Science
AAAS

# Supplementary Materials for

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

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*Science* **377**, eabn7950 (2022)
DOI: 10.1126/science.abn7950

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**Other Supplementary Material for this manuscript includes the following:**

Data S1

## 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 (Supplementary Table S3). For each we extracted information on evidence for self-perpetuation, temperature thresholds, hysteresis/irreversibility, transition timescales, and global/regional impacts on climate, which we then use subjective expert judgment to determine our best estimates. From this evidence (or lack of it) we drew up shortlists (Main text Table 1) of 'core' global tipping elements and regional 'impact' tipping elements (Main text Fig. 1), for which we summarize the rationale in the main text and Supplementary Text S2 & S3. Candidates that did not make the shortlists (Supplementary 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 non-feedback response to climate change; and (c) 'threshold-free feedbacks' – where feedbacks 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 to past lists of tipping elements are described in Supplementary Table S4.

## Supplementary Text

### S1) Climate tipping points and elements definition

The technical definition for a climate tipping point (CTP) provided by (*1*) is as follows: a tipping point is a critical point ($\rho_{crit}$) in a (forcing) 'control parameter' ($\rho$) at which a small additional perturbation ($\delta\rho>0$) causes a qualitative change ($\hat{F}$) in the future state of a system after some system-specific observation time ($T>0$):

$$|F(\rho \geq \rho_{crit} + \delta\rho|T) - F(\rho_{crit}|T)| \geq \hat{F} > 0$$ **Equation 1**

Assuming that the control parameter can be related to global temperature, a "small" additional perturbation was taken to be $0<\delta\rho<0.2$ °C, i.e., within natural temperature variability or 10% of the 2 °C Paris Agreement limit (*1*). A "qualitative change" in system state is taken to mean one that is significantly larger than the standard deviation of natural variability (of that system variable). It has been specified for some tipping elements in past expert elicitation (*4*) and is described in each case below. It may represent a fundamental change in the (balance of) feedbacks maintaining the new state (versus the old), i.e., a change in dynamical attractor. The observation time over which qualitative change is observed can range from ~10y for e.g., monsoons, to ~10ky for ice sheets. Additional requirements for the climate tipping element to be considered policy-relevant were: for its tipping point to be triggered by human activities within a 'political' time horizon ($T_P$ = <100y in (*1*)); for observed qualitative change in the tipping element to occur within an 'ethical' time horizon ($T_E$ = ~1000y in (*1*), here extended to ~10ky to better account for slower but irreversible ice sheet change), and; for a "*significant number of people care about the fate of the [tipping element], because it contributes significantly to the overall mode of operation of the Earth system (such that tipping it modifies the qualitative state of the whole system), it contributes significantly to human welfare (such that tipping it impacts on many people), or it has great value in itself as a unique feature of the biosphere*". Here we adjust these final criteria, adding that tipping impacts >100 million people for human welfare, and expand from biosphere to the whole Earth system for unique valuable features, and note that near-synchronous, large-scale crossing of smaller-scale tipping points that would otherwise be categorized as regional impact elements can qualify as a global core element if it amplifies warming by >0.1°C.

A key additional requirement in our updated definition is a clearly defined self-perpetuation mechanism, so that if the original forcing (e.g. global warming) stopped the system change will tend to carry on until a qualitative change in system state is reached. Such self-perpetuation requires active countering in order to stop, but unlike some definitions, irreversibility is not specified. Some authors use 'tipping point' as a synonym for catastrophic fold bifurcations or basin boundary crossings in systems featuring hysteresis and alternative stable states. These certainly meet the definition, but self-perpetuating change to a new system state can also occur across non-catastrophic thresholds with and without bifurcations or reversibility (*102*, *103*) (*27*).

For example, crossing non-catastrophic cusp, trans-critical, or Hopf bifurcations can all trigger critical transitions and self-perpetuating change (mathematically, in these bifurcations the real part of the system's eigenvalue reaches zero, representing the transition from stabilizing net-negative feedbacks to destabilizing net-positive feedbacks (*103*–*106*)) often (but not always) resulting in instability detectable by resilience indicators (*102*, *103*, *107*–*110*). A degree of self-perpetuation can also occur in reversible cases without a true bifurcation (or the real part of the system's eigenvalues, i.e. net-negative feedbacks, reaching zero); for example if the system's response to strong forcing across a non-catastrophic threshold is lagged leading to the system overshooting the threshold, this would result in a substantial non-linear readjustment to the equilibrium.

## S2) Climate tipping points and elements definition

In this section we explain how we arrived at our estimates for tipping thresholds, timescales, and impacts in Data S1 (Climate Tipping Elements Database), as well as the basis for our confidence level for each and for the overall tipping element categorization. Confidence levels are based on IPCC's confidence rating system as a product of the authors' judgements of both the robustness (the type, amount, quality, and consistency of the evidence available) and the degree of agreement of the assessed literature, giving five confidence level qualifiers: very low, low, medium, high, and very high (*101*).

### S2.1) Cryosphere

**Greenland ice sheet (GrIS).** We take qualitative change for GrIS collapse to be loss of the majority of its volume of ~7m SLE (*38*, *44*). Threshold estimates for GrIS of 1.5°C (0.8-3°C) largely follow (*39*), with additional support for a best estimate of ~1.5°C from both modelling and palaeorecords (*40*, *43*, *44*, *111*, *112*). Negative surface mass balance from 2000-2005 (at regional warming of ~2°C, i.e. at ~0.8°C GMST) and early warning signals from Central-west Greenland after regional 2°C provide a lower threshold bound (*11*, *37*). For the upper bound, (*44*) indicates 5m of sea level rise equivalent (SLE) from GrIS is locked in at >3°C, (*64*) indicates that ~2.5°C is likely sufficient for collapse in >10ky and ~4.5°C is sufficient for collapse within 6ky (so we estimate >3°C is therefore potentially sufficient for GrIS collapse in <10kyr), palaeoclimate data suggests past GrIS and WAIS retreats occurred in the 300-400 ppm $CO_2$ range (i.e. ~0.5-2.5°C at an Earth system sensitivity of ~6°C per $CO_2$ doubling, but also depending on orbital forcing) (*42*), and IPCC AR6 assess >3°C as leading to near complete GrIS loss over multiple millennia (and that >2.5°C was sufficient for this in the mid-Pliocene Warm Period), so we tighten the upper bound to 3°C. We give the GrIS threshold range *high confidence* based on multiple consistent estimates from different evidence bases (modelling and palaeorecords).

We adopt a central estimate of ~10ky for GrIS timescale from (*40*), lowering the minimum timescale to ~1ky following (*42*, *113*) and raising the maximum to ~15ky based on palaeorecords and models of GrIS collapse in MIS11 (*111*, *114*) – greater scatter in timescale estimates in the literature lead to our estimate of *medium confidence*. For impacts, we rely on the results of (*115*) – limited literature here result in *low confidence* for GrIS impacts. Multiple different models indicate the existence of a threshold beyond which GrIS collapse becomes inevitable as a result of self-perpetuating feedbacks such as the melt-elevation feedback, while both models and palaeorecords indicate GrIS has strong hysteresis and bistability. However, (*44*) suggest that the threshold may not be abrupt, although they do still find hysteresis and irreversible loss beyond 3-4m SLE at ~2-2.5°C and so our CTP definition is still satisfied. Together, this indicates *high confidence* in GrIS having a CTP, and we categorize it as a global core element based on its substantial sea level impact and importance for defining the current Earth system as being in a bipolar icehouse state.

**Arctic winter sea ice (AWSI).** We take qualitative change for AWSI collapse to be less than 1M $km^2$ of sea ice remaining in March (*32*). Threshold estimates of 6.3 (4.5-8.2)°C for AWSI largely follow the range found for models featuring abrupt shifts in CMIP5 (*19*), with the upper bound increased to 8.7°C in line with the central estimate from all models of (*32*, *116*). Timescale estimates of 20 (10-50) years are estimated from (*32*), with the upper bound extended to 100 years to match some shifts observed in (*19*). The quantity of models involved provides *high confidence* for the threshold and timescale ranges. Global impact of ~0.6°C is based on several estimates (*116*–*118*) and so has *high confidence*, but regional impacts of an additional ~0.6-1.2°C are based on scaling the ratio between regional and global impacts for Arctic Summer Sea Ice (ASSI) (an extra ~0.25-0.5°C relative to global 0.19-0.3°C (*115*)) and so has *low confidence*. Support for AWSI featuring self-perpetuating feedback mechanisms driving the abrupt shifts and potential hysteresis and rate-dependence come from (*20*, *31*). A reversible non-catastrophic threshold not driven by self-perpetuating feedbacks has also been proposed (*119*), but has been critiqued as being unable to explain the spread in abruptness seen across CMIP5 models (*31*). Based on this we assign *medium confidence* to AWSI having a CTP, with a clear global impact via global warming feedback and loss of unique ice-associated ecosystems.

**West Antarctic ice sheet (WAIS).** We take qualitative change for WAIS collapse to be loss of the majority of WAIS's volume of ~3-5m SLE (*7*, *25*, *120*, *121*). We estimate the WAIS threshold to be 1.5°C (1-3°C) based on a mixture of palaeorecords, observations, and modelling. Palaeorecords indicate that WAIS retreats previously occurred when $CO_2$ was 300-400ppm (i.e. ~0.5-2.5°C at an Earth system sensitivity of ~6°C per $CO_2$ doubling, but also depending on orbital forcing) (*42*), and likely occurred during previous interglacials (including the Last Interglacial; LIG) at around ~1-1.5°C (*46*, *50*, *120*). The upper bound of the latter provides our central estimate, on the basis that collapse would unfold very slowly at the threshold. The upper bound is supported by future model projections finding that long-term WAIS collapse could be committed by ~2.7°C (*64*) or at ~2-3°C (*122*), 2-2.7°C (*123*, *124*), or 2.5-3°C (*40*), as well as palaeoclimate models and records indicating no WAIS during the warm Pliocene (~3°C) (*125*, *126*). Including Marine Ice Cliff Instability (MICI) in models results in near-term WAIS collapse by ~3°C (*51*, *127*) or in the equally warm Pliocene (*128*), although the importance of MICI is debated (*49*, *129*). Some of these are likely over-estimates as the models involved may not have been run for long enough for observed retreats on lower warming pathways to progress to full collapses within the modelled time (e.g. (*124*, *130*)). The lower bound of 1°C is supported by: the lower temperature bound during LIG (*46*, *50*); recent observations that ice shelf retreat around WAIS is progressing rapidly (*131*–*135*) (although ice shelf retreat could be slowed by pinning points and does not necessarily trigger ice sheet collapse) (*136*, *137*); modelling suggesting that current melt rates might be enough for self-sustained grounding line retreat to occur (*7*) and at least partial collapse when run to equilibrium (*25*); and observations that grounding lines may already be close to this threshold (*8*, *138*), with rapid grounding line retreat close to the retrograde slope in the Thwaites and Pine Island glaciers (*9*, *10*, *139*) and modelling suggesting that although irreversible retreat is not currently occurring in Antarctica long-term irreversible retreat in the Amundsen Sea Embayment cannot be ruled out for current climate conditions (*140*). We give the WAIS threshold range *high confidence* based on multiple consistent estimates from different evidence bases (modelling, observations, and palaeorecords), which is in contrast to the IPCC's assessment of limited evidence for complete WAIS loss at 2-3°C (although substantial long-term losses are projected in this range) (*21*).

Our central WAIS timescale estimate of 2ky is based on palaeorecords from the LIG which suggest 1-1.5°C resulted in WAIS collapse over ~2ky (*46*), which is mirrored by some future modelling (*50*, *64*) and the upper end of (*42*)'s Earth system equilibration time to $CO_2$ changes. The upper timescale bound of 13ky is provided by (*7*), and is mirrored by several other modelling studies showing collapse timescales of ~10ky when the threshold is only marginally transgressed (*40*, *50*, *122*). The lower timescale bound of 500y is from models forced by very high emissions (*64*, *121*) and also reflects some of the faster collapses resulting from including MICI in models (*51*, *127*, *128*) and the lower end of (*42*)'s Earth system equilibration time to $CO_2$ changes. We give *medium confidence* for WAIS tipping timescale given the variation seen across the modest number of long-term modelling studies available. Tipping impacts of ~0.05°C globally and ~1°C regionally are primarily based on (*115*) with some indirect support from (*126*, *141*), but we assign *low confidence* given the limited number of studies. Multiple studies provide support for WAIS featuring a self-perpetuating tipping mechanism in the form of the Marine Ice Sheet Instability (MISI) (e.g. (*7*, *8*, *25*, *40*, *50*, *142*)) and to a more debated extent MICI (*49*, *51*, *127*–*129*), and some also find hysteresis (*25*, *46*) (although it is not evident in long-term palaeorecords, possibly the result of insufficient temporal resolution for faster-timescale ice sheets (*42*)), providing *high confidence* that WAIS features tipping dynamics. The significant impact of WAIS collapse on sea level categorizes it as a global core element.

**East Antarctic subglacial basins (EASB).** We take qualitative change for EASB collapse to be loss of the majority of the ice volume for either the Wilkes, Aurora, or Recovery Basins (~3m SLE each) (*25*). We estimate the EASB thresholds to be 3°C (2-6°C) based on a combination of palaeorecords, modelling, and observations. Ice sheet collapse occur in models for the Wilkes Basin – the EASB with the greatest losable ice volume (*143*) – in scenarios warmer than RCP6.0 (at 3.6-3.9°C) in (*40*), beyond ~3°C in (*122*), and in the 3-6°C range in (*25*), while the Aurora basin is lost in scenarios warmer than RCP8.5 (at peak 4.6-4.9°C) in (*40*), by ~5.5°C in (*122*), and in the 6-8°C range in (*25*). In contrast, (*124*) find that both Wilkes and Aurora collapse only occurs beyond RCP 6.0 (>4.5°C) and (*121*) find that holding RCP8.5 warming at 2100 levels (~4.3°C) until 3000CE triggers Wilkes and Aurora retreat only in extreme sub-shelf melt parameterizations, while another modelling study found substantial long-term losses from both WAIS and EASB by ~2.7°C (*64*). Models resolving MICI feature future EASB collapse triggered by 2100 in RCP8.5 (i.e. at <5°C) but not at ~3°C by 2300 (although collapse at this level cannot be ruled out on longer timescales, and occurs when maintained long-term around this level in the Pliocene) (*51*, *127*). Palaeorecords suggest a more mobile portion of the EAIS grows and retreats alongside WAIS and GrIS in the 300-400 ppm $CO_2$ range, (i.e. ~0.5-2.5°C at an Earth system sensitivity of ~6°C per $CO_2$ doubling, but also depending on orbital forcing) (*42*), supporting the possibility of EASB retreat below 3°C. Palaeorecords and models of the warm Pliocene indicate EASB retreat by ~3°C (*125*, *126*, *128*, *144*), with some contribution from EAIS (likely via EASBs) postulated as necessary to fit sea level records (*42*, *51*, *128*, *145*), although this interpretation is not universal (*49*) and MICI depends on glacier geometry (*129*) and the loss of an ice 'plug' for Wilkes Basin (*143*). In contrast, substantial EASB retreat is not found for previous interglacials such as LIG (~1-1.5°C) in palaeorecords (*42*) or models (*50*, *51*), supporting a lower threshold bound between ~1.5°C and ~3°C. Current observations also support current warming being insufficient to drive significant grounding line retreat in the EASBs (*140*). Based on the above, we assess palaeo and observational evidence as supporting a lower bound around 2°C (i.e. between LIG and Pliocene levels and above now), a central estimate at 3°C representing model and palaeorecord support for substantial retreat in at least the Wilkes Basin, and an upper bound of 6°C for Wilkes collapse being very likely in models and palaeorecords with Aurora Basin collapse also likely to have begun. Our range also aligns with the AR6's assessment that at 3-5°C "substantial parts or all of Wilkes Subglacial Basin in East Antarctica will be lost over multiple millennia" (*21*). Given moderate model spread and palaeorecord uncertainty though, we assign only *medium confidence* to these estimates.

For EASB timescales, we take 2ky as our central estimate based on (*64*, *128*), the lower bound of (*40*), and AR6's estimate of 1-2.5ky for the response timescale of Wilkes Basin during LIG (*21*). The upper bound of 10ky is based on Pliocene palaeorecords (*144*) and the upper bound or best estimate of several modelling studies (*40*, *64*, *122*, *143*), while the lower bound of 500y is from models incorporating MICI or under a very high warming scenario (*64*, *127*, *128*). Given the literature variability here, we assign *medium confidence* to this timescale range. There are no direct estimates for warming impacts of EASB collapse, with (*126*) constraining the global impact of reduced GrIS, no WAIS, and no EASBs to 0.3d°C together with high spatial heterogeneity, and so we assume a similar global impact to WAIS loss (~0.05°C (*115*)) and assign *low confidence*. As with WAIS, multiple studies provide evidence of self-perpetuation dynamics once beyond a global warming threshold for EASB via MISI (*50*, *51*, *124*, *142*) and potentially MICI (*49*, *51*, *127–129*), with additional evidence of hysteresis (*25*, *143*) and potential rate-dependence (*143*). On this basis, we assign *high confidence* that the EASBs feature tipping dynamics, and their significant impact on sea level categorizes them as a global core element.

**East Antarctic ice sheet (EAIS).** We take qualitative change for EAIS collapse to be loss of the majority of EAIS land-based volume of ~40-45m SLE (*25*). The central estimate of 7.5°C for EAIS collapse is based on both the modelling of (*25*) and the palaeorecord compilation of (*42*), with additional support from the lower and upper bounds respectively of (*122*) and (*64*). The lower bound of 5°C is based on the modelling of (*40*) which found large-scale EAIS retreat in scenarios warmer than RCP8.5, as well as the lower bound of (*64*) in which scenarios peaking at more than 5°C result in at least two thirds of the EAIS being lost over 10ky with loss continuing beyond that. The upper bound of 10°C is provided by the modelling of (*25*), beyond which minimal ice remains on Antarctica at equilibrium, and palaeorecords suggesting minimal EAIS volume above ~1200 ppm $CO_2$ (i.e. ~10°C at a long-term Earth system sensitivity of 6°C per $CO_2$ doubling). Palaeorecords and modelling indicate substantial EAIS hysteresis, with substantial ice sheet growth once temperatures go below ~5-7°C GMST but able to survive if temperatures subsequently rise beyond that to ~8-10°C (*25*, *42*, *53*, *146*) – this provides additional support for using 5°C as a lower threshold bound in case EAIS hysteresis is over-estimated (and the collapse threshold is unlikely to be below the formation threshold). We therefore assign *medium confidence* to our threshold range of 7.5°C (5-10°C) based on mixture of modelling and palaeoclimate evidence from a modest number of studies, which overlaps with AR6's assessment of a commitment to an ice-free Earth at 7-13°C (*21*).

EAIS tipping timescales of at least 10ky are reported from several modelling studies (*40*, *64*, *122*) while EAIS formation likely took place in ~40ky steps (*146*–*148*), and so we use 10ky as our lower bound with *medium confidence*, but few high-resolution models have been run long enough to fully resolve EAIS collapse timescales at different forcing levels to establish the upper bound (for which we assign *low confidence*). For tipping impacts on warming, we use ~0.6°C for global and ~2°C for regional from the SI of (*115*), and as it is only from one study we assign *low confidence* for impacts. There is some evidence for self-perpetuation of EAIS collapse through e.g. the melt-elevation feedback (*25*, *40*, *64*), although this has not been fully tested, and strong evidence for EAIS hysteresis (*25*, *42*, *53*, *146*), and so we assign *medium confidence* for EAIS acting as a tipping element. EAIS collapse would have a very substantial impact on the Earth system through sea level rise and the end to the current icehouse state, justifying its inclusion as a global core element.

