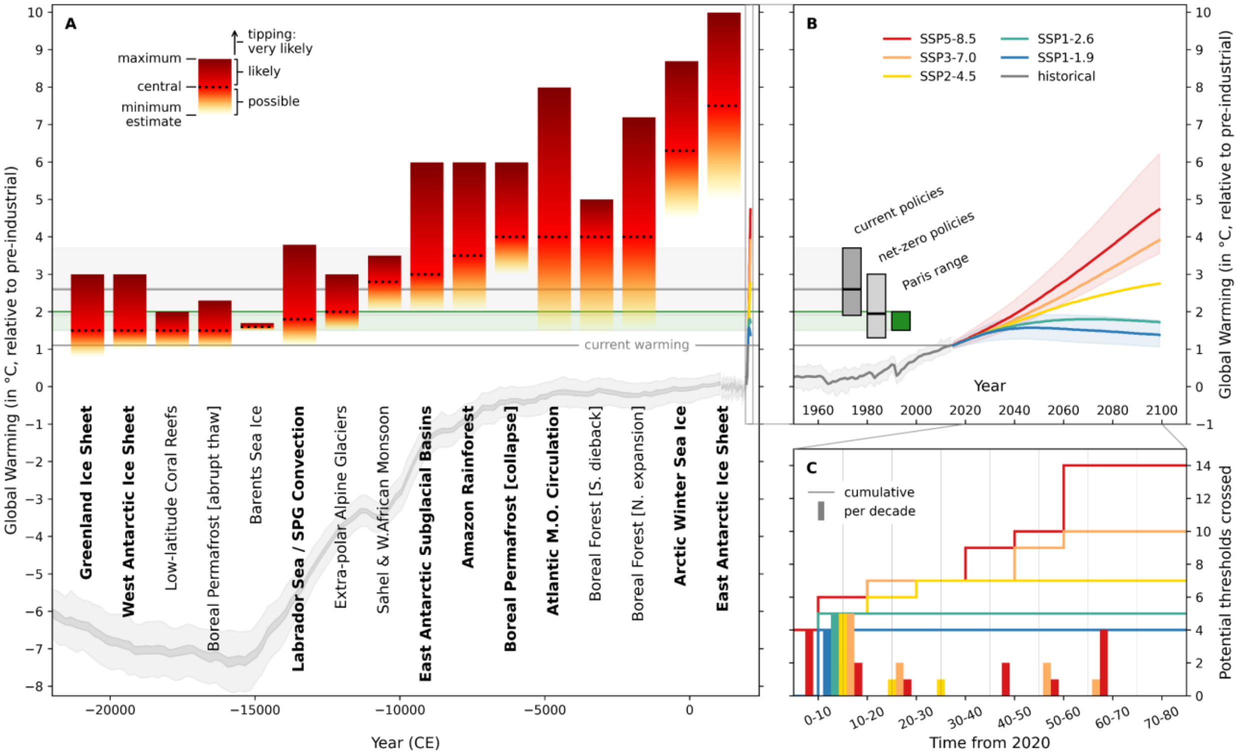

Fig. 2. Our global warming threshold estimates for global 'core' and regional 'impact' climate tipping elements (a) relative to IPCC SSP projections and likely future scenarios given current policies and targets (b) and how many thresholds may be crossed per SSP projection (c). Bars in (a) show the minimum (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 palaeorecord of Global Mean Surface Temperature (GMST) over the past ~25ky (*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 (grey 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-<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).

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 indicates elements featured in previous climate tipping element characterizations.

Category	**Proposed Climate Tipping Element [& 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/ 00.04°C per °C @2100; ~25 GtC/35 GtCe/ 00.11°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 & 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 pre-industrial and declines with further degrees of warming (by ~21% per °C).