**Mountain glaciers (GLCR).** We take qualitative change for GLCR to be the loss of the majority (>50%) of glaciers outside Greenland and Antarctica. GLCR does not have one systemic global tipping point, as each glacier has its own local thresholds and feedback dynamics, but there appear to be global warming levels at which many of these thresholds are near-synchronously passed. "Peak Water" from meltwater as a result of glacier melt is projected to occur globally at around 2°C (with some spatial heterogeneity), implying eventual disappearance for many of these glaciers (*62*), while 2°C is sufficient to commit near-total loss of European glaciers (*20*). Modelling by (*64*) suggests warming of ~2.7°C will lead to ~68% of extra-Antarctic glacier mass being lost after 200 years (and more if Arctic is excluded), committing total glacier loss across many non-polar regions. Another modelling study indicated that ~65% of glaciers outside

Greenland and Antarctica are committed to be lost at ~2°C and ~75-80% lost by ~3°C (*149*). Additional support for an upper bound of ~3°C is provided by a recent assessment of future glacier mass loss across multiple glacier models (*150*) the median loss is ~18% by 2100 and some small glacier regions semi-stabilize in RCP2.6 (max. ~1.6°C), but under RCP4.5 (~2.4°C) and above the rate of mass loss continues to increase up to 2100, and under RCP8.5 (~4.3°C by 2100) the global median loss by 2100 is ~36% and reaches >85% in some small glacier regions (e.g. the Rocky mountains, Europe, and low latitudes) and ~70% in Central and South Asia. Many of the glaciers in these regions would therefore likely be lost beyond 2100 in higher emission scenarios, with the modelling of (*40*) showing all glaciers (including polar glaciers) were eventually lost on millennial timescales at 1.7°C, supporting the lower bound of 1.5°C. Even at ~1°C around 36-45% of glacier mass loss may already be committed (*149*), although at this level mass would likely stabilize in the long-term. On this basis, we estimate GLCR thresholds to be 2°C (1.5-3°C) with *medium confidence*, with 2°C reflecting commitment to widespread loss in small glacier regions across the globe. This corresponds with AR6's assessment (with low confidence) that 40-50% of glacier mass outside Antarctica (but including the Arctic) will be lost at 1.5-2°C, 50-60% by 2-3°C, and 60-75% at 3-5°C (the latter corresponding with near-total loss across many extra-polar regions) (*21*). For timescales, we take 200y for our central estimate from the stabilization time for the lowest scenario in (*64*) as well as the total loss horizon being beyond 2100 in most cases in (*150*), although in some cases for the latter mass loss under RCP8.5 could be complete in only ~50 years (providing our lower bound). Our upper timescale bound is provided by the long-term modelling of (*40*) –being from only one model gives a lower confidence than for the central/lower estimates (*low* vs. *medium confidence*, respectively). For warming impact, we take the global estimate of 0.08°C of (*115*), and assign *low confidence* given limited studies. We assign *medium confidence* for GLCR being a regional impact tipping element, as although there is no single global threshold there is evidence from several studies for multiple regions being committed to glacier loss by ~2°C, which would have significant ramifications for people dependent on glacial meltwater in these regions.

**Boreal permafrost [collapse] (PFTP).** We take qualitative change for PFTP collapse to be the self-sustained thawing across ~1M km$^2$ (i.e. on the order of 1000km, as defined for tipping elements covering at least sub-continental scales) of the Circum-Arctic permafrost region affecting ~100 GtC in the Yedoma and other vulnerable regions. For PFTP, we base the threshold range on estimates for large regions of northerly permafrost experiencing abrupt drying at 4°C (3-6°C) (*58*), which puts this permafrost at greater risk of decay and internal heat production leading to self-perpetuating thaw (the "compost bomb" instability). Similar soil drying feedbacks occur in a CMIP5 model which leads to abrupt permafrost loss at ~5.6°C (*19*), supporting the upper bound of this range. Additional support for this range is provided by a detailed permafrost model in which local mean annual temperature breaching ~0°C (which would be widely reached across the carbon-rich continuous permafrost zones beyond warming of ~5°C GMST (*151*)) allows self-perpetuating thaw in carbon-rich permafrost (*61*), while the deep and carbon-rich Yedoma permafrost has been estimated to be at risk to abrupt thaw at ~9°C local warming (~5°C GMST)

(*17*, *152*) with abrupt thaw reaching the deepest Yedoma by 2300 under RCP8.5 (~5-10°C) (*153*). By ~6°C the vast majority of permafrost including the Yedoma region is committed to thaw, supporting our upper bound of 6°C (*151*). However, given the limited number of models capable of resolving deep abrupt thaw in Yedoma domain and uncertainties around the carbon pool available for degradation upon abrupt Yedoma thaw or the carbon pool at risk from abrupt drying, we assign *low confidence* to this threshold range. We estimate tipping timescales of ~50y (10-300y) on the basis of the abrupt permafrost loss observed in an Earth system model by (*19*) and the time taken for deep permafrost carbon release to become significant in an abrupt thaw-capable permafrost model (*153*), with the lower bound supported by abrupt drying in (*58*) occurring in as little as 15y and self-perpetuating heating becoming significant within 10y (*61*), and a higher upper bound supported by estimates for Yedoma collapse taking around a century to reach deeper deposits (*17*, *154*) and continuing until at least 2300 in a permafrost model (*153*) – we assign *medium confidence* for these timescales based on converging estimates from different models.

For PFTP impact, we assume that ~25-50% of carbon in the Yedoma domain (estimated at~400 GtC by (*59*), of which ~10% and a maximum of 40% is estimated to be at risk of decomposition over 50y, but with no abrupt thaw thermo-erosional processes which we assume increases carbon loss) and permafrost in regions subject to abrupt drying beyond ~4°C (2.2 $Mkm^2$ (*58*), i.e. ~15% of total permafrost area of ~15 $Mkm^2$ (*21*, *151*, *155*, *156*) which would contain ~155 GtC in the top 3m if scaled linearly from (*54*)) decomposes over 50 years (assuming abrupt drying (*58*) leads to enhanced decomposition (*54*, *157*, *158*) and fast thaw processes make deep Yedoma accessible (*54*, *59*)). This would release up to ~125-250 GtC, which when released at the ~4°C GMST threshold and accounting for amplification by partial methane release of ~40% (*153*) leads to ~0.2-0.4°C additional global warming. Given this is an inferred rather than modelled impact though and relies on multiple assumptions, we assign this impact estimate *low confidence*, as is our estimate of minimal regional warming impact (which assumes limited vegetation-climate feedbacks). We assign only *low confidence* for PFTP being a global core tipping element, as although there is evidence for a potential self-perpetuation threshold mechanism via abrupt drying, internal heat production, and abrupt thaw reaching deep Yedoma deposits (*58*, *60*, *61*, *94*, *152–154*, *159*, *160*) and the impact would be global, the possible extent of these mechanisms across the permafrost region has not been fully assessed.

**Boreal permafrost [abrupt thaw] (PFAT).** We estimate qualitative change for PFAT as being abrupt thaw area increasing by 50% (beyond the historical baseline of ~0.9M $km^2$, out of a total vulnerable extent of ~3.6M $km^2$ within the Circum-Arctic permafrost region (*57*, *161*, *162*)). We base the PFAT threshold range on estimates for gradual thaw (PFGT) on the assumption that their extent expands at a similar rate in models (*57*), and that the threshold represents when permafrost thaw becomes widespread. Our threshold range of 1.5°C (1-2.4°C) is based on palaeorecords showing thaw in non-continuous Siberian permafrost in the MIS-5 interglacial (~1-1.5°C, providing our lower bound) and substantial permafrost thaw during LIG (~1.5°C, providing our central estimate) (*55*, *163*), vegetation models indicating widespread abrupt ecosystem regime shifts to boreal forest in tundra regions (likely leading to amplified regional warming and permafrost thaw) by 1.5°C (*84*), permafrost-enabled Earth system models showing substantial permafrost thaw under RCP4.5 scenarios (~2.4°C by 2100 in CMIP5, providing our upper bound) (*164*–*166*) and in some cases under RCP2.6 (peak ~1.6°C in CMIP5) (*167*), and an assessment of permafrost distribution sensitivity indicating that 4.8 million $km^2$ of permafrost will be committed to loss at 1.5°C and 6.6 $Mkm^2$ at 2°C (*151*). Additionally, palaeorecords and modelling indicate mid-Pliocene warmth (~3.3°C) would result in the majority of alpine permafrost being lost (*168*), while Fennoscandia and Northwest Siberia will become unsuitable for permafrost-peatlands by ~1.7°C and ~2.8°C respectively (*169*). In contrast, methane budgets up to 2016-2017 show limited contribution by permafrost thaw to observed global methane increases, suggesting warming of ~1°C was insufficient to generate a significant permafrost-carbon feedback at least on decadal timescales (*170*, *171*). We assign this threshold range *medium confidence* as it incorporates robust evidence from multiple evidence streams. While localized PFAT is by definition abrupt (~10y), global aggregate PFAT timescales of 300y (100-300<y) follow estimates for (*57*) and PFGT (which is assumed to respond at a similar rate), in which around half of the modelled permafrost-carbon feedback occurs 2000-2100, the other half 2100-2300, and models rarely extending beyond 2300 (but a long tail of gradual long-term emissions likely) (*54*, *57*, *167*, *172*–*174*). Given the match between PFGT timescales and the PFAT estimates of (*57*), but also limited post-2300 modelling for constraining the upper bound and the lack of abrupt thaw processes in most models that could make timescales faster, we assign *medium confidence* to this timescale range for PFAT.

For PFAT impact, it has previously been suggested that abrupt thaw processes (such as slope slumping, thermokarst lake formation, erosion gullies, etc.) could up to double permafrost emissions from gradual thaw (*161*). (*57*) used permafrost inventory models to provide a first-order estimate ~80 GtC of permafrost carbon emissions due to abrupt thaw by 2300, amounting to feedback of ~2.3-3.1 GtC per °C from 2000 to 2100 (RCP4.5-8.5) and ~7.2-11.6 GtC per °C from 2100 to 2300 (RCP8.5-4.5 – note that emissions are greater for RCP4.5 in the long-term, indicating nonlinearity). Abrupt thaw results in greater methane amplification than for gradual thaw as methane reaches >20% of carbon emissions, accounting for ~75% of forcing at 2100 and ~50% of the forcing at 2300 (Fig. 2a in (*57*)). Adjusting the figures above by these ratios gives ~9.2-12.4 GtCe per °C and ~14.4-23.2 GtCe per °C by 2100 and 2300 respectively, resulting in ~0.03-0.06°C per °C at 2100-2300, i.e. an extra ~33% feedback versus PFGT. This is lower than the ~100% extra suggested by (*57*, *161*), as the gradual thaw emission estimates used for comparison in (*57*) were on the low side compared to the literature range assessed earlier ((*57*) quotes ~70.8 $GtCO_2$ / ~19.2 GtC emitted in 2000-2100 for RCP8.5, i.e. ~7.9 GtC per °C, versus ~57.4 GtC in 2010-2100 for RCP8.5, i.e. ~23.6 GtC per °C in the study (*175*) cited, and our synthesized estimate of ~20 GtC per °C by 2100). (*54*)'s expert judgement raised their estimate for permafrost carbon emissions from ~92 GtC from modelled gradual thaw to 130-160 GtC when accounting for unresolved processes, implying a greater ~58% (41-74%) amplification by abrupt thaw processes. Interactions of abrupt thaw processes with abrupt drying and carbon-rich Yedoma deposits could produce even more emissions in some regions, which we consider under PFTP. Based on these studies, we estimate that abrupt thaw adds an extra ~50% (25-75%) on top of gradual thaw emissions, which is 10 GtC / 14 GtCe / 0.04°C per °C by 2100 and 25 GtC / 35 GtCe / 0.11°C per °C by 2300. Given this is based on only two studies, one of which is a first-order estimate from modelling and the other an expert judgement, we assign *low confidence* to this impact estimate prior to further modelling. Abrupt permafrost thaw features self-reinforcing feedbacks such as thaw subsidence in thermokarst lakes and vegetation-albedo in wetlands (*57*), but these processes are relatively localized. However, the evidence summarized suggests that such localized tipping dynamics will become synchronously widespread beyond particular global warming levels. The lack of abrupt permafrost thaw in Earth system models means this has not yet been fully demonstrated in models – we therefore assign *medium confidence* for PFAT being a regional impact tipping element.

**Barents Sea ice (BARI).** We take qualitative change for BARI collapse to be <10% annual mean sea ice cover remaining (*19*). Our threshold estimates of 1.6°C (1.5-1.7°C) and timescale estimate (~25y) come from 2 models in (*19*), although as an assessment of abrupt shifts across 37 CMIP5 models we assign these *low confidence*. Quantitative estimates of regional and global warming impacts are lacking, but we assign *high confidence* to minimal global impacts but significant regional warming being likely (with the Barents sea region currently seeing experiencing warming of up to 2.7°C per decade (*176*)). We have *medium confidence* that BARI constitutes a regional impact tipping element based on some model evidence that collapse can be self-reinforced by an increased inflow of warm Atlantic waters (*19*, *33*, *34*) and has substantial regional impacts (*34*, *176*, *177*).

### S2.2) Ocean-Atmosphere (circulation)

**Atlantic Meridional Overturning Circulation (AMOC).** We take qualitative change for AMOC collapse to be an 80% decline in overturning strength (*1*, *178*). There is substantial uncertainty over the potential tipping threshold for the AMOC, which is reflected by our wide estimate range of 4°C (1.4-8°C). Support for our central estimate comes from modelling of long-term cryosphere change, in which warming greater than ~4°C along with GrIS collapse causes the AMOC to collapse (although it recovers after ~1000y once GrIS runoff reduces, suggesting collapse is reversible in this model) (*40*), and the post-CMIP5 model HadGEM3-GC2 which found rate-dependent weakening at freshwater forcing of 0.1-0.3 Sv but rapid rate-independent collapses after 0.3 Sv (which can be reached under RCP8.5, i.e. ~4.3°C (*179*)). The AMOCMIP assessment, which used CMIP5 models and an emulator incorporating improved GrIS runoff (*178*) assessed most AMOC collapses as occurring more gradually, with only one model showing a hysteretic-type collapse, and the ~80% weakening threshold for collapse becoming likely at ~8°C (providing our upper bound) with quasi-linear weakening rather than total collapse below ~4.5-5°C (*22*). However, CMIP5 and CMIP6 models likely tend towards over-stability (*21*) with a CCSM3 model bias-corrected to counter this exhibiting collapse at only ~1.5°C (*14*), a lower bound supported by two CMIP5 models showing abrupt collapses at ~1.9°C (*19*, *65*), along with the AMOC potentially having already declined by ~15% (*67*, *180*) (the value expected by ~2°C in AMOCMIP, although the observed trend is not yet possible to fully differentiate from natural variability (*181*, *182*)) and possible early warning signals of instability in AMOC fingerprint indices over the past century (*12*). Given the wide range and lack of agreement amongst models, as well as potential complexities from sensitivity to freshwater forcing location, rate-dependence, and a possibly 'fractal' threshold (*69*, *183*), we assign *low confidence* to this threshold range.

For AMOC collapse timescales, we adopt the 50y time horizon observed in models showing abrupt hysteretic-type collapses (*19*, *183*), with a lower bound of ~15y based on extreme (~1 Sv) forcing (*65*) and an upper bound of 300y based on the more gradual AMOC collapses observed in many models (*14*, *40*, *69*, *71*, *178*). We assess this timescale range as having *medium confidence* given their basis in multiple different models. We estimate AMOC collapse impact as being a global cooling of ~-0.5°C and regional North Atlantic cooling of ~-4°C (as well as localized cooling of up to ~-10°C in deep convection regions and see-saw warming in the Southern Ocean) (*14*, *65*, *69*) once the total impact is separated from LABC collapse (which is connected but collapses earlier) (*19*, *65*, *72*), which is supported by projections of ~-0.3°C global cooling and ~3°C regional cooling with a 40% AMOC weakening (*184*). We assign the regional impact estimate *medium confidence* as it is supported by multiple different models, but only *low confidence* for the overall global cooling as fewer models provide this estimate and it requires further investigation. There is considerable observational and model evidence that the AMOC is self-sustaining due to salt-advection feedback and palaeoclimate evidence for abrupt switches between alternative 'strong' and 'weak' AMOC stable states in the past (*68*), and that this feedback-driven bistability could lead to AMOC instability and collapse as a result of current warming (*12*, *14*, *19*, *69*, *183*). However, given model disagreement and uncertainty we assign *medium confidence* to AMOC being a climate tipping element. We categorize it as a global core element based on its substantial potential global impact.

**North Atlantic SPG / Labrador-Irminger Sea Convection (LABC).** We take qualitative change for LABC collapse to be a 50% decline in mixed layer depth over the SPG region (*19*, *65*, *66*). Threshold estimates for LABC of 1.8°C (1.1-3.8°C) were adopted from the CMIP5 assessment of (*65*), in which ~18% of models projected rapid SPG cooling independent of AMOC collapse and which covered some additional cases compared with the CMIP5 abrupt events database (*19*). A follow-up with CMIP6 found a ~36% risk of SPG collapse-triggered abrupt cooling (marginally lower than the ~46% found for CMIP5), which occurred in the low-emission SSP1-2.6 and SSP-4.5 scenarios in the ~2040s (i.e. at ~1.5-2°C GMST) and so supports the best estimate above (*66*). Given the agreement of several different models across both CMIP5 and CMIP6, we assign *high confidence* to this threshold range. Similarly we adopt timescale estimates of 10y (5-50y) based on abrupt cooling in CMIP5 and CMIP6 models (*19*, *65*), assigning *high confidence* based on model agreement. For impact, we adopt the ~0.5°C global cooling found in (*65*) by comparing model ensembles with and without SPG collapses. However, part of this difference could be due to non-uniform model sampling or climate sensitivities across the ensembles, and so we assign *low confidence* for this (and the regional cooling of ~3°C from (*19*, *65*)) prior to more systematic exploration of the impacts of LABC collapse. Potentially self-reinforcing convection feedbacks perpetuating warming-induced stratification giving rise to bistability have been identified, but as further exploration is needed to understand these feedback dynamics more fully we assign *medium confidence* for LABC being a climate tipping element. We categorize it as a global core element given its potentially substantial regional and global impacts.

## S2.3) Biosphere

**Low-latitude Coral Reefs (REEF).** We take qualitative change for REEF die-off to be a 90% loss of low-latitude coral reefs (*93*, *185–187*). Our threshold range of 1.5°C (1-2°C) for REEF is based on modelling studies in which 70-90% of warm-water coral reefs are severely degraded at ~1.5°C, after reaching a die-off threshold of bleaching event recurrence of twice a decade, reaching ~99% by 2°C (*93*, *186*). In a more recent analysis a different and slightly higher critical thermal threshold of 8 Degree Heating Weeks is reached around 2°C, providing support for this as an upper bound (*187*) (in this study bleaching events reach 3 a decade even at 1.5°C, higher than the 2 a decade at 1.5°C in (*186*)), while current local-scale thermal refugia in global coral reefs decline from 84% now to 0.2% at 1.5˚C (and 0% at 2.0˚C) (*185*) making ~1.5˚C catastrophic for coral reef ecosystems. Current observations support the lower bound, with mass bleaching events now occurring frequently across the tropics and for example in the Great Barrier Reef five times since 1998 (*187*). While there is some uncertainty about the exact bleaching threshold and the degree to which coral adaptation possibly affects it (*92*, *93*, *188*), we assign *high confidence* to the threshold range given current observations of increasingly frequent bleaching events and severe impacts by 1.5-2°C. We approximate the tipping timescale at 10y (*medium confidence*), as while bleaching can occur within a season the time from reaching a thermal threshold for a reef to die-off is unclear but likely short. We have high confidence that coral reef die-off has a minimal impact on global or regional warming, with impacts mostly severely affecting biodiversity and people dependent on reefs (*92*). There is clear evidence that coral die-off is self-perpetuating and irreversible beyond a threshold (with symbiotic algae being expelled often leading to coral death), but is localized to that reef system (*93*, *188*). However, given that localized tipping is projected to occur synchronously across low-latitude waters at a sub-continental scale (>1000km scale, e.g. the Great Barrier Reef) with substantial regional impacts, we assign *high confidence* to REEF being a regional impact climate tipping element.

**Sahel & the West African Monsoon (SAHL).** An exact definition for Sahel greening is unclear in the literature, but we take qualitative change for Sahel greening to be a biome shift (e.g. from desert to savanna or savanna to forest) across at least 1M km$^2$ (i.e. sub-continental scale) (*19*, *86*, *88*, *189*). We base our SAHL threshold range of 2.8°C (2-3.5°C) primarily on the temperature range in which abrupt shifts occur in CMIP5 models (*19*), with additional support for the lower bound from WAM shifts occurring beyond regional warming of 2°C in the early Holocene African humid period and future (*190*, *191*) and for the upper bound from other models showing Sahel greening during the 21$^{st}$ century but later declining under RCP8.5 (<4.3°C) (*91*, *189*, *192*, *193*) and in general statistically significant changes in regional precipitation is expected by 2.5-3°C (*23*).

However, as the range of (*19*) is based on only one CMIP5 model demonstrating abrupt shifts and that many models struggle to resolve West African Monsoon and vegetation shifts during the African humid period (*70*, *88*) or disagree on future trends (*189*, *193*), we assign only *low confidence* to this threshold range. For timescales we also follow the abrupt shift in (*19*) of ~50y and a lower bound of 10y, but based on Holocene palaeorecords of past abrupt monsoon shifts we extend the upper bound to 500y (*88*, *194*), and we assign *low confidence* to SAHL timescales for the same rationale as for the threshold estimates. Although abrupt greening would increase regional vegetation carbon storage, global impacts are likely to be minimal (*medium confidence* based on limited carbon storage in dry shrubland biomes, but prior to model confirmation), while regional impacts are expected to be significant but lack robust quantification (*low confidence*). There is some support from palaeoclimate studies for Holocene Sahel greening being associated with strong vegetation or dust feedbacks (*88*, *195*–*197*) potentially driving locally abrupt shifts but at differing times across latitudes (*194*), but as it has not yet been demonstrated to what extent these feedback-driven shifts are self-perpetuating we assign *low confidence* to SAHL being a regional impact tipping element.

**Boreal forest [southern dieback] (BORF).** We take qualitative change for BORF dieback to be a biome shift from forest to steppe (<50% tree cover) across at least 1M km$^2$ (i.e. sub-continental scale) (*83*–*85*). We estimate a threshold range for BORF of 4°C (1.5-5°C), with the central estimate provided by vegetation modelling showing abrupt ecosystem shifts in this region beyond ~3.5°C, becoming widespread by ~4°C, and very widespread by ~5°C (marking our upper bound) (*198*). IPCC SR1.5 (*90*) estimated boreal forest tipping at 3-4°C with low confidence based on previous assessments and modelling (*1*, *4*, *17*, *199*), but also assessed that tree mortality will increase along the southern boreal forest by 1.5°C. Together with a study taking an alternative climate niche approach to bypass vegetation model limitations which indicates substantial southern boreal forest retreat occurs by 2050 under RCP4.5 (i.e. at ~1.4°C) (*85*), and an emerging reversal in boreal forest greening at only ~1°C (*200*), this sets our lower bound of 1.5°C. Given the limited evidence base and emerging model-observation disagreements, we assign *low confidence* for the BORF threshold range. For timescale we adopt 100y as our central estimate from the vegetation modelling of (*84*, *199*) and 50y as a lower bound from the assessment of (*1*), but given the limited evidence base we assign this *low confidence*.

For BORF impact, (*3*) estimate that ~50% boreal forest dieback would lead to ~52 GtC release (~0.06°C global warming at tipping threshold of 4°C) based on the difference between estimated boreal forest and temperate grassland carbon densities. (*201*) estimated boreal forests contain ~109 GtC in biomass (~54 GtC) and deadwood, litter, etc. (~54 GtC) and ~163 GtC in soil carbon, while (*202*) estimated 65-195 GtC for total vegetation biomass including deadwood, and (*203*) estimated ~41 GtC in live biomass. In contrast, arbitrary total boreal deforestation by (*204*) released only ~8 GtC, (*205*) estimates only ~17.1 GtC in above-ground vegetation for the 60-80°N latitudes, and a linear scaling of the latest IPCC estimate for potential boreal forest loss carbon release yields ~35 GtC at 4°C (*56*, *85*). Despite the wide range in boreal forest carbon storage and release estimates, we take ~100 GtC as a plausible upper bound for total losable biomass, including above and below-ground biomass and deadwood but ignoring potential soil carbon change, and keep ~52 GtC as our 50% boreal dieback estimate. Biogeophysical-only effects for total dieback in the 60-80°N latitude band are estimated at ~0.48°C global cooling and ~1-4°C regional cooling (*204*, *205*), half of which would result in a net global cooling of ~0.18°C (and regional cooling of ~0.5-2°C) when combined with the carbon release above. Given the multiple sources for carbon release range and the agreement that counter-acting biogeophysical feedbacks are greater in magnitude (*204–206*), we assign global BORF impact as having *medium confidence*, but regional impact as *low confidence* until there is further spatially explicit modelling. Several studies posit potential feedback mechanisms capable of driving boreal forest dieback, for example via drying and increased wildfire frequency or linked to permafrost thaw, leading to observations indicating biome bistability between boreal forest and more open savanna or steppe (*82*, *83*, *207*). This supports the existence of tipping dynamics for BORF, but given the currently limited capacity of vegetation models to incorporate these feedbacks we assign *medium confidence*, and as tipping would likely be localized but occur semi-synchronously (*84*) we class it as a regional impact climate tipping element.

**Boreal forest [northern expansion] (TUND).** We take qualitative change for TUND afforestation to be a biome shift from tundra to savanna/forest (>50% tree cover) across at least 1M km$^2$ (i.e. sub-continental scale; largely north of 70°N) (*19*, *83–85*). We estimate a threshold range for TUND of 4°C (1.5-7.2°C), for which the central estimate is derived from vegetation modelling showing widespread abrupt biome shifts in the boreal tundra region at ~4°C (*84*, *199*). However, some more localized abrupt shifts can be seen from ~1.5°C (*84*) and ~2.4°C (*199*) in this modelling, while in another model, woody cover increases by up to 52% in the Arctic by ~2°C (*208*), tracking shifting climate zones suggests significant tundra afforestation beyond ~1.4°C (*85*), and boreal forest expansion to parts of the Arctic coast are reported for the mid-Holocene (*19*), supporting our lower bound of 1.5°C. For our upper bound, we use the threshold where one CMIP5 model experiences abrupt tundra afforestation (~7.2°C) (*19*). We assign only *low confidence* to this threshold range, as it is primarily based on a limited number of vegetation models, and CMIP5 did not feature many models with sufficiently complex dynamic vegetation to resolve this shift (*19*). For timescale, we take 100y as our central estimate based on shifts observed in dynamic vegetation models (*19*, *199*) and a lower bound of ~40y from modelled changes for 2010-2050 (*208*), but given the limited evidence base we assign this *low confidence*.

Fewer estimates are available for carbon uptake due to boreal forest expansion into the boreal tundra than for southern dieback, but ~13 GtC has been projected for total boreal afforestation (*204*) and IPCC AR6 estimating a similar value for boreal expansion carbon uptake as for boreal forest dieback carbon release (~21 GtC scaling to 4°C (*56*, *85*). Taking a different approach, using biome areas and carbon densities from (*3*) would give a larger ~71.9 GtC drawdown of carbon if half of the tundra afforested and reached the carbon density of the boreal forest. However, boreal forest expansion also results in counteracting biogeophysical feedbacks (adding 0.3°C to global warming for total boreal afforestation (*204*)). Here, given the lack of specific modelling of the global impacts of tundra afforestation for both biogeophysical and biogeochemical feedbacks, we simply adopt the biogeophysical estimate of (*204*) and scale it by 50% to represent partial afforestation, which yields ~0.14°C net global warming (and ~0.5-1°C regional warming). This partly balances out warming from dieback on the southern edge of the boreal forest biome, but regional effects and nonlinear interactions will be non-negligible. Given this impact estimate is based on one modelling study from 2010, takes an assumed afforestation extent, and biogeochemical and ecological feedbacks are poorly resolved in this region in models, we assign *low confidence* for TUND impact. Some evidence exists for self-perpetuation in TUND via decreasing albedo and increasing evapotranspiration amplifying local warming and boosting further forest expansion in the vicinity (*19*, *84*, *208*, *209*) and for biome bistability in the boreal-tundra region (*82*, *83*, *207*), but as with BORF this has not yet been fully demonstrated in vegetation or Earth system models and tipping is likely to be localized (but widespread by ~4°C), and so we assign *medium confidence* for TUND being a regional impact climate tipping element.

Both boreal forest dieback and expansion also have complex and poorly quantified interactions with permafrost thaw (*54*). In some regions thaw can lead to forest loss and wetland formation (*210*, *211*). Boreal forest disturbances like wildfires are likely to accelerate permafrost thaw in some but not all ecosystems (*212–214*). Regional warming of up to ~1°C from forest expansion (*204*) could potentially accelerate permafrost thaw in tundra regions, which could either restrict or enhance further forest expansion depending on whether thaw leads to localized wetting or drying (*58*, *210*, *211*). In this assessment we focus on climate drivers rather than ecological interactions to produce independent estimates for each element but note that these interactions add uncertainty and require further study to constrain.

**Amazon rainforest (AMAZ).** We take a qualitative change for AMAZ dieback to be a biome shift from forest to savanna (<50% tree cover) or degraded forest across at least 1M km$^2$ (i.e. sub-continental scale) due to climate change rather than deforestation (*77*, *84*, *215–219*). Threshold estimates for AMAZ of 3.5°C (2-6°C) are based on a number of models, but subject to high uncertainty. The central estimate is based on several different vegetation and Earth system models projecting partial dieback in the 3-4°C range (*78*), including abrupt vegetation shifts in the Amazon above ~3.5°C in a dynamic vegetation model (*84*), localized losses in the south and east under RCP8.5 by 2070 (~3°C, (*218*)) and 2100 (~4°C, (*77*)) in hydrological and statistical models of the Amazon's climate niche, most of the Amazon becoming bistable and therefore at risk of tipping by ~4°C in a global hydrological model (*18*), the likely precipitation threshold of <1500 mm/y being passed at ~3°C in HadCM3 (*220*), and dieback in the east in one vegetation model occurring at 2-3°C if $CO_2$ fertilization rates fall by 100% vs. 1960-1990 and 4-5°C if $CO_2$ fertilization rates fall by 75%, which is the basis of the commonly cited 3-4°C estimate in (*78*) along with (*1*) and (*221*). Additionally, substantial retreat of the hydrologically-defined tropical rainforest niche (ignoring feedbacks) occurs by ~4°C (*222*), ~20% of HadCM3 runs exploring its parameter space committed to dieback by ~3.4°C (with another ~38% of runs experiencing loss) (*223*), long-term projections using HadCM3-TRIFFID resulting in widespread (~80%) Amazon dieback after 2100 under RCP4.5 or hotter (at ~3.5°C in ~2200) (*224*), and localized partial (~20%)

diebacks occurring in the north and eastern Amazon at 1.3-2.8°C in CMIP6 models contributing to net Amazon vegetation carbon decline beyond 3°C (*216*).

The upper AMAZ threshold bound is supported by one of the two abrupt Amazon diebacks in CMIP5 occurring at ~6.2°C (*19*) as well as more widespread vegetation shifts occurring at ~5°C in (*84*), the upper end of the dieback threshold range (5°C) of (*221*) for low $CO_2$ fertilization, and committed dieback reaching ~90% by ~5°C in an earlier climate-vegetation model (*217*). The lower bound is supported by the other of the two CMIP5 models to feature abrupt dieback (*19*) as well as partial dieback being committed beyond 2°C in (*217*), dieback in one instance of HadCM3-ESE beyond ~2.2°C (*225*), ~15% of HadCM3 runs exploring its parameter space committed to dieback by ~2°C (with another ~30% of runs experiencing loss) (*223*), the low end of the no $CO_2$ fertilization dieback range (2°C) of (*221*), partial retreat of the hydrologically-defined tropical rainforest niche (ignoring feedbacks) from ~2°C (*222*), much of the Amazon breaching a thermal threshold for substantial carbon loss around 2°C (*226*), a ~200 ppm increase in atmospheric $CO_2$ (which would be associated with ~2°C warming) triggering as much change in precipitation as total deforestation in one vegetation-climate model (*227*), localized abrupt dieback occurring in the north and eastern Amazon from as low as ~1.3-1.7°C in three CMIP6 models (*216*), and the Science Panel for the Amazon listed warming exceeding 2°C as one of several potential Amazon dieback triggers, although considered uncertain and a specific basin-wide threshold was not identified (*228*). Furthermore, recent observations suggest that the capacity of the Amazon carbon sink has declined since the 1990s (~0.5°C) and combined with direct human degradation has recently become a net carbon source (~1.1°C) and will be a carbon source even without anthropogenic interventions by ~1.5°C, although this does not represent a self-perpetuating dieback tipping point (*15*, *226*, *229*, *230*).

AMAZ threshold estimates from several different models and approaches cluster at 3-4°C, but given the lack of sufficient representation in many vegetation-climate models of aspects such as tree physiology and ecology (such as adaptation (*231*) , heat mortality (*15*, *226*) drought mortality (*232*, *233*), potential limits to $CO_2$ fertilization (*81*, *231*), and key mechanisms and feedbacks involving fire and rainfall (*234*), and conversely some studies arguing that previous models over-estimated Amazon sensitivity to dieback (*80*, *235*, *236*), we assign *low confidence* to our AMAZ threshold range. For timescale, we adopt 100y as our central estimate based on the time taken in several vegetation and vegetation-climate models (*84*, *217*, *225*), with an upper bound of 200y from the longer timescale observed in for example the two CMIP5 abrupt shifts (*19*, *217*), and a lower bound of 50y from diebacks observed in HadCM3C-ESE (*223*) and the more rapid localized abrupt shifts observed in several CMIP6 models (*216*). Given the model limitations mentioned above for threshold confidence though, some of which could affect timescales (e.g. droughts creating intense wildfires that could accelerate dieback), we assign *low confidence* to these AMAZ timescale estimates.

For AMAZ impact, we first had to establish best estimates for total above-ground biomass (AGB; ~70 GtC, i.e. ~127 MgC/ha), below-ground biomass (BGB; ~21 GtC, assuming relationship of

(*237*)), and soil carbon (60-110 GtC – approximately similar to biomass), which together amount to 150-200 GtC (*3*, *74*, *75*, *238*). If all of the Amazon was converted to degraded secondary forest or savanna and we assume an AGB density of ~20 MgC/ha (based on repeatedly burnt secondary forest in (*239*) and neighboring Cerrado savanna (*240*, *241*)) and constant soil carbon (as soil carbon response to deforestation is more complex, and can even increase (*242*)) then AGB would decline to ~11 GtC and BGB to ~4 GtC, releasing ~75 GtC to the atmosphere (causing a global warming of ~0.1°C, plus ~0.1°C biogeophysical feedbacks (*204*, *205*)). A partial ~40% dieback (matching current bistable area (*18*, *77*, *215*, *243*)) would therefore release ~30 GtC (~0.1°C), and a total dieback (possible if bistable area grows by the time of tipping threshold (*18*)) ~75 GtC (~0.2°C), along with regional warming of ~1-2°C (~0.4-1°C) under total (partial) dieback. We assign this impact estimate *medium confidence*, as the biomass and bistability extent estimates come from several different sources and approaches, but some assumptions had to be made, for example on carbon storage in post-dieback degraded ecosystems. Support for a self-perpetuation mechanism in the form of moisture recycling and fire feedbacks (*19*, *77*, *78*, *223*, *225*, *228*, *243*–*245*), early warning signals indicative of declining resilience and/or approaching tipping points (*13*, *225*), and for biome bistability (*18*, *215*, *243*, *245*–*247*) comes from multiple sources, but given the model limitations and disagreements discussed for the thresholds confidence we assign *medium confidence* for AMAZ featuring tipping dynamics. The substantial Earth system impacts and bio-cultural losses justify it as global core element.

## S3) Other climate tipping element candidates

In this section we describe other systems that have been proposed as potential climate tipping elements and included in Data S1 (Climate Tipping Elements Database), including their proposed dynamics and why we have designated them as either uncertain, unlikely, or threshold-free feedbacks. Uncertain elements are candidate elements for which some evidence exists for tipping dynamics but high uncertainty results in *very low confidence*. Unlikely elements are elements with evidence suggesting that they do not (or no longer) have tipping dynamics but are not clearly feedbacks either. Threshold-free feedbacks are elements where the available evidence indicates no tipping dynamics exist but they can act as a quasi-linear feedback on global warming.

### S3.1) Uncertain potential climate tipping elements

**Southern Ocean sea-ice (SOSI).** Several abrupt shifts in SOSI occur in CMIP5 models (*19*). Abrupt loss was detected in the Pacific and Atlantic Ocean sectors at ~2.1°C (1.4-2.9°C) in two models, an abrupt increase occurred at ~1.6°C in the Indian Ocean sector in one model, and forced bimodal switches occurred in the Southern Ocean at ~2.9°C (1.7-4.7°C) in two models. These shifts are likely feedback-driven and may be self-perpetuating, although further analysis is required to determine threshold dynamics. However, AR6 has only low confidence in past and future simulations for Antarctic sea ice due to model limitations (*21*). Hence, we include Southern Ocean sea ice as an uncertain potential regional/impact tipping element with limited global impacts, and best estimates of thresholds and timescales 25-50y based on Drijfhout et al. (2015) [with low to medium confidence depending on number of models].

**Tibetan Plateau Snow (TIBS).** Abrupt snow melt on the Tibetan Plateau was detected in two CMIP5 models at 1.7-2°C (*19*). Despite its abruptness, this abrupt melt is not driven by self-perpetuating feedback. Instead, this nonlinear response to warming is a threshold mechanism related to a negative annual mass flux balance resulting from greater seasonality in snow cover. It also occurs in only two CMIP5 models. As a result, we categorize Tibetan Plateau snow melt as an uncertain tipping element.

**Indian summer monsoon (INSM).** Simple models suggest that the existence of a self-propelling moisture-advection feedback can result in two stable states (the current wet state and an alternative dry state) and threshold behavior for the South Asian monsoon (*248*, *249*). Past research has suggested that if planetary albedo over South Asia becomes greater than 0.5 the INSM could collapse, based on the possible presence of multiple metastable regimes (*249*). However, more recently there has been debate as to whether this feedback is strong enough to give rise to alternative stable states (*24*, *250*, *251*). It is also uncertain as to whether a global warming threshold exists for INSM separate to pollution, with warming instead tending to counteract the aerosol effect and overall strengthening likely by 3°C (*90*, *252*). We therefore categorize INSM as an uncertain potential tipping element with a non-GMST anthropogenic driver.

**Indian Ocean upwelling (IOUP).** An abrupt but temporary increase in upwelling and an associated phytoplankton bloom occurs in one CMIP5 model at ~10.9°C (*19*). This is driven by self-amplifying increase in upwelling (initially triggered by increased wind stress and equatorial divergence) that delivers extra nutrients to the surface, but the reversal a few decades later makes it unclear as to what extent these feedbacks are self-perpetuating. If evidence emerged from several sources supporting the existence of this as a tipping point, then IOUP would be categorized as a regional impact tipping element, but for now we categorize it as an uncertain potential tipping element.

**Equatorial stratocumulus clouds (EQSC).** In a recent model a positive feedback-driven abrupt breakup of equatorial stratocumulus clouds occurs at >1200 ppm atmospheric $CO_2$ (1400-2200 ppm in sensitivity analysis), which is equivalent to a GMST of 6.3°C (7-8.9°C) (*97*). This results in a dramatic ~8°C increase in GMST (~10°C in subtropics) in only ~10 years, and substantial model hysteresis indicates the existence of bistable states. However, this has only been resolved in one model so far, and so remains highly uncertain. If further research supports the existence of this tipping point, EQSC would constitute a global core tipping element, albeit one that is unlikely to triggered by anthropogenic warming unless global policy fails.

**Ocean deoxygenation (ANOX).** A tipping threshold for weathered phosphorus input to the ocean triggering global ocean anoxia has been previously identified and was likely triggered multiple times during the Mesozoic era, with extreme consequences for the marine biosphere (*1*, *253*, *254*). However, the associated global warming level required to reach this phosphorous threshold is unclear, although it is likely that RCP8.5 would be sufficient if maintained for tens of millennia (*253*, *255*, *256*). We conclude that there is likely an oceanic anoxia tipping point that would have serious global consequences if triggered. However, given the uncertainty around the climate forcing required and the length of time likely needed to trigger tipping we categorize ocean anoxia as an uncertain potential tipping element.

**Antarctic bottom water / Southern MOC (AABW).** The impact of Antarctic ice sheet meltwater on AABW formation is not resolved in most Earth system models, and did not feature in any CMIP5 model (*257*). However, observations suggest it may already be weakening, and collapse over ~50 years was found to be possible beyond a freshwater melt threshold (equivalent to 1.75-3°C GMST) in one model adapted to include this process (*257*). It is categorized as an uncertain potential tipping element, due to lack of models, but if confirmed it would likely act as a Global/Core tipping element as its collapse would have global consequences.

**Cloud feedbacks (CLFB).** Several recent models indicate that cloud feedbacks (especially over the Southern Ocean) could also transition to net-positive and amplify climate sensitivity beyond a threshold in the 3-5°C range (*258–260*). This could be a rare example of a global tipping point in that it markedly increases climate sensitivity from ~3°C to ~5°C global warming for each $CO_2$ doubling. However, the realism of these high-sensitivity models has been questioned (*261*, *262*), and although it features a threshold it is unclear if this threshold results from tipping dynamics. We therefore categorize this as an uncertain potential tipping element, requiring further study to constrain.

**Temperate forests (TEMF).** Recent observations suggest that temperate forests are experiencing regional mortality increases as a result of heat stress, droughts, extreme weather, and insect outbreaks (*263–271*). Potential self-amplification might occur under increasing soil moisture deficits stemming from reduced forest cover, which in turn influence precipitation regimes (*272–275*) and amplify local warming (*276*). However, it is unclear from theory or models whether temperate forests feature strong enough self-amplifying feedbacks to result in the same scale bistability associated with parts of the Amazon rainforest and boreal forest (*277*). As such, we categorize temperate forests as an uncertain potential regional impact tipping element.

**Congo forest (CONG).** The Congo rainforest has been proposed as a potential climate tipping element with similar possible tipping dynamics to the Amazon (*18*), but evidence of a specific tipping threshold across large parts of the forest is currently lacking. Furthermore, the regional forest-rainfall feedback in the Congo is weaker than in the Amazon. Bistability analysis indicates that currently the whole Congo rainforest lacks resilience against rainfall decline, but unlike the Amazon, global warming may actually increase resilience and create larger mono-stable rainforest areas and a greater potential forest range (*18*). Conversely, this same analysis indicated that southeast Asian rainforests are not vulnerable to forest-rainfall feedback (as the climate zone is largely maritime across mainland and maritime southeast Asia) and is therefore not proposed as a potential climate tipping element.

**Other potential tipping elements or feedbacks.** There are a number of other potential climate tipping points suggested or implied by the literature, for example aridification of inner East Asia (*278*), forest colonization of non-frozen peatlands (*279*), and soil organic carbon (*280*). However, there is currently insufficient evidence to classify them or determine their potential thresholds and impacts, and so we leave them out of this assessment.

### S3.2) Unlikely tipping elements

**Arctic ozone hole (AOZH).** Stratospheric ozone depletion has been driven by now-declining anthropogenic CFC emissions but can be enhanced by cooler temperatures. It has previously been suggested that global warming, which is associated with stratospheric cooling, could therefore lead to increased ozone destruction in polar regions by increasing polar stratospheric clouds and strengthening the polar vortex (*20*, *281–285*). As ozone destruction itself also leads to cooling this could have potentially triggered an abrupt self-perpetuating expansion of the Arctic ozone hole, potentially seriously impacting Europe (*20*). However, stratospheric ozone is gradually recovering since the Montreal Protocol limited CFC emissions from 1987, and it is projected that a global warming-induced Arctic ozone hole expansion will become impossible beyond 2030-2060, although some uncertainties in the response of polar vortex behavior to high global warming levels remain (*17*, *20*). As such, we categorize it is unlikely to be a tipping element unless a substantial breakdown in the Montreal Protocol occurs.

**El Niño Southern Oscillation (ENSO).** (*1*) identified ENSO as a potential tipping element on the basis that ENSO was possibly persistent during the Pliocene (~3°C above pre-industrial) and so could potentially tip into a persistent-El Nino state with warming. Alternatively, it was posited that ENSO could tip to a higher amplitude regime (*1*). However, subsequent modelling has shown there is insufficient evidence for a sharp regime threshold for a more extreme or persistent ENSO, although the amplitude of rainfall variability is projected to increase with warming (*22*, *23*). We therefore conclude that ENSO is unlikely to be a tipping element itself, although other tipping points might have substantial impacts on ENSO.

**Northern polar jet stream (JETS).** It has been proposed that Arctic warming amplification has destabilized the Northern polar jet stream, leading to increased extreme weather events in Northern mid-latitudes (*286*). This led to the jet stream being included as a potential tipping element by Steffen et al. (2018), although no justification was given for the 3-5°C temperature threshold estimate. However, the link between Arctic amplification and mid-latitude weather trends has been challenged, with longer datasets suggesting the previous correlation may not have been causal (*287*). IPCC AR6 concluded that there was low agreement on mechanisms linking Arctic amplification and jet stream response (*70*) and low confidence on the contribution of Arctic warming to mid-latitude climate (*288*). As a result of this uncertainty and the lack of a proposed self-perpetuating feedback mechanism for jet stream instability we categorize the Northern polar jet stream as unlikely to be a tipping element.

## S3.3) Threshold-free feedbacks

**Arctic summer sea ice (ASSI).** ASSI has been declining since the 1970s particularly since the 1990s, outpacing past IPCC projections (*35*). This decline is amplified by the ice-albedo feedback (sea ice retreat exposes darker water that absorbs more incoming solar energy), and might be further amplified by feedbacks to cloud cover, but negative feedbacks can act to prevent runaway sea ice loss (*20*). CMIP6 models better capture historical ASSI decline, and project occasional ice-free Septembers will occur above 1.5°C GMST, becoming common beyond 2°C and permanent around 3°C (*36*). However, current models suggest that it is unlikely to feature a tipping point beyond which loss would self-perpetuate (*21*). Hence, we re-categorize ASSI as a threshold-free feedback, adding ~0.25°C to global warming (*116*).

**Marine methane hydrates (MMHD).** Methane hydrates (also known as clathrates) are deposits of methane in subsea sediments that under high pressure and low temperature are locked into ice-like structures. The widespread dissociation of subsea methane hydrates has previously been hypothesized as a tipping element in the climate system that may have previously driven the Eocene hyperthermal events (*289–294*). As such, it has been suggested that anthropogenic warming, which is projected to be of a similar magnitude but faster rate if unabated, could also trigger hydrate dissociation (*1*, *289*, *295*). However, more detailed mechanistic modelling of the response of hydrates to warming suggests a lag of 100s-1000s of years between warming and methane release due to latent heat slowing heat propagation and the loss of much of the released methane during sediment transport processes (*292*). There is also no clear mechanism for hydrate dissociation to be able to self-perpetuate independently of thermal forcing, with latent heat processes instead resisting rather than amplifying thermal propagation through hydrate deposits. Instead, hydrates may have more likely acted as a gradual feedback during events like the PETM, helping to amplify and lengthen the hyperthermal rather than causing the abrupt initial warming itself (*296*, *297*). As hydrates are scattered around the Earth's continental shelves and slopes in isolated deposits, they are unlikely to trigger each other, but if deposits were concentrated around a particular depth, then ocean warming could hypothetically trigger synchronous dissociation and release that could amount to a threshold-like response. However, no such depth concentration is known and ocean warming and hydrate dissociation are slow enough processes to smooth out any release. Instead, smaller shallow hydrate deposits are expected to gradually begin to dissociate and release methane in to the overlying ocean in the next few centuries under higher warming scenarios while larger deep deposits remain relatively stable until much later (*298*). IPCC AR6 projects a minimal release of hydrate-derived methane in the 21$^{st}$ Century, with a maximum increase in atmospheric methane of ~20 ppb (*56*). Based on the evidence that hydrate dissociation likely does not independently self-perpetuate beyond a clear global threshold, we categorize methane hydrates as a threshold-free feedback that will somewhat amplify the future stabilized global warming level on geological timescales.

**Boreal permafrost [gradual thaw] (PFGT).** Permafrost is permanently frozen soil containing substantial organic carbon deposits, and its thaw with global warming leads to the respiration and release of this carbon as $CO_2$ and methane (*54*). Gradual permafrost thaw (PFGT) in the Circum-Arctic permafrost region is observable in modern and palaeorecords beyond 1-1.5°C (*54*–*56*, *163*) and in several models acts as a potentially nonlinear but threshold-free feedback (*153*, *164*, *165*, *167*, *173*, *174*, *299*). We summarize the literature (Table S3) as indicating that gradual thaw processes act as a threshold-free feedback that becomes widespread by 1.5°C (1-2.3°C) [high confidence], occurring over a timescale of 200y (100-300y) [medium confidence], with emissions of ~20-50 GtC at 2100-2300 respectively per degree of warming (~0.09-0.21°C per °C at pre-industrial, including estimated ~40% amplification by methane (*54*)). For PFGT impact, we subjectively judge a central estimate reflecting the range assessed literature. We estimate a feedback strength of ~20 GtC (~0.09°C from a pre-industrial baseline) released per degree of global warming at 2100 (when many studies evaluate permafrost feedback strength at; IPCC AR6 (*56*) estimated ~18 GtC, (*54*) implied ~25 GtC), increasing to ~50 GtC (~0.21°C) by 2300, reflecting that the majority of emissions likely occurs after 2100 (~59% in (*54*)). The assessed studies range from 10 to 27 GtC per °C by 2100 (reflecting the IPCC AR6 $5^{th}$-$95^{th}$ percentile range of 3-41 GtC), and 27 to 65 GtC per °C by 2300 (excluding some outliers). The above temperature figures also include a ~40% amplification due to methane (assuming ~2.3% of carbon is emitted as methane based on Schuur et al. (2015)), although some studies suggest a smaller amplification by methane (e.g. 10-18% amplification in (*173*), and even less in (*300*) where methane is estimated to account for only ~0.2% of carbon emissions). These estimates exclude carbon uptake by surface vegetation growth, which partly or wholly offsets permafrost carbon losses in some studies (e.g. (*160*, *166*)) but is far less in others (e.g. (*300*)), with complex ecological interactions making the response highly uncertain.

**Ocean biological pump and ocean carbon sink (PUMP).** The ocean takes up around a quarter of all anthropogenic $CO_2$ emissions, making it a substantial carbon sink (*301*). While this mostly driven by the 'solubility pump' (i.e. dissolution of $CO_2$ into seawater), the flow of carbon from surface to deep ocean is modulated by the 'biological pump' (*302*). This describes the drawdown of $CO_2$ from the surface ocean into marine biomass and the export of this biomass into the deep ocean, where it remains for several centuries. This export is weakening in response to climate change, with warming leading to the expansion of low-nutrient 'oligotrophic' regions and a shift to smaller-sized plankton that produce less exportable carbon, slightly reducing the capacity of the ocean carbon sink (*303*, *304*). The biological pump has been presented by some as a potential tipping element (e.g. https://www.pik-potsdam.de/en/output/infodesk/tipping-elements/kippelemente), but there is no known self-perpetuation mechanism that enables its decline to become independent of climate forcing, and in models the changes scale quasi-linearly with emission scenario (*304*). The solubility pump also declines with rising $CO_2$ and warming (as warmer and more acidic water can dissolve less $CO_2$) but like the biological pump also has no known tipping behavior, leading to an eventual peak but not a reversal of the overall ocean carbon sink in the latest CMIP6 models (*56*). Potential ocean tipping points mostly consist of ecosystem regime shifts in response to warming or acidification rather than for ocean carbon storage in general (*305*). It has been hypothesized that there may be a reachable threshold for carbon release rate into the ocean carbon cycle that could trigger a more substantial carbon cycle disruption like in previous mass extinction events (*306*, *307*), but this relies on a highly simplified model and remains speculative. As such, we categorize the warming-induced decline of the ocean biological pump (and the ocean carbon sink in general) as threshold-free feedbacks rather than tipping points, although nonlinear behavior cannot be fully ruled out.

**Land carbon sink (LAND).** Alongside the ocean carbon sink, the terrestrial biosphere takes up around another quarter of anthropogenic $CO_2$ emissions, mostly as a result of higher $CO_2$ concentrations leading to more productive plants (the '$CO_2$ fertilization' effect) (*301*). However, increasing temperatures, droughts, and nutrient limitations will eventually limit how much $CO_2$ the land biosphere can take up, leading to a reduced fraction of emitted $CO_2$ being drawn down and eventually to a transition from net carbon sink to net carbon source after 2100 (*56*). Projections of the future global land sink vary widely though as a result of missing model processes such as nutrient limitation or vegetation dynamics, leading to low agreement in AR6 on the timing and eventual magnitude of this transition. Recent observations indicate that land carbon sink slowdown may have already begun after 2000 (~0.7°C) and entered decline since ~2015 (~1.0°C) (*200*, *308*), while another analysis of observations suggests $CO_2$ fertilization began to decline above as low as ~0.3°C and may reach zero beyond ~1.2°C (*309*). This suggests that models are overestimating $CO_2$ fertilization and underestimating land carbon sink slowdown, in particular in the boreal region (*200*, *310*). The carbon sink of individual ecoregions and biomes such as tropical forests are already declining in some cases, with for example the Amazon's carbon uptake rate declining beyond ~0.5°C, projected to become a net sink by ~1.5°C, and in combination with deforestation the south-eastern likely a net source already (*15*, *226*, *229*, *230*). Parts of the Amazon and the Boreal forests may also have tipping points beyond which a regime shift and therefore carbon storage capacity substantially shifts (*78*, *85*). At a global scale though these changes are currently compensated by other still active land sinks increasing instead, with for example boreal and tundra greening compensating for the decline in the tropical sink (*311*). While a global sink-to-source transition will occur at some point, for example as a result of photosynthesis rates peaking and falling in sub-tropical ecoregions while respiration rates continue to increase (*312*), this transition is not a tipping point in itself as it is a gradual shift in feedback strengths which is not self-perpetuating. Hence, we categorize the land carbon sink as a threshold-free feedback, although nonlinear behavior is still probable.

**Table S1.** Thresholds, timescales, and impacts of previously proposed climate tipping elements. Red boxes indicate thresholds <2°C (i.e. accessible under Paris Agreement), yellow 2-4°C (accessible this century), and green >4°C (only accessible with high emissions/sensitivity). For impact, +/-/~ indicate unquantified positive/negative/minimal impact on global warming, regn. a substantial regional impact, @2°C the global feedback at 2°C, ? indicates value is unclear in source study, and blanks are where a value is not stated.

| Proposed Climate Tipping Element [and Tipping Point] or Abrupt Event (Drijfhout et al., 2015) | Lenton et al. (2008) | | | Schellnhuber et al. (2016) | | | Steffen et al. (2018) | | | Lenton et al. (2019) | | | Drijfhout et al. (2015) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Thres-hold (°C) | Time-scale (y) | Impact (°C) | Thres-hold (°C) | Time-scale (y) | Impact (°C) | Thres-hold (°C) | Time-scale (y) | Impact (°C) | Thres-hold (°C) | Time-scale (y) | Impact (°C) | Thres-hold (°C) | Time-scale (y) | Impact (°C) |
| Arctic Summer Sea Ice [loss] (ASSI) | 0.5-2 | 10 | + | 0.8-2.5 | | | 1-3 | | + | 2< | - | +regn. | Rapid ice melt feedbacks not well represented | | |
| Greenland Ice Sheets [collapse] (GrIS) | 1-2 | >300 | ~ | 0.8-3.2 | | | 1-3 | | + | 1.5 | 1k-10k | | | | |
| West Antarctic Ice Sheet [collapse] (WAIS) | 3-5 | >300 | ~ | 0.8-5.5 | | | 1-3 | | + | 1-1.5 | 100-1k< | | | | |
| Atlantic M.O. Circulation [collapse] (AMOC) | 3-5 | 100 | -regn. | 3.5-5.5 | | | 3-5 | | ±regn. | | | ±regn. | 1.6* | 50 | -4 regn. |
| Amazon Rainforest [dieback] (AMAZ) | 3-4 | 50 | ~ | 3.5-4.5 | | | 3-5 | | 0.05@2°C | | | + | 2.5 / 6.2 | 150 | |
| Boreal Forest [southern dieback] (BORF) | 3-5 | 50 | ~ | 3.5-5.5 | | | 3-5 | | 0.06@2°C | | | + | Limited veg. dynamics | | |
| Boreal Permafrost [collapse] (PFTP) | N/A | <100 | + | 4.8-9+ | | | 5+ | | 0.1@2°C | | | + | 5.6 | 50 | |
| Sahel & W. African Monsoon [greening] (SAHL) | 3-5 | 10 | ~ | 3.5-5.5 | | | 3-5 | | ~? | | | | 2.8 | 50 | |
| El Niño [permanent/extreme] (ENSO) | 3-6 | 100 | ~ | 3.5-7.0 | | | 3-5 | | regn.? | | | | | | |
| Low-latitude Coral Reefs [die-off] (REEF) | | | | 1.3-1.8? | | | 1-3 | | ~? | <2 | | | Not represented | | |
| East Antarctic Ice Sheet [collapse] (EAIS) | | | | 4.5-9+ | | | 5+ | | +? | | | | Timescale not modelled | | |
| Arctic Winter Sea Ice [collapse] (AWSI) | | | | 5.5-9+ | | | 5+ | | +? | | | | 6.3 | 100 | +regn. |
| Mountain Glaciers [loss] (GLCR) | | | | 1-2.6 | | | 1-3 | | ~? | | | | | | |
| Northern Polar Jet Stream [instability] (JETS) | | | | | | | 3-5 | | ~? | | | | | | |
| Indian Summer Monsoon [collapse] (INSM) | N/A | 1 | ~ | | | | 3-5 | | ~? | | | | | | |
| Ocean Oxygenation [global anoxia] (ANOX) | | 10k | ~ | | | | | | | | | | | | |
| Arctic Ozone Hole [abrupt expansion] (AOZH) | | <1 | ~ | | | | | | | | | | | | |
| Antarctic Bottom Water [collapse] (AABW) | | 100 | ~ | | | | | | | | | | | | |
| Marine Methane Hydrates [dissoc.] (MMHD) | | 1k-100k | + | | | | N/A | 1k< | 0.5 | | | | | | |
| Boreal forest [northern expansion] (TUND) | N/A | 100 | + | | | | | | | | | | 7.2 | 100 | +regn. |
| Southern Ocean sea ice [bimodality] (SOSI-Bi) | | | | | | | | | | | | | 2.9 | 50 | +regn. |
| Indian Ocean upwelling [increase] (IOUP) | | | | | | | | | | | | | 10.9 | 25 | |
| Barents sea ice [loss] (BARI) | | | | | | | | | | | | | 1.6 | 25 | +regn. |
| Southern Ocean sea ice [loss] (SOSI-AP) | | | | | | | | | | | | | 2.1 | 25 | +regn. |
| Southern Ocean sea ice [increase] (SOSI-In) | | | | | | | | | | | | | 1.6 | 25 | -regn. |
| Labrador Sea / SPG Convection [collapse] (LABC) | | | | | | | | | | | | | 1.7 | 10 | -regn. |
| Tibetan Plateau Snow [abrupt loss] (TIBS) | | | | | | | | | | | | | 1.8 | 25 | +regn. |
| Equatorial Stratocumulus Clouds [breakup] (EQSC) | | | | | | | | | | ~6.3 | | 8 | | | |
| Ocean Biological Pump [weaken] (PUMP) | | | | | | | N/A | | 0.02@2°C | | | | | | |
| Global Land Carbon Sink [weaken] (LAND) | | | | | | | N/A | | 0.25@2°C | | | | | | |

**Likely too low*

**Table S2.** Summary of abrupt events detected in CMIP5 by Drijfhout et al. (2015). Colors for GMST thresholds indicate tipping points occurring below 2°C (red), between 2 and 5°C (yellow), and above 5°C (green). Bolded abrupt event names indicate phenomena that have previously been characterized as climate tipping points. Bolded number of models indicate the abrupt event is found in more than three models, and italic font only in one model.

| **CMIP5 Abrupt Event** | **Global Mean Surface Temperature (°C) the abrupt event occurs at:** | | | | **Number of models found in** |
|---|---|---|---|---|---|
| | **Mean** | **RCP8.5** | **RCP4.5** | **RCP2.6** | |
| Southern Ocean sea ice bimodality | **2.9** | 4.7 | 2.1 | | 2 |
| Indian Ocean Upwelling change | **10.9** | 10.9 | | | *1* |
| **Arctic winter sea ice collapse** | **6.3** | 6.3 | | | **5** |
| Barents Sea ice loss | **1.6** | 1.6 | | | 2 |
| Southern Ocean sea ice loss (Pacific/Atlantic) | **2.1** | 2.6 | 1.9 | 1.4 | 2 |
| Southern Ocean sea ice increase (Indian) | **1.6** | | 1.6 | | *1* |
| Labrador Sea convection collapse | **1.9** | 3.8 | 1.6 | 1.5 | **4** |
| **AMOC collapse** | **1.6** | 1.9 | 1.6 | 1.4 | *1* |
| **Permafrost collapse** | **5.6** | 5.6 | | | *1* |
| Tibetan Snow Melt | **1.8** | 2.0 | 1.7 | | 2 |
| **East Sahel Vegetation changes** | **2.8** | 3.5 | 2.8 | 2.1 | *1* |
| Boreal Forest expansion | **7.2** | 7.2 | | | *1* |
| **Amazon Forest dieback** | **4.4** | 2.5-6.2 | | | 2 |

**Table S3.** Summary Table of literature-based estimates for thresholds, timescales, impact, activation time, self-perpetuation, rate-dependence, and hysteresis (see Materials and Methods for details). Colors for element acronyms represent Earth system domains (blue = cryosphere; green = biosphere; orange = ocean/atmosphere), all other colors represent confidence (red = low confidence; yellow = medium confidence; green = high confidence). For impact, +/-/~ indicate unquantified positive/negative/minimal impact on global warming, and ? indicates unknown. Threshold and timescale values for threshold-free feedbacks and unlikely tipping elements represent the temperature ranges these feedbacks or phenomena are expected to become substantial/widespread by and the timescales their impacts will occur over.

| Category | Proposed Climate Tipping Element [and Tipping Point]* | | Threshold (°C) | | | Timescale (y) | | | Max. Impact** (°C) | | Activ-ation Time | Dynamics | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Est. | Min. | Max. | Est. | Min. | Max. | Global | Regional | | Self-perpetuate? | Rate-dependent? | Hyster-esis/bi-stability? | |
| 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 | ? | Y | N | Y | GrIS has partially or fully collapsed over long millennial timescales within the Paris Agreement Target range in previous warm interglacials (albeit with orbital forcing differences), with models also supporting a tipping threshold and significant hysteresis in this range. IPCC express uncertainty on tipping below 3°C, but indicates collapse beyond 3°C is likely and cites studies with lower thresholds. |
| | **WAIS** | **West Antarctic Ice Sheet [collapse]** | 1.5 | 1.0 | 3.0 | 2k | 500 | 13k | 0.05 | 1.0 | 60 | Y | N | Y | WAIS has partially or fully collapsed over millennial timescales within the Paris Agreement Target range in previous warm interglacials, with some models and observations showing current or near-future warming already potentially sufficient to trigger collapse. Faster collapse within coming centuries possible beyond 2°C. Features clear potential self-perpetuation mechanisms (via MISI, or more uncertainly MICI). |
| | LABC | Labrador-Irminger Sea / SPG Convec-tion [collapse] | 1.8 | 1.1 | 3.8 | 10 | 5 | 50 | -0.5 | -3.0 | ? | M | M | M | Labrador-Irminger Sea / North Atlantic SPG convection collapse is resolved by multiple CMIP5 & CMIP6 models, and has strong regional consequences. Effectively a branch of AMOC with marginally smaller consequences but a much lower warming threshold in models that do resolve it. Potential self-reinforcing convection feedbacks can maintain warming-induced stratification and give rise to bistability |
| | EASB | East Antarctic Subglacial Basins [collapse] | 3.0 | 2.0 | 6.0 | 2k | 500 | 10k | 0.05 | ? | 200 | Y | P | Y | Consists of Wilkes, Aurora, and Recovery Basins. Marine-based like WAIS and unlike rest of EAIS, but thresholds are higher than WAIS. Wilkes has range of ~2-6°C, and Aurora & Recovery ~6-8°C. Partly depends on the debated MICI feedback, though is also vulnerable to MISI (depending on local factors such as buttressing) and so still has a self-perpetuation mechanism. |

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| | AMAZ | **Amazon Rainforest [dieback]** | 3.5 | 2.0 | 6.0 | 100 | 50 | 200 | Partial Dieback: 30 GtC / 0.1°C Total Dieback: 75 GtC / 0.2°C | Partial: 0.4-1 Total: 1 to 2 | 5-50 | Y | P | Y | Partial bistability amplified by moisture recycling provides a clear self-perpetuation mechanism. However, not all models show Amazon dieback, but not all relevant processes are resolved and observations indicate higher mortality than modelled. There is also a strong non-climate driver in deforestation that makes dieback more likely, complicating temperature threshold estimation (our estimates assume climate-only forcing, and so are likely over-estimates). Total dieback (assuming most Amazon becomes bistable by ~4°C) = 75 GtC released (~0.2°C, including biogeophysical feedbacks), partial dieback (~40% currently bistable, S. & E. Amazon) = 30 GtC (~0.09°C). |
| | PFTP | **Boreal Perma-frost [collapse]** | 4.0 | 3.0 | 6.0 | 50 | 10 | 300 | 125-250 GtC / 175-350 GtCe / 0.2-0.4°C | ~ | ? | Y | P | P | Warming beyond 4°C may risk wide-scale abrupt-drying regime shifts followed by self-perpetuating thawing in carbon-rich High Arctic & Yedoma regions (the "compost bomb"). The exact carbon pool vulnerable to drying/compost bomb instabilities is uncertain, so our estimate here assumes 25-50% C loss over 100y in Yedoma domain (~400GtC [Strauss et al., 2017]) & Teufel et al., (2019) abrupt drying area (2.2Msqkm = ~15% PF area [Turetsky et al., 2020] = ~155GtC [Schuur et al., 2015]), rounded down to account for some area overlap. This instability is subject to hysteresis as soil C would take a long time to reform if climate were to cool, and has partial rate-dependence as although the "compost bomb" is rate-dependent itself abrupt drying could abruptly induce collapse instead. |
| | AMOC | **Atlantic Meriod-ional Overturn-ing Circula-tion [collapse]** | 4.0 | 1.4 | 8.0 | 50 | 15 | 300 | -0.5 | -4 to -10 | ? | Y | P | M | Palaeo data and simple models suggest AMOC bistability and tipping thresholds, but CMIP models tend to show linear AMOC weakening rather than abrupt collapse. However, CMIP models are likely under-sensitive and do not include e.g. GrIS runoff effects. A runoff threshold is moderately likely (~0.1-0.5 Sv) but associated GMST highly uncertain; rate-dependence at lower end of range (0.1-0.3 Sv) is also likely but uncertain. Overshoot may also be possible, but the exceedance time is uncertain. May not be fully hysteretic as in some models the AMOC recovers when GRIS forcing declines (i.e. AMOC collapse is a response to GrIS rather than to global warming directly). |
| | AWSI | **Arctic Winter** | 6.3 | 4.5 | 8.7 | 20 | 10 | 100 | 0.6 | 0.6 to 1.2 | <10 | M | M | M | Unlike ASSI, AWSI features a threshold for abrupt decline in many CMIP5 models, which may be |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Sea Ice [collapse]** | | | | | | | | | | | | | feedback-driven and hysteretic. Regional warming scaled from ASSI by global impact ratio. |
| | **EAIS** | **East Antarctic Ice Sheet [collapse]** | 7.5 | 5.0 | 10.0 | ? | 10k | ? | 0.6 | 2.0 | ? | M | N | Y | The land-based EAIS is subject to strong hysteresis that protects it above its formation temperature (~5°C). Very gradual melt is projected, self-amplified by elevation feedback although unconfirmed if fully self-perpetuating due to modelling constraints for long timescales. |
| **Regional Impact Tipping Elements** | **REEF** | **Low-latitude Coral Reefs [die-off]** | 1.5 | 1.0 | 2.0 | 10 | / | / | ~ | ~ | ? | L/P | M | P | 70-90% warm-water coral reef loss is likely at ~1.5°C, with ~99% loss likely by 2°C. Partial hysteresis/self-perpetuation results from bleached reefs being irrecoverable directly, but new reefs can re-grow below threshold. There may be some rate dependence as slower warming rate may be adaptable to through ecosystems shifts to thermally-adapted species/taxa. |
| | **PFAT** | **Boreal Perma-frost [abrupt thaw]** | 1.5 | 1.0 | 2.4 | 300 | 100 | 300< | Abrupt thaw adds c. 50% to gradual: 10GtC / 14GtCe / 0.04°C per°C @2100; 25GtC / 35GtCe / 0.11°C per°C @2300 | ~ | ? | L | P | P | While most permafrost thawing below ~4°C is likely to be gradual, ~20% of the circum-arctic permafrost region is vulnerable to abrupt thaw processes (e.g. thermokarst lakes, slumping, etc.) which are not yet in models. These add an extra ~2.3 to ~11.6 GtC/°C (0.03-0.07°C/°C) at 2100-2300 in Turetsky et al., (2020) (i.e. ~33% extra) and ~41-74% extra in Schuur et al., (2015)'s expert judgement - we loosely estimate ~50% (25-75%) extra based on this. Very fast warming (RCP8.5) suppresses CH4 & total feedback over longer timescales, with highest PCF strength in RCP4.5-6. Palaeorecords & models indicate both gradual & abrupt wide-scale thaw starts by ~1.5°C and in RCP2.6-4.5. |
| | BARI | Barents Sea Ice [abrupt loss] | 1.6 | 1.5 | 1.7 | 25 | ? | ? | ~ | + | ? | M | N | ? | Some models show abrupt loss of winter sea ice in Barents Sea region (resulting from a positive feedback-driven shift in sea ice state) is possible in both the past and with further warming, with significant impacts on regional warming and weather patterns |
| | **GLCR** | **Mountain Glaciers [loss]** | 2.0 | 1.5 | 3.0 | 200 | 50 | 1000 | 0.08 | + | ? | L/P | N | N | Not a global tipping point, with each glacier having local thresholds & elevation feedbacks. 1.5°C leads to semi-stabilisation by 2100 in many small-glacier regions (but long-term survival not guaranteed); models & AR6 suggests widespread small glacier losses outside Antarctica expected to be committed by ~2-3°C, satisfying our synchronous sub-continental localised tipping requirement. High Mountain Asia threshold might be a bit higher / take longer, but "peak water" (and therefore societal impacts) are also reached at ~2°C. |

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| | **SAHL** | **Sahel & West African Monsoon [greening]** | 2.8 | 2.0 | 3.5 | 50 | 10 | 500 | ~ | + | ? | M | N | M | Recent models suggest further global warming will lead to overall stronger WAM, leading to drying in W.Africa and wetting in parts of Sahel, likely leading to greening & forest expansion in current grasslands that might be self-perpetuating and hysteretic to some degree via rainfall/dust feedbacks. However, the existence of tipping threshold for WAM and/or Sahel greening is uncertain, but based on evidence for regime shifts in palaeo data we maintain Sahel/WAM as a likely regional tipping element. |
| | **BORF** | **Boreal Forest [southern dieback]** | 4.0 | 1.4 | 5.0 | 100 | 50 | ? | Partial: -0.18°C (biogeophys.:-0.24, carbon: 52GtC / 0.06dC) [Total: -0.36°C (biogeophys.:-0.48, carbon: 100GtC / 0.12dC)] | Partial: -0.5 to -2 [Total: -1 to -4] | ? | M | M | Y | More likely to occur as localised dieback rather than a large swathe all at once, but widespread synchronous dieback is likely at higher warming (and is possibly rate-dependent). Current DGVMs may under-predict dieback (Koven, 2013), and there are substantial uncertainties around the relative effect of $CO_2$ fertilisation and nutrient limitation in models. Boreal dieback would predominantly cause global/regional cooling despite carbon release due to biogeophysical feedbacks. Here we assume an arbitrary partial dieback of 50% loss C & albedo for our impact estimate. |
| | **TUND** | **Boreal Forest [northern expan-sion]** | 4.0 | 1.5 | 7.2 | 100 | 40 | ? | Partial afforest: -6 GtC / net +0.14°C [Total afforest: 13GtC / net +0.28°C] | Partial: 0.5-1 [Total: 1-2] | ? | M | N | M | Self-amplification (and possible bistability/hysteresis) likely from tree cover maintaining local warmth, but unclear if self-amplification is sufficient to become self-perpetuating. Threshold and impact estimates are uncertain with wide ranges, but a net warming is likely despite carbon sink gain due to biogeophysical feedbacks. Impact estimated by assuming arbitrary 50% C gain & albedo from Bathiany et al. (2010) |
| **Threshold -free nonlinear feedbacks** | **PFGT** | **Boreal Perma-frost [gradual thaw]** | 1.5 | 1.0 | 2.4 | 300 | 100 | 300< | 20 GtC/28 GtCe/0.09°C per °C @2100; 50 GtC/70 GtCe/0.21°C per °C @2300, up to max. c. 260 GtC (0.7°C) | ~ | N/A | N | P | P | In most regions and at GWLs below ~4°C, permafrost thawing is likely to primarily act as a gradual threshold-free feedback semi-proportional to global warming (with some non-linearities). For gradual thaw, we estimate a permafrost carbon feedback (PCF) of approx. 90GtC by 2100 RCP8.5, i.e. 20 GtC/°C & 0.09°C/°C (inc. +40% from CH4), & 60% of total emissions after 2100, i.e. 50 GtC/°C & 0.21°C/°C total (up to a max. of ~0.73°C, accounting for decline in forcing strength at higher GWLs). Palaeorecords & models indicate both gradual & abrupt wide-scale thaw starts by ~1.5°C and in RCP2.6-4.5. |
| | **ASSI** | **Arctic Summer Sea Ice [loss]** | 2.0 | 1.3 | 2.9 | 20 | 10 | 50 | 0.25 | 0.25 to 0.5 | N/A | N | N | N | ASSI is best represented as a threshold-free feedback as it lacks self-perpetuation (due to countering negative feedbacks) or hysteresis, and it would semi-linearly regrow if warming was reversed (in contrast to |

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| | | | | | | | | | | | | | | | AWSI, which features more nonlinear dynamics and possible hysteresis). |
| | LAND | **Global Land Carbon Sink [weaken]** | 2.0 | 1.0 | 3.5 | ? | ? | ? | >0.13°C per °C | ~ | N/A | L | M | L | Collectively the decline of the terrestrial carbon sink behaves as a threshold-free feedback with no clear global threshold featuring a self-perpetuation mechanism (although a sink-to-source transition threshold is likely) - our threshold estimates instead demarcate the point beyond which there is significant sink decline. Observations suggest weakening is occurring faster than in models, implying models over-estimate the net effect of $CO_2$ fertilisation or under-estimate nutrient limitation or tree mortality. Total impact is uncertain due to wide model spread and missing processes, and a faster rate would likely yield greater decline due to biome migration lag. Declining C sinks with increasing temperature/$CO_2$ leads to more $CO_2$ in atmosphere per unit emission, but simultaneously this $CO_2$ has less effect at higher $CO_2$ baselines (i.e. C sink weakening is counteracted by logarithmic greenhouse effect) and so counters C sink decline to some extent. |
| | PUMP | **Ocean Biological Pump [weaken]** | N/A | 1.0 | ? | ? | ? | ? | 5GtC / 0.01°C per °C | ~ | N/A | N | N | N | There is no known tipping dynamics or nonlinear threshold for the ocean biological pump, and so we class it as a threshold-free feedback with a magnitude of 2-6 GtC per °C (rounded estimate 5GtC/°C). Some simple mathematical models have suggested that the ocean carbon sink as a whole (which the biological pump modulates) may have thresholds for massive carbon injections into ocean-atmosphere system (Rothman, 2017, 2019), but this remains hypothetical |
| | MMHD | **Marine Methane Hydrates [dissoc-iation]** | ~2.0 | ? | ? | 1k< | 1k | 5k | <0.5 | ~ | 100 | N | M | P | A global threshold for clathrates is uncertain - more likely to act as a threshold-free feedback at the global scale as likely not self-perpetuating in itself. Max. impact based on modelling of Archer et al. (2009) is generous due to simplistic hydrate representation. Possibly subject to hysteresis as it takes a long time for hydrates to "recharge" after global re-cooling, and possible rate-dependence for overcoming methane-degradation at higher production rates. IPCC AR6 concludes that for 21st Century the clathrate impact is effectively zero (only relevant on millennial timescales). |

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| **Uncertain Potential Tipping Elements** | **INSM** | **Indian Summer Monsoon [shift]** | N/A (only if AMOC collapses) | | | ? | 1 | 100 | ~ | ? | 10-100 | M | N | M | Uncertain as to whether a global warming threshold exists for INSM separate to e.g. pollution, with warming instead tending to the counteract pollution effect and strengthen the monsoon. Global monsoon tipping/irreversible change only projected by IPCC AR6 if the AMOC collapses, in which case it would be an abrupt response to a different tipping point |
| | SOSI-In | South. Ocean Sea Ice [Ind. increase] | 1.6 | ? | ? | 25 | ? | ? | ~ | - | ? | M | N | ? | CMIP5 Abrupt Event catalogue indicate a positive feedback-driven abrupt increase in Southern Ocean sea ice in the Indian Ocean sector, but IPCC AR6 has low confidence in SOSI model projections due to significant model limitations in this region. |
| | SOSI-AP | South. Ocean Sea Ice [Pac./Atl. loss] | 2.1 | 1.4 | 2.9 | 25 | ? | ? | ~ | + | ? | M | N | ? | CMIP5 Abrupt Event catalogue indicate a positive feedback-driven abrupt decrease in Southern Ocean sea ice in the Atlantic & Pacific Ocean sectors, but IPCC AR6 has low confidence in SOSI model projections due to significant model limitations in this region. |
| | SOSI-Bi | South. Ocean Sea Ice [bi-modality] | 2.9 | 1.7 | 4.5 | 50 | ? | ? | ~ | +/- | ? | M | N | M | CMIP5 Abrupt Event catalogue indicates a positive feedback-driven shift in sea ice state to bimodality, potentially indicating bistable states and hysteresis, but IPCC AR6 has low confidence in SOSI model projections due to significant model limitations in this region. |
| | EQSC | Equatorial Strato-cumulus Clouds [breakup] | ~6.3 | ~6.3 | ~8.9 | 10 | ? | ? | 8.0 | 10.0 | ? | Y | N? | Y | Occurs at 1200+ppm (1400-2200ppm sens. analysis) => approx. 6.3°C (7-8.9°C) at ECS of 3°C per 2x$CO_2$. Only in one model so far, so relatively uncertain. If proven then could be involved in high palaeo climate sensitivity for hothouse periods |
| | **AABW** | **Antarctic Bottom Water [collapse]** | 2.0 | 1.8 | 3.0 | 50 | 30 | 100 | ? | ? | ? | M | Y | Y | Uncertain as CMIP models lack Antarctic freshwater melt forcing, so only based on one model, and is also sensitive to e.g. sea ice (which AR6 has low confidence in projections for). SMOC collapse likely to be globally impactful if it occurred though, making it a potential candidate for global core tipping element |
| | IOUP | Indian Ocean Upwelling [abrupt increase] | 10.9 | ? | ? | 25 | ? | ? | ~ | ~ | ? | M | N | M | Features in CMIP5 Abrupt Event catalogue nut only in one model, results in strong productivity increase as a result of a self-amplifying increase in upwelling strength (triggered by increased wind stress & equatorial divergence). |
| | TIBS | Tibetan Plateau Snow [abrupt loss] | 1.8 | 1.4 | 2.2 | 25 | ? | ? | ~ | + | ? | N | N | ? | CMIP5 Abrupt Event catalogue indicates abrupt snow loss from Tibetan Plateau passed a threshold (likely due to a threshold mechanism rather than positive feedbacks), but this only occurs in a couple of model runs. |

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| | **ANOX** | **Ocean Deoxygen-ation [global anoxia]** | ? | ? | 8.0 | 10k | 2k | 500k | ~ | ~ | >1k | Y | M | Y | Level of warming required to double phosphorus weathering (which is theoretically sufficient for a GOAE to eventually develop) is uncertain, and most ESMs cannot run long enough for a GOAE to fully develop, but RCP8.5 may be sufficient to more than double P weathering over long enough timescales |
| **Unlikely to be a Tipping Element** | **AOZH** | **Arctic Ozone Hole [abrupt expan-sion]** | N/A | ? | ? | 1 | ? | ? | ? | ? | N/A | M | N | N | Only a climate tipping point in combination with CFC emissions (with stratospheric cooling from both global warming & ozone destruction by CFCs triggering further ozone destruction, providing a potential self-perpetuation mechanism). However, due to reversed CFC emissions and ozone layer recovery this is projected to be an insignificant risk by mid 21st Century |
| | **ENSO** | **El Nino Southern Oscillation [perm-anent / extreme]** | N/A | 3.0 | 6.0 | 100 | ? | ? | N/A | ? | N/A | N | N | N | Insufficient evidence for a sharp regime threshold for more extreme or persistent ENSO, though rainfall amplitude variability is projected to increase with warming by AR6 |
| | **JETS** | **Northern Polar Jet Stream [in-stability]** | N/A | ? | ? | ? | ? | ? | N/A | ? | N/A | ? | ? | ? | Insufficient evidence to confirm Arctic amplification / Jet stream instability link, and no evidence yet for a warming threshold driven by tipping dynamics. Only included as a candidate tipping element in map of Steffen et al. (2018), with no explanation provided as to likely tipping dynamics |

*Bold = featured in previous climate tipping element characterizations in Table S1

**Global feedback strengths in °C are calculated using ECS and baseline $CO_2$ corresponding to the central tipping threshold estimate (or pre-industrial for gradual/abrupt permafrost thaw). Feedback strength declines with further degrees of warming (by ~21% per °C). Actual feedback strength for a given warming should be calculated with original GtC emission and then converted to equivalent °C.

***Self-perpetuation, rate-dependence, and hysteresis key: Y = Yes; M = Maybe; N = No; P = Partial; L = Localized; ? = Unknown

**Table S4.** Table comparing estimated tipping threshold ranges in past climate tipping element characterizations, CMIP5 abrupt events, and in this assessment. Bolded elements are global core elements, normal font indicates regional impact elements, and italics indicates uncertain tipping elements, unlikely tipping elements, or threshold-free feedbacks. Colors indicate the proximity of the central threshold estimate (red = <2°C, yellow = 2-4°C, green = >4°C; where no central threshold is given we take the lower bound), and ? indicates value is unknown.

| **Proposed Climate Tipping Element [& Tipping Point] or Abrupt Event (Drijfhout et al., 2015)** | **Thresholds (°C)** | | | | | |
|---|---|---|---|---|---|---|
| | **Lenton et al. (2008)** | **Schellnhuber et al. (2016)** | **Steffen et al. (2018)** | **Lenton et al. (2019)** | **Drijfhout et al. (2015)** | **This Assessment** |
| *Arctic Summer Sea Ice [loss] (ASSI)* | 0.5-2 | 1-2.6 | 1-3 | 2< | Rapid ice melt feedbacks not well represented | 2.0 (1.3-2.9) |
| **Greenland Ice Sheets [collapse] (GrIS)** | 1-2 | 1-3.2 | 1-3 | 1.5 | | 1.5 (0.8-3.0) |
| **West Antarctic Ice Sheet [collapse] (WAIS)** | 3-5 | 1-5.6 | 1-3 | 1-1.5 | | 1.5 (1.0-3.0) |
| **Atlantic M.O. Circulation [collapse] (AMOC)** | 3-5 | 3.5-5.6 | 3-5 | | 1.6* | 4.0 (1.4-8.0) |
| **Amazon Rainforest [dieback] (AMAZ)** | 3-4 | 3.5-4.6 | 3-5 | | 2.5 / 6.2 | 3.5 (2.0-6.0) |
| Boreal Forest [southern dieback] (BORF) | 3-5 | 3.5-5.6 | 3-5 | | Limited veg. dynamics | 4.0 (1.4-5.0) |
| **Boreal Permafrost [collapse] (PFTP)** | N/A | 4.8-9+ | 5+ | | 5.6 | 4.0 (3.0-6.0) |
| Sahel & W. African Monsoon [greening] (SAHL) | 3-5 | 3.5-5.6 | 3-5 | | 2.8 | 2.8 (2.0-3.5) |
| *El Niño [permanent/extreme] (ENSO)* | 3-6 | 3.5-6.6 | 3-5 | | | N/A (3.0-6.0) |
| Low-latitude Coral Reefs [die-off] (REEF) | | ~1.3-1.8 | 1-3 | <2 | Not represented | 1.5 (1.0-2.0) |
| **East Antarctic Ice Sheet [collapse] (EAIS)** | | 4.5-9+ | 5+ | | Timescale not modelled | 7.5 (5.0-10.0) |
| **Arctic Winter Sea Ice [collapse] (AWSI)** | | 5.5-9+ | 5+ | | 6.3 | 6.3 (4.5-8.7) |
| Mountain Glaciers [loss] (GLCR) | | 1-2.6 | 1-3 | | | 2.0 (1.5-3.0) |
| *Northern Polar Jet Stream [instability] (JETS)* | | | 3-5 | | | N/A |
| *Indian Summer Monsoon [collapse] (INSM)* | N/A | | 3-5 | | | N/A (only if AMOC) |
| *Ocean Deoxygenation [global anoxia] (ANOX)* | | | | | | ? (<8.0) |
| *Arctic Ozone Hole [abrupt expansion] (AOZH)* | | | | | | N/A |
| *Antarctic Bottom Water [collapse] (AABW)* | | | | | | 2.0 (1.8-3.0) |
| *Marine Methane Hydrates [dissoc.] (MMHD)* | | | N/A | | | 2.0 |
| Boreal forest [northern expansion] (TUND) | N/A | | | | 7.2 | 4.0 (1.5-7.2) |
| *Southern Ocean sea ice [bimodality] (SOSI-Bi)* | | | | | 2.9 | 2.9 (1.7-4.5) |
| *Indian Ocean upwelling [increase] (IOUP)* | | | | | 10.9 | 10.9 |
| Barents sea ice [loss] (BARI) | | | | | 1.6 | 1.6 (1.5-1.7) |
| *Southern Ocean sea ice [loss] (SOSI-AP)* | | | | | 2.1 | 2.1 (1.4-2.9) |
| *Southern Ocean sea ice [increase] (SOSI-In)* | | | | | 1.6 | 1.6 |
| **Labrador Sea/SPG Convection [collapse] (LABC)** | | | | | 1.7 | 1.8 (1.1-3.8) |
| *Tibetan Plateau Snow [abrupt loss] (TIBS)* | | | | | 1.8 | 1.8 (1.4-2.2) |
| *Equatorial Stratocumul. Clouds [breakup] (EQSC)* | | | | 1200ppm (~6.3°C) | | ~6.3 (6.3-8.9) |
| *Ocean Biological Pump [weaken] (PUMP)* | | | N/A | | | N/A |
| *Global Land Carbon Sink [weaken] (LAND)* | | | N/A | | | 2.0 (1.0-3.5) |

*Likely too low

## References and Notes

1. T. M. Lenton, H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, H. J. Schellnhuber, Tipping elements in the Earth's climate system. *Proc. Natl. Acad. Sci. U.S.A.* **105**, 1786–1793 (2008). doi:10.1073/pnas.0705414105 Medline

2. T. M. Lenton, J. Rockström, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen, H. J. Schellnhuber, Climate tipping points - too risky to bet against. *Nature* **575**, 592–595 (2019). doi:10.1038/d41586-019-03595-0 Medline

3. W. Steffen, J. Rockström, K. Richardson, T. M. Lenton, C. Folke, D. Liverman, C. P. Summerhayes, A. D. Barnosky, S. E. Cornell, M. Crucifix, J. F. Donges, I. Fetzer, S. J. Lade, M. Scheffer, R. Winkelmann, H. J. Schellnhuber, Trajectories of the Earth System in the Anthropocene. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 8252–8259 (2018). doi:10.1073/pnas.1810141115 Medline

4. E. Kriegler, J. W. Hall, H. Held, R. Dawson, H. J. Schellnhuber, Imprecise probability assessment of tipping points in the climate system. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 5041–5046 (2009). doi:10.1073/pnas.0809117106 Medline

5. H. J. Schellnhuber, S. Rahmstorf, R. Winkelmann, Why the right climate target was agreed in Paris. *Nat. Clim. Chang.* **6**, 649–653 (2016). doi:10.1038/nclimate3013

6. Y. Cai, T. M. Lenton, T. S. Lontzek, Risk of multiple interacting tipping points should encourage rapid CO2 emission reduction. *Nat. Clim. Chang.* **6**, 520–525 (2016). doi:10.1038/nclimate2964

7. J. Feldmann, A. Levermann, Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 14191–14196 (2015). doi:10.1073/pnas.1512482112 Medline

8. M. S. Waibel, C. L. Hulbe, C. S. Jackson, D. F. Martin, Rate of Mass Loss Across the Instability Threshold for Thwaites Glacier Determines Rate of Mass Loss for Entire Basin. *Geophys. Res. Lett.* **45**, 809–816 (2018). doi:10.1002/2017GL076470

9. E. Rignot, J. Mouginot, M. Morlighem, H. Seroussi, B. Scheuchl, Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophys. Res. Lett.* **41**, 3502–3509 (2014). doi:10.1002/2014GL060140

10. I. Joughin, B. E. Smith, B. Medley, Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica. *Science* **344**, 735–738 (2014). doi:10.1126/science.1249055

11. N. Boers, M. Rypdal, Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2024192118 (2021). doi:10.1073/pnas.2024192118 Medline

12. N. Boers, Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. *Nat. Clim. Chang.* **11**, 680–688 (2021). doi:10.1038/s41558-021-01097-4

13. C. A. Boulton, T. M. Lenton, N. Boers, Pronounced loss of Amazon rainforest resilience

since the early 2000s. *Nat. Clim. Chang.* **12**, 271–278 (2022). doi:10.1038/s41558-022-01287-8

14. W. Liu, S.-P. Xie, Z. Liu, J. Zhu, Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Sci. Adv.* **3**, e1601666 (2017). doi:10.1126/sciadv.1601666 Medline

15. W. Hubau, S. L. Lewis, O. L. Phillips, K. Affum-Baffoe, H. Beeckman, A. Cuní-Sanchez, A. K. Daniels, C. E. N. Ewango, S. Fauset, J. M. Mukinzi, D. Sheil, B. Sonké, M. J. P. Sullivan, T. C. H. Sunderland, H. Taedoumg, S. C. Thomas, L. J. T. White, K. A. Abernethy, S. Adu-Bredu, C. A. Amani, T. R. Baker, L. F. Banin, F. Baya, S. K. Begne, A. C. Bennett, F. Benedet, R. Bitariho, Y. E. Bocko, P. Boeckx, P. Boundja, R. J. W. Brienen, T. Brncic, E. Chezeaux, G. B. Chuyong, C. J. Clark, M. Collins, J. A. Comiskey, D. A. Coomes, G. C. Dargie, T. de Haulleville, M. N. D. Kamdem, J.-L. Doucet, A. Esquivel-Muelbert, T. R. Feldpausch, A. Fofanah, E. G. Foli, M. Gilpin, E. Gloor, C. Gonmadje, S. Gourlet-Fleury, J. S. Hall, A. C. Hamilton, D. J. Harris, T. B. Hart, M. B. N. Hockemba, A. Hladik, S. A. Ifo, K. J. Jeffery, T. Jucker, E. K. Yakusu, E. Kearsley, D. Kenfack, A. Koch, M. E. Leal, A. Levesley, J. A. Lindsell, J. Lisingo, G. Lopez-Gonzalez, J. C. Lovett, J.-R. Makana, Y. Malhi, A. R. Marshall, J. Martin, E. H. Martin, F. M. Mbayu, V. P. Medjibe, V. Mihindou, E. T. A. Mitchard, S. Moore, P. K. T. Munishi, N. N. Bengone, L. Ojo, F. E. Ondo, K. S.-H. Peh, G. C. Pickavance, A. D. Poulsen, J. R. Poulsen, L. Qie, J. Reitsma, F. Rovero, M. D. Swaine, J. Talbot, J. Taplin, D. M. Taylor, D. W. Thomas, B. Toirambe, J. T. Mukendi, D. Tuagben, P. M. Umunay, G. M. F. van der Heijden, H. Verbeeck, J. Vleminckx, S. Willcock, H. Wöll, J. T. Woods, L. Zemagho, Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* **579**, 80–87 (2020). doi:10.1038/s41586-020-2035-0 Medline

16. N. Wunderling, J. F. Donges, J. Kurths, R. Winkelmann, Interacting tipping elements increase risk of climate domino effects under global warming. *Earth Syst. Dyn.* **12**, 601–619 (2021). doi:10.5194/esd-12-601-2021

17. T. M. Lenton, Arctic climate tipping points. *Ambio* **41**, 10–22 (2012). doi:10.1007/s13280-011-0221-x Medline

18. A. Staal, I. Fetzer, L. Wang-Erlandsson, J. H. C. Bosmans, S. C. Dekker, E. H. van Nes, J. Rockström, O. A. Tuinenburg, Hysteresis of tropical forests in the 21st century. *Nat. Commun.* **11**, 4978 (2020). doi:10.1038/s41467-020-18728-7 Medline

19. S. Drijfhout, S. Bathiany, C. Beaulieu, V. Brovkin, M. Claussen, C. Huntingford, M. Scheffer, G. Sgubin, D. Swingedouw, Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models. *Proc. Natl. Acad. Sci. U.S.A.* **112**, E5777–E5786 (2015). doi:10.1073/pnas.1511451112 Medline

20. A. Levermann, J. L. Bamber, S. Drijfhout, A. Ganopolski, W. Haeberli, N. R. P. Harris, M. Huss, K. Krüger, T. M. Lenton, R. W. Lindsay, D. Notz, P. Wadhams, S. Weber, Potential climatic transitions with profound impact on Europe. *Clim. Change* **110**, 845–878 (2012). doi:10.1007/s10584-011-0126-5

21. B. Fox-Kemper, H. T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S. S. Drijfhout, T. L. Edwards, N. R. Golledge, M. Hemer, R. E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I. S. Nurhati, L. Ruiz, J.-B. Sallée, A. B. A. Slangen, Y. Yu, “Climate Change 2021: The

Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou, Eds. (Cambridge Univ. Press, 2021).

22. M. Collins, M. Sutherland, L. Bouwer, S.-M. Cheong, T. L. Frölicher, H. Jacot Des Combes, M. K. Roxy, I. Losada, K. L. McInnes, B. Ratter, E. Rivera-Arriaga, R. D. Susanto, D. Swingedouw, L. Tibig, P. Bakker, C. M. Eakin, K. Emanuel, M. Grose, M. Hemer, L. Jackson, A. Kääb, J. B. Kajtar, T. Knutson, C. Laufkötter, I. Noy, M. Payne, R. Ranasinghe, G. Sgubin, M.-L. Timmermans, "IPCC Special Report on the Ocean and Cryosphere in a Changing Climate" H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. M. Weyer, Eds. (2019); pp. 589–655.

23. J. Y. Lee, J. Marotzke, G. Bala, L. Cao, S. Corti, J. P. Dunne, F. Engelbrecht, E. Fischer, J. C. Fyfe, C. Jones, A. Maycock, J. Mutemi, O. Ndiaye, S. Panickal, T. Zhou, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou, Eds. (Cambridge Univ. Press, 2021).

24. W. R. Boos, T. Storelvmo, Near-linear response of mean monsoon strength to a broad range of radiative forcings. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 1510–1515 (2016). doi:10.1073/pnas.1517143113 Medline

25. J. Garbe, T. Albrecht, A. Levermann, J. F. Donges, R. Winkelmann, The hysteresis of the Antarctic Ice Sheet. *Nature* **585**, 538–544 (2020). doi:10.1038/s41586-020-2727-5 Medline

26. D. Chen, M. Rojas, B. H. Samset, K. Cobb, A. D. Niang, P. Edwards, S. Emori, S. H. Faria, E. Hawkins, P. Hope, P. Huybrechts, M. Meinshausen, S. K. Mustafa, G.-K. Plattner, A.-M. Tréguier, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou, Eds. (Cambridge Univ. Press, 2021).

27. M. Scheffer, J. Bascompte, W. A. Brock, V. Brovkin, S. R. Carpenter, V. Dakos, H. Held, E. H. van Nes, M. Rietkerk, G. Sugihara, Early-warning signals for critical transitions. *Nature* **461**, 53–59 (2009). doi:10.1038/nature08227 Medline

28. R. Ranasinghe, A. C. Ruane, R. Vautard, N. Arnell, E. Coppola, F. A. Cruz, S. Dessai, A. S. Islam, M. Rahimi, D. R. Carrascal, J. Sillmann, M. B. Sylla, C. Tebaldi, W. Wang, R. Zaaboul, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N.

Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou, Eds. (Cambridge Univ. Press, 2021), p. 73.

29. National Research Council, *Abrupt Climate Change: Inevitable Surprises* (The National Academies Press, 2002); https://www.nap.edu/catalog/10136.

30. R. E. Kopp, R. L. Shwom, G. Wagner, J. Yuan, Tipping elements and climate–economic shocks: Pathways toward integrated assessment. *Earths Future* **4**, 346–372 (2016). doi:10.1002/2016EF000362

31. C. Hankel, E. Tziperman, The Role of Atmospheric Feedbacks in Abrupt Winter Arctic Sea Ice Loss in Future Warming Scenarios. *J. Clim.* **34**, 4435–4447 (2021). doi:10.1175/JCLI-D-20-0558.1

32. P. J. Hezel, T. Fichefet, F. Massonnet, Modeled Arctic sea ice evolution through 2300 in CMIP5 extended RCPs. *Cryosphere* **8**, 1195–1204 (2014). doi:10.5194/tc-8-1195-2014

33. D. Docquier, R. Fuentes-Franco, T. Koenigk, T. Fichefet, Sea Ice—Ocean Interactions in the Barents Sea Modeled at Different Resolutions. *Front. Earth Sci.* **8**, 1–21 (2020). doi:10.3389/feart.2020.00172

34. F. Lehner, A. Born, C. C. Raible, T. F. Stocker, Amplified Inception of European Little Ice Age by Sea Ice–Ocean–Atmosphere Feedbacks. *J. Clim.* **26**, 7586–7602 (2013). doi:10.1175/JCLI-D-12-00690.1

35. I. Allison, N. L. Bindoff, R. A. Bindoff, R. A. Bindschadler, P. M. Cox, N. de Noblet, M. H. England, J. E. Francis, N. Gruber, A.M. Haywood, D. J. Karoly, G. Kaser, C. Le Quéré, T. M. Lenton, M. E. Mann, B. I. McNeil, A. J. Pitman, S. Rahmstorf, E. Rignot, H. J. Schellnhuber, S. H. Schneider, S. C. Sherwood, R .C. J. Somerville, K. Steffen, E. J. Steig, M. Visbeck, A. J. Weaver, "The Copenhagen Diagnosis" (The Univ. of New South Wales Climate Change Research Centre, 2009); https://www.ccrc.unsw.edu.au/sites/default/files/Copenhagen_Diagnosis_LOW.pdf).

36. D. Notz, S. Community, Arctic Sea Ice in CMIP6. *Geophys. Res. Lett.* **47**, 1–26 (2020). doi:10.1029/2019GL086749

37. M. D. King, I. M. Howat, S. G. Candela, M. J. Noh, S. Jeong, B. P. Y. Noël, M. R. van den Broeke, B. Wouters, A. Negrete, Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat. *Commun. Earth Environ.* **1**, 1–7 (2020). doi:10.1038/s43247-020-0001-2

38. A. Shepherd, E. Ivins, E. Rignot, B. Smith, M. van den Broeke, I. Velicogna, P. Whitehouse, K. Briggs, I. Joughin, G. Krinner, S. Nowicki, T. Payne, T. Scambos, N. Schlegel, G. A, C. Agosta, A. Ahlstrøm, G. Babonis, V. R. Barletta, A. A. Bjørk, A. Blazquez, J. Bonin, W. Colgan, B. Csatho, R. Cullather, M. E. Engdahl, D. Felikson, X. Fettweis, R. Forsberg, A. E. Hogg, H. Gallee, A. Gardner, L. Gilbert, N. Gourmelen, A. Groh, B. Gunter, E. Hanna, C. Harig, V. Helm, A. Horvath, M. Horwath, S. Khan, K. K. Kjeldsen, H. Konrad, P. L. Langen, B. Lecavalier, B. Loomis, S. Luthcke, M. McMillan, D. Melini, S. Mernild, Y. Mohajerani, P. Moore, R. Mottram, J. Mouginot, G. Moyano, A. Muir, T. Nagler, G. Nield, J. Nilsson, B. Noël, I. Otosaka, M. E. Pattle, W. R. Peltier, N. Pie, R. Rietbroek, H. Rott, L. Sandberg Sørensen, I. Sasgen, H. Save, B. Scheuchl, E. Schrama,

L. Schröder, K. W. Seo, S. B. Simonsen, T. Slater, G. Spada, T. Sutterley, M. Talpe, L. Tarasov, W. J. van de Berg, W. van der Wal, M. van Wessem, B. D. Vishwakarma, D. Wiese, D. Wilton, T. Wagner, B. Wouters, J. Wuite, Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature* **579**, 233–239 (2020).

39. A. Robinson, R. Calov, A. Ganopolski, Multistability and critical thresholds of the Greenland ice sheet. *Nat. Clim. Chang.* **2**, 429–432 (2012). doi:10.1038/nclimate1449

40. J. Van Breedam, H. Goelzer, P. Huybrechts, Semi-equilibrated global sea-level change projections for the next 10 000 years. *Earth Syst. Dyn.* **11**, 953–976 (2020). doi:10.5194/esd-11-953-2020

41. B. Noël, L. van Kampenhout, J. T. M. Lenaerts, W. J. van de Berg, M. R. van den Broeke, A 21st Century Warming Threshold for Sustained Greenland Ice Sheet Mass Loss. *Geophys. Res. Lett.* **48**, 1–9 (2021). doi:10.1029/2020GL090471

42. G. L. Foster, E. J. Rohling, Relationship between sea level and climate forcing by CO2 on geological timescales. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 1209–1214 (2013). doi:10.1073/pnas.1216073110 Medline

43. A. J. Christ, P. R. Bierman, J. M. Schaefer, D. Dahl-Jensen, J. P. Steffensen, L. B. Corbett, D. M. Peteet, E. K. Thomas, E. J. Steig, T. M. Rittenour, J.-L. Tison, P.-H. Blard, N. Perdrial, D. P. Dethier, A. Lini, A. J. Hidy, M. W. Caffee, J. Southon, A multimillion-year-old record of Greenland vegetation and glacial history preserved in sediment beneath 1.4 km of ice at Camp Century. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2021442118 (2021). doi:10.1073/pnas.2021442118 Medline

44. J. M. Gregory, S. E. George, R. S. Smith, Large and irreversible future decline of the Greenland ice sheet. *Cryosphere* **14**, 4299–4322 (2020). doi:10.5194/tc-14-4299-2020

45. R. B. Alley, S. Anandakrishnan, K. Christianson, H. J. Horgan, A. Muto, B. R. Parizek, D. Pollard, R. T. Walker, Oceanic Forcing of Ice-Sheet Retreat: West Antarctica and More. *Annu. Rev. Earth Planet. Sci.* **43**, 207–231 (2015). doi:10.1146/annurev-earth-060614-105344

46. C. S. M. Turney, C. J. Fogwill, N. R. Golledge, N. P. McKay, E. van Sebille, R. T. Jones, D. Etheridge, M. Rubino, D. P. Thornton, S. M. Davies, C. B. Ramsey, Z. A. Thomas, M. I. Bird, N. C. Munksgaard, M. Kohno, J. Woodward, K. Winter, L. S. Weyrich, C. M. Rootes, H. Millman, P. G. Albert, A. Rivera, T. van Ommen, M. Curran, A. Moy, S. Rahmstorf, K. Kawamura, C.-D. Hillenbrand, M. E. Weber, C. J. Manning, J. Young, A. Cooper, Early Last Interglacial ocean warming drove substantial ice mass loss from Antarctica. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 3996–4006 (2020). doi:10.1073/pnas.1902469117 Medline

47. H. Yu, E. Rignot, H. Seroussi, M. Morlighem, Impact of iceberg calving on the retreat of Thwaites Glacier, West Antarctica over the next century with different calving laws and ocean thermal forcing. *Geophys. Res. Lett.* **46**, 14539–14547 (2019). doi:10.1029/2019GL084066

48. R. J. Arthern, C. R. Williams, The sensitivity of West Antarctica to the submarine melting feedback. *Geophys. Res. Lett.* **44**, 2352–2359 (2017). doi:10.1002/2017GL072514

49. T. L. Edwards, M. A. Brandon, G. Durand, N. R. Edwards, N. R. Golledge, P. B. Holden, I.

J. Nias, A. J. Payne, C. Ritz, A. Wernecke, Revisiting Antarctic ice loss due to marine ice-cliff instability. *Nature* **566**, 58–64 (2019). doi:10.1038/s41586-019-0901-4 Medline

50. P. U. Clark, F. He, N. R. Golledge, J. X. Mitrovica, A. Dutton, J. S. Hoffman, S. Dendy, Oceanic forcing of penultimate deglacial and last interglacial sea-level rise. *Nature* **577**, 660–664 (2020). doi:10.1038/s41586-020-1931-7 Medline
51. R. M. DeConto, D. Pollard, R. B. Alley, I. Velicogna, E. Gasson, N. Gomez, S. Sadai, A. Condron, D. M. Gilford, E. L. Ashe, R. E. Kopp, D. Li, A. Dutton, The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* **593**, 83–89 (2021). doi:10.1038/s41586-021-03427-0 Medline
52. D. J. Wilson, R. A. Bertram, E. F. Needham, T. van de Flierdt, K. J. Welsh, R. M. McKay, A. Mazumder, C. R. Riesselman, F. J. Jimenez-Espejo, C. Escutia, Ice loss from the East Antarctic Ice Sheet during late Pleistocene interglacials. *Nature* **561**, 383–386 (2018). doi:10.1038/s41586-018-0501-8 Medline
53. E. Gasson, R. M. DeConto, D. Pollard, R. H. Levy, Dynamic Antarctic ice sheet during the early to mid-Miocene. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 3459–3464 (2016). doi:10.1073/pnas.1516130113 Medline
54. E. A. G. Schuur, A. D. McGuire, C. Schädel, G. Grosse, J. W. Harden, D. J. Hayes, G. Hugelius, C. D. Koven, P. Kuhry, D. M. Lawrence, S. M. Natali, D. Olefeldt, V. E. Romanovsky, K. Schaefer, M. R. Turetsky, C. C. Treat, J. E. Vonk, Climate change and the permafrost carbon feedback. *Nature* **520**, 171–179 (2015). doi:10.1038/nature14338 Medline
55. A. Vaks, O. S. Gutareva, S. F. M. Breitenbach, E. Avirmed, A. J. Mason, A. L. Thomas, A. V. Osinzev, A. M. Kononov, G. M. Henderson, Speleothems Reveal 500,000-Year History of Siberian Permafrost. *Science* **340**, 183–186 (2013). doi:10.1126/science.1228729
56. J. G. Canadell, P. M. S. Monteiro, M. H. Costa, L. C. da Cunha, P. M. Cox, A. V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P. K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, K. Zickfeld, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou, Eds. (Cambridge Univ. Press, 2021).
57. M. R. Turetsky, B. W. Abbott, M. C. Jones, K. W. Anthony, D. Olefeldt, E. A. G. Schuur, G. Grosse, P. Kuhry, G. Hugelius, C. Koven, D. M. Lawrence, C. Gibson, A. B. K. Sannel, A. D. McGuire, Carbon release through abrupt permafrost thaw. *Nat. Geosci.* **13**, 138–143 (2020). doi:10.1038/s41561-019-0526-0
58. B. Teufel, L. Sushama, Abrupt changes across the Arctic permafrost region endanger northern development. *Nat. Clim. Chang.* **9**, 858–862 (2019). doi:10.1038/s41558-019-0614-6
59. J. Strauss, L. Schirrmeister, G. Grosse, D. Fortier, G. Hugelius, C. Knoblauch, V. Romanovsky, C. Schädel, T. Schneider von Deimling, E. A. G. Schuur, D. Shmelev, M.

Ulrich, A. Veremeeva, Deep Yedoma permafrost: A synthesis of depositional characteristics and carbon vulnerability. *Earth Sci. Rev.* **172**, 75–86 (2017). doi:10.1016/j.earscirev.2017.07.007

60. C. M. Luke, P. M. Cox, Soil carbon and climate change: From the Jenkinson effect to the compost-bomb instability. *Eur. J. Soil Sci.* **62**, 5–12 (2011). doi:10.1111/j.1365-2389.2010.01312.x

61. J. Hollesen, H. Matthiesen, A. B. Møller, B. Elberling, Permafrost thawing in organic Arctic soils accelerated by ground heat production. *Nat. Clim. Chang.* **5**, 574–578 (2015). doi:10.1038/nclimate2590

62. M. Huss, R. Hock, Global-scale hydrological response to future glacier mass loss. *Nat. Clim. Chang.* **8**, 135–140 (2018). doi:10.1038/s41558-017-0049-x

63. R. Hock, G. Rasul, C. Adler, B. Cáceres, S. Gruber, Y. Hirabayashi, M. Jackson, A. Kääb, S. Kang, S. Kutuzov, A. Milner, U. Molau, S. Morin, B. Orlove, H. I. Steltzer, "IPCC Special Report on the Ocean and Cryosphere in a Changing Climate" H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. M. Weyer, Eds. (Cambridge Univ. Press, 2019), pp. 131–202.

64. P. U. Clark, J. D. Shakun, S. A. Marcott, A. C. Mix, M. Eby, S. Kulp, A. Levermann, G. A. Milne, P. L. Pfister, B. D. Santer, D. P. Schrag, S. Solomon, T. F. Stocker, B. H. Strauss, A. J. Weaver, R. Winkelmann, D. Archer, E. Bard, A. Goldner, K. Lambeck, R. T. Pierrehumbert, G.-K. Plattner, Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nat. Clim. Chang.* **6**, 360–369 (2016). doi:10.1038/nclimate2923

65. G. Sgubin, D. Swingedouw, S. Drijfhout, Y. Mary, A. Bennabi, Abrupt cooling over the North Atlantic in modern climate models. *Nat. Commun.* **8**, 14375 (2017). doi:10.1038/ncomms14375 Medline

66. D. Swingedouw, A. Bily, C. Esquerdo, L. F. Borchert, G. Sgubin, J. Mignot, M. Menary, On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models. *Ann. N. Y. Acad. Sci.* **1504**, 187–201 (2021). doi:10.1111/nyas.14659 Medline

67. L. Caesar, S. Rahmstorf, A. Robinson, G. Feulner, V. Saba, Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature* **556**, 191–196 (2018). doi:10.1038/s41586-018-0006-5 Medline

68. J. Lynch-Stieglitz, The Atlantic Meridional Overturning Circulation and Abrupt Climate Change. *Annu. Rev. Mar. Sci.* **9**, 83–104 (2017). doi:10.1146/annurev-marine-010816-060415 Medline

69. J. Lohmann, P. D. Ditlevsen, Risk of tipping the overturning circulation due to increasing rates of ice melt. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2017989118 (2021). doi:10.1073/pnas.2017989118 Medline

70. H. Douville, K. Raghavan, J. Renwick, R. P. Allan, P. A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T. Y. Gan, J. Gergis, D. Jiang, A. Khan, W. P. Mba, D. Rosenfeld, J. Tierney, O. Zolina, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on

Climate Change" V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou, Eds. (Cambridge Univ. Press, 2021), p. 73.

71. L. C. Jackson, R. Kahana, T. Graham, M. A. Ringer, T. Woollings, J. V. Mecking, R. A. Wood, Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Clim. Dyn.* **45**, 3299–3316 (2015). doi:10.1007/s00382-015-2540-2

72. S. Drijfhout, Competition between global warming and an abrupt collapse of the AMOC in Earth's energy imbalance. *Sci. Rep.* **5**, 14877 (2015). doi:10.1038/srep14877 Medline

73. A. Bozbiyik, M. Steinacher, F. Joos, T. F. Stocker, L. Menviel, Fingerprints of changes in the terrestrial carbon cycle in response to large reorganizations in ocean circulation. *Clim. Past* **7**, 319–338 (2011). doi:10.5194/cp-7-319-2011

74. L. V. Gatti, L. S. Basso, J. B. Miller, M. Gloor, L. Gatti Domingues, H. L. G. Cassol, G. Tejada, L. E. O. C. Aragão, C. Nobre, W. Peters, L. Marani, E. Arai, A. H. Sanches, S. M. Corrêa, L. Anderson, C. Von Randow, C. S. C. Correia, S. P. Crispim, R. A. L. Neves, Amazonia as a carbon source linked to deforestation and climate change. *Nature* **595**, 388–393 (2021). doi:10.1038/s41586-021-03629-6 Medline

75. Science Panel for the Amazon (SPA), "Executive Summary of the Amazon Assessment Report 2021" C. Nobre, A. Encalada, E. Anderson, F.H. Roca Alcazar, M. Bustamante, C. Mena, M. Peña-Claros, G. Poveda, J.P. Rodriguez, S. Saleska, S. Trumbore, A.L. Val, L. Villa Nova, R. Abramovay, A. Alencar, A.C.R. Alzza, D. Armenteras, P. Artaxo, S. Athayde, H.T. Barretto Filho, J. Barlow, E. Berenguer, F. Bortolotto, F.A. Costa, M.H. Costa, N. Cuvi, P.M. Fearnside, J. Ferreira, B.M. Flores, S. Frieri, L.V. Gatti, J.M. Guayasamin, S. Hecht, M. Hirota, C. Hoorn, C. Josse, D.M. Lapola, C. Larrea, D.M. Larrea-Alcazar, Z. Lehm Ardaya, Y. Malhi, J.A. Marengo, M.R. Moraes, P. Moutinho, M.R. Murmis, E.G. Neves, B. Paez, L. Painter, A. Ramos, M.C. Rosero-Peña, M. Schmink, P. Sist, H. ter Steege, P. Val, H. van der Voort, M. Varese, Zapata-Ríos, Eds. (United Nations Sustainable Development Solutions Network, 2021); https://www.theamazonwewant.org/wp-content/uploads/2021/09/SPA-Executive-Summary-11Mb.pdf.

76. A. Staal, O. A. Tuinenburg, J. H. C. Bosmans, M. Holmgren, E. H. Van Nes, M. Scheffer, D. C. Zemp, S. C. Dekker, Forest-rainfall cascades buffer against drought across the Amazon. *Nat. Clim. Chang.* **8**, 539–543 (2018). doi:10.1038/s41558-018-0177-y

77. D. C. Zemp, C.-F. Schleussner, H. M. J. Barbosa, M. Hirota, V. Montade, G. Sampaio, A. Staal, L. Wang-Erlandsson, A. Rammig, Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nat. Commun.* **8**, 14681 (2017). doi:10.1038/ncomms14681 Medline

78. C. A. Nobre, G. Sampaio, L. S. Borma, J. C. Castilla-Rubio, J. S. Silva, M. Cardoso, Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 10759–10768 (2016). doi:10.1073/pnas.1605516113 Medline

79. T. E. Lovejoy, C. Nobre, Amazon Tipping Point. *Sci. Adv.* **4**, eaat2340 (2018). doi:10.1126/sciadv.aat2340 Medline

80. P. M. Cox, D. Pearson, B. B. Booth, P. Friedlingstein, C. Huntingford, C. D. Jones, C. M. Luke, Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability. *Nature* **494**, 341–344 (2013). doi:10.1038/nature11882 Medline

81. C. Terrer, R. B. Jackson, I. C. Prentice, T. F. Keenan, C. Kaiser, S. Vicca, J. B. Fisher, P. B. Reich, B. D. Stocker, B. A. Hungate, J. Peñuelas, I. McCallum, N. A. Soudzilovskaia, L. A. Cernusak, A. F. Talhelm, K. Van Sundert, S. Piao, P. C. D. Newton, M. J. Hovenden, D. M. Blumenthal, Y. Y. Liu, C. Müller, K. Winter, C. B. Field, W. Viechtbauer, C. J. Van Lissa, M. R. Hoosbeek, M. Watanabe, T. Koike, V. O. Leshyk, H. W. Polley, O. Franklin, Nitrogen and phosphorus constrain the CO2 fertilization of global plant biomass. *Nat. Clim. Chang.* **9**, 684–689 (2019). doi:10.1038/s41558-019-0545-2

82. B. Abis, V. Brovkin, Environmental conditions for alternative tree-cover states in high latitudes. *Biogeosciences* **14**, 511–527 (2017). doi:10.5194/bg-14-511-2017

83. M. Scheffer, M. Hirota, M. Holmgren, E. H. Van Nes, F. S. Chapin 3rd, Thresholds for boreal biome transitions. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 21384–21389 (2012). doi:10.1073/pnas.1219844110 Medline

84. D. Gerten, W. Lucht, S. Ostberg, J. Heinke, M. Kowarsch, H. Kreft, Z. W. Kundzewicz, J. Rastgooy, R. Warren, H. J. Schellnhuber, Asynchronous exposure to global warming: Freshwater resources and terrestrial ecosystems. *Environ. Res. Lett.* **8**, 034032 (2013). doi:10.1088/1748-9326/8/3/034032

85. C. D. Koven, Boreal carbon loss due to poleward shift in low-carbon ecosystems. *Nat. Geosci.* **6**, 452–456 (2013). doi:10.1038/ngeo1801

86. F. S. R. Pausata, M. Gaetani, G. Messori, A. Berg, D. Maia de Souza, R. F. Sage, P. B. deMenocal, The Greening of the Sahara: Past Changes and Future Implications. *One Earth* **2**, 235–250 (2020). doi:10.1016/j.oneear.2020.03.002

87. M. W. Schmidt, P. Chang, A. O. Parker, L. Ji, F. He, Deglacial Tropical Atlantic subsurface warming links ocean circulation variability to the West African Monsoon. *Sci. Rep.* **7**, 15390 (2017). doi:10.1038/s41598-017-15637-6 Medline

88. P. O. Hopcroft, P. J. Valdes, Paleoclimate-conditioning reveals a North Africa land-atmosphere tipping point. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2108783118 (2021). doi:10.1073/pnas.2108783118 Medline

89. A. Dosio, M. W. Jury, M. Almazroui, M. Ashfaq, I. Diallo, F. A. Engelbrecht, N. A. B. Klutse, C. Lennard, I. Pinto, M. B. Sylla, A. T. Tamoffo, Projected future daily characteristics of African precipitation based on global (CMIP5, CMIP6) and regional (CORDEX, CORDEX-CORE) climate models. *Clim. Dyn.* **57**, 3135–3158 (2021). doi:10.1007/s00382-021-05859-w

90. O. Hoegh-Guldberg, D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K. L. Ebi, F. Engelbrecht, J. Guiot, Y. Hijioka, S. Mehrotra, A. Payne, S. I. Seneviratne, A. Thomas, R. Warren, G. Zhou, "Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty."

V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield, Eds. (2018), pp. 175–311.

91. A. Erfanian, G. Wang, M. Yu, R. Anyah, Multimodel ensemble simulations of present and future climates over West Africa: Impacts of vegetation dynamics. *J. Adv. Model. Earth Syst.* **8**, 1411–1431 (2016). doi:10.1002/2016MS000660

92. T. P. Hughes, M. L. Barnes, D. R. Bellwood, J. E. Cinner, G. S. Cumming, J. B. C. Jackson, J. Kleypas, I. A. van de Leemput, J. M. Lough, T. H. Morrison, S. R. Palumbi, E. H. van Nes, M. Scheffer, Coral reefs in the Anthropocene. *Nature* **546**, 82–90 (2017). doi:10.1038/nature22901 Medline

93. K. Frieler, M. Meinshausen, A. Golly, M. Mengel, K. Lebek, S. D. Donner, O. Hoegh-Guldberg, Limiting global warming to 2 °C is unlikely to save most coral reefs. *Nat. Clim. Chang.* **3**, 165–170 (2013). doi:10.1038/nclimate1674

94. P. D. L. Ritchie, J. J. Clarke, P. M. Cox, C. Huntingford, Overshooting tipping point thresholds in a changing climate. *Nature* **592**, 517–523 (2021). doi:10.1038/s41586-021-03263-2 Medline

95. M. B. Osman, J. E. Tierney, J. Zhu, R. Tardif, G. J. Hakim, J. King, C. J. Poulsen, Globally resolved surface temperatures since the Last Glacial Maximum. *Nature* **599**, 239–244 (2021). doi:10.1038/s41586-021-03984-4 Medline

96. M. Meinshausen, J. Lewis, C. McGlade, J. Gütschow, Z. Nicholls, R. Burdon, L. Cozzi, B. Hackmann, Realization of Paris Agreement pledges may limit warming just below 2 °C. *Nature* **604**, 304–309 (2022). doi:10.1038/s41586-022-04553-z Medline

97. T. Schneider, C. M. Kaul, K. G. Pressel, Possible climate transitions from breakup of stratocumulus decks under greenhouse warming. *Nat. Geosci.* **12**, 163–167 (2019). doi:10.1038/s41561-019-0310-1

98. M. Rietkerk, R. Bastiaansen, S. Banerjee, J. Van De Koppel, Evasion of tipping in complex systems through spatial pattern formation. **374**, abj0359 (2021), doi:10.1126/science.abj0359.

99. T. M. Bury, R. I. Sujith, I. Pavithran, M. Scheffer, T. M. Lenton, M. Anand, C. T. Bauch, Deep learning for early warning signals of tipping points. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2106140118 (2021). doi:10.1073/pnas.2106140118 Medline

100. T. M. Lenton, Early warning of climate tipping points. *Nat. Clim. Chang.* **1**, 201–209 (2011). doi:10.1038/nclimate1143

101. M. D. Mastrandrea, C. B. Field, T. F. Stocker, O. Edenhofer, K. L. Ebi, D. J. Frame, H. Held, E. Kriegler, K. J. Mach, P. R. Matschoss, G.-K. Plattner, G. W. Yohe, F. W. Zwiers, "Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties." (IPCC, 2010); www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf.

102. E. H. van Nes, B. M. S. Arani, A. Staal, B. van der Bolt, B. M. Flores, S. Bathiany, M. Scheffer, What Do You Mean, 'Tipping Point'? *Trends Ecol. Evol.* **31**, 902–904 (2016).

doi:10.1016/j.tree.2016.09.011 Medline

103. S. Kéfi, V. Dakos, M. Scheffer, E. H. Van Nes, M. Rietkerk, Early warning signals also precede non-catastrophic transitions. *Oikos* **122**, 641–648 (2013). doi:10.1111/j.1600-0706.2012.20838.x

104. P. C. de Ruiter, A.-M. Neutel, J. C. Moore, Energetics, Patterns of Interaction Strengths, and Stability in Real Ecosystems. *Science* **269**, 1257–1260 (1995).

105. J. J. Kuiper, C. van Altena, P. C. de Ruiter, L. P. A. van Gerven, J. H. Janse, W. M. Mooij, Food-web stability signals critical transitions in temperate shallow lakes. *Nat. Commun.* **6**, 7727 (2015). doi:10.1038/ncomms8727 Medline

106. S. J. Lade, T. Gross, Early warning signals for critical transitions: A generalized modeling approach. *PLOS Comput. Biol.* **8**, e1002360 (2012). doi:10.1371/journal.pcbi.1002360 Medline

107. P. S. Dutta, Y. Sharma, K. C. Abbott, Robustness of early warning signals for catastrophic and non-catastrophic transitions. *Oikos* **127**, 1251–1263 (2018). doi:10.1111/oik.05172

108. C. Boettiger, N. Ross, A. Hastings, Early warning signals: The charted and uncharted territories. *Theor. Ecol.* **6**, 255–264 (2013). doi:10.1007/s12080-013-0192-6

109. C. Kuehn, A mathematical framework for critical transitions: Bifurcations, fast–slow systems and stochastic dynamics. *Physica D* **240**, 1020–1035 (2011). doi:10.1016/j.physd.2011.02.012

110. C. Kuehn, A mathematical framework for critical transitions: Normal forms, variance and applications. *J. Nonlinear Sci.* **23**, 457–510 (2013). doi:10.1007/s00332-012-9158-x

111. N. Irvalı, E. V. Galaasen, U. S. Ninnemann, Y. Rosenthal, A. Born, H. K. F. Kleiven, A low climate threshold for south Greenland Ice Sheet demise during the Late Pleistocene. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 190–195 (2020). doi:10.1073/pnas.1911902116 Medline

112. A. N. Sommers, B. L. Otto-Bliesner, W. H. Lipscomb, M. Lofverstrom, S. L. Shafer, P. J. Bartlein, E. C. Brady, E. Kluzek, G. Leguy, K. Thayer-Calder, R. A. Tomas, Retreat and Regrowth of the Greenland Ice Sheet During the Last Interglacial as Simulated by the CESM2-CISM2 Coupled Climate–Ice Sheet Model. *Paleoceanogr. Paleoclimatol.* **36**, 1–19 (2021). doi:10.1029/2021PA004272

113. A. Aschwanden, M. A. Fahnestock, M. Truffer, D. J. Brinkerhoff, R. Hock, C. Khroulev, R. Mottram, S. A. Khan, Contribution of the Greenland Ice Sheet to sea level over the next millennium. *Sci. Adv.* **5**, eaav9396 (2019). doi:10.1126/sciadv.aav9396 Medline

114. A. Robinson, J. Alvarez-Solas, R. Calov, A. Ganopolski, M. Montoya, MIS-11 duration key to disappearance of the Greenland ice sheet. *Nat. Commun.* **8**, 16008 (2017). doi:10.1038/ncomms16008 Medline

115. N. Wunderling, M. Willeit, J. F. Donges, R. Winkelmann, Global warming due to loss of large ice masses and Arctic summer sea ice. *Nat. Commun.* **11**, 5177 (2020). doi:10.1038/s41467-020-18934-3 Medline

116. K. Pistone, I. Eisenman, V. Ramanathan, Radiative Heating of an Ice-Free Arctic Ocean.

*Geophys. Res. Lett.* **46**, 7474–7480 (2019). doi:10.1029/2019GL082914

117. S. R. Hudson, Estimating the global radiative impact of the sea ice–albedo feedback in the Arctic. *J. Geophys. Res.* **116** (D16), D16102 (2011). doi:10.1029/2011JD015804

118. D. Yumashev, C. Hope, K. Schaefer, K. Riemann-Campe, F. Iglesias-Suarez, E. Jafarov, E. J. Burke, P. J. Young, Y. Elshorbany, G. Whiteman, Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements. *Nat. Commun.* **10**, 1900 (2019). doi:10.1038/s41467-019-09863-x Medline

119. S. Bathiany, D. Notz, T. Mauritsen, G. Raedel, V. Brovkin, On the potential for abrupt Arctic winter sea ice loss. *J. Clim.* **29**, 2703–2719 (2016). doi:10.1175/JCLI-D-15-0466.1

120. D. Pollard, R. M. DeConto, Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature* **458**, 329–332 (2009). doi:10.1038/nature07809 Medline

121. C. Chambers, R. Greve, T. Obase, F. Saito, A. Abe-Ouchi, Mass loss of the Antarctic ice sheet until the year 3000 under a sustained late-21st-century climate. *J. Glaciol.* **68**, 605–617 (2022). doi:10.1017/jog.2021.124

122. R. Winkelmann, A. Levermann, A. Ridgwell, K. Caldeira, Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet. *Sci. Adv.* **1**, e1500589 (2015). doi:10.1126/sciadv.1500589 Medline

123. F. Pattyn, C. Ritz, E. Hanna, X. Asay-Davis, R. DeConto, G. Durand, L. Favier, X. Fettweis, H. Goelzer, N. R. Golledge, P. Kuipers Munneke, J. T. M. Lenaerts, S. Nowicki, A. J. Payne, A. Robinson, H. Seroussi, L. D. Trusel, M. van den Broeke, The Greenland and Antarctic ice sheets under 1.5 °C global warming. *Nat. Clim. Chang.* **8**, 1053–1061 (2018). doi:10.1038/s41558-018-0305-8

124. N. R. Golledge, D. E. Kowalewski, T. R. Naish, R. H. Levy, C. J. Fogwill, E. G. W. Gasson, The multi-millennial Antarctic commitment to future sea-level rise. *Nature* **526**, 421–425 (2015). doi:10.1038/nature15706 Medline

125. M. Yamane, Y. Yokoyama, A. Abe-Ouchi, S. Obrochta, F. Saito, K. Moriwaki, H. Matsuzaki, Exposure age and ice-sheet model constraints on Pliocene East Antarctic ice sheet dynamics. *Nat. Commun.* **6**, 7016 (2015). doi:10.1038/ncomms8016 Medline

126. D. J. Lunt, A. M. Haywood, G. A. Schmidt, U. Salzmann, P. J. Valdes, H. J. Dowsett, C. A. Loptson, On the causes of mid-Pliocene warmth and polar amplification. *Earth Planet. Sci. Lett.* **321–322**, 128–138 (2012). doi:10.1016/j.epsl.2011.12.042

127. R. M. DeConto, D. Pollard, Contribution of Antarctica to past and future sea-level rise. *Nature* **531**, 591–597 (2016). doi:10.1038/nature17145 Medline

128. D. Pollard, R. M. DeConto, R. B. Alley, Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure. *Earth Planet. Sci. Lett.* **412**, 112–121 (2015). doi:10.1016/j.epsl.2014.12.035

129. J. N. Bassis, B. Berg, A. J. Crawford, D. I. Benn, Transition to marine ice cliff instability controlled by ice thickness gradients and velocity. *Science* **372**, 1342–1344 (2021). doi:10.1126/science.abf6271

130. D. P. Lowry, M. Krapp, N. R. Golledge, A. Alevropoulos-Borrill, The influence of emissions scenarios on future Antarctic ice loss is unlikely to emerge this century. *Commun. Earth Environ.* **2**, 221 (2021). doi:10.1038/s43247-021-00289-2

131. J. Etourneau, G. Sgubin, X. Crosta, D. Swingedouw, V. Willmott, L. Barbara, M.-N. Houssais, S. Schouten, J. S. S. Damsté, H. Goosse, C. Escutia, J. Crespin, G. Massé, J.-H. Kim, Ocean temperature impact on ice shelf extent in the eastern Antarctic Peninsula. *Nat. Commun.* **10**, 304 (2019). doi:10.1038/s41467-018-08195-6 Medline

132. K. E. Alley, C. T. Wild, A. Luckman, T. A. Scambos, M. Truffer, E. C. Pettit, A. Muto, B. Wallin, M. Klinger, T. Sutterley, S. F. Child, C. Hulen, J. T. M. Lenaerts, M. Maclennan, E. Keenan, D. Dunmire, Two decades of dynamic change and progressive destabilization on the Thwaites Eastern Ice Shelf. *Cryosphere* **15**, 5187–5203 (2021). doi:10.5194/tc-15-5187-2021

133. C. T. Wild, K. E. Alley, A. Muto, M. Truffer, T. A. Scambos, E. C. Pettit, Weakening of the pinning point buttressing Thwaites Glacier, West Antarctica. *Cryosphere* **16**, 397–417 (2022). doi:10.5194/tc-16-397-2022

134. E. C. Pettit, C. Wild, K. Alley, A. Muto, M. Truffer, D. Benn, in *AGU Fall Meeting* (New Orleans, USA, 2021).

135. P. Milillo, E. Rignot, P. Rizzoli, B. Scheuchl, J. Mouginot, J. L. Bueso-Bello, P. Prats-Iraola, L. Dini, Rapid glacier retreat rates observed in West Antarctica. *Nat. Geosci.* **15**, 48–53 (2022). doi:10.1038/s41561-021-00877-z

136. D. I. Benn, A. Luckman, J. A. Åström, A. J. Crawford, S. L. Cornford, S. Bevan, R. Gladstone, T. Zwinger, K. Alley, E. Pettit, J. Bassis, Rapid fragmentation of Thwaites Eastern Ice Shelf *Cryosphere*, **16**, 2545–2564 (2021). doi:10.5194/tc-16-2545-2022

137. J. N. Bassis, in *APS March Meeting 2022* (Chicago, 2022).

138. A. K. Wåhlin, A. G. C. Graham, K. A. Hogan, B. Y. Queste, L. Boehme, R. D. Larter, E. C. Pettit, J. Wellner, K. J. Heywood, Pathways and modification of warm water flowing beneath Thwaites Ice Shelf, West Antarctica. *Sci. Adv.* **7**, eabd7254 (2021). doi:10.1126/sciadv.abd7254 Medline

139. L. Favier, G. Durand, S. L. Cornford, G. H. Gudmundsson, O. Gagliardini, F. Gillet-Chaulet, T. Zwinger, A. J. Payne, A. M. Le Brocq, Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nat. Clim. Chang.* **4**, 117–121 (2014). doi:10.1038/nclimate2094

140. R. Reese, J. Garbe, E. A. Hill, B. Urruty, K. A. Naughten, O. Gagliardini, G. Durand, F. Gillet-chaulet, D. Chandler, P. M. Langebroek, R. Winkelmann, The stability of present-day Antarctic grounding lines — Part B: Possible commitment of regional collapse under current climate. *The Cryosphere Discuss.* tc-2022-105 [Preprint] (2022); https://tc.copernicus.org/preprints/tc-2022-105/.

141. E. J. Steig, K. Huybers, H. A. Singh, N. J. Steiger, Q. Ding, D. M. W. Frierson, T. Popp, J. W. C. White, Influence of West Antarctic Ice Sheet collapse on Antarctic surface climate. *Geophys. Res. Lett.* **42**, 4862–4868 (2015). doi:10.1002/2015GL063861

142. S. Sun, F. Pattyn, E. G. Simon, T. Albrecht, S. Cornford, R. Calov, C. Dumas, F. Gillet-

Chaulet, H. Goelzer, N. R. Golledge, R. Greve, M. J. Hoffman, A. Humbert, E. Kazmierczak, T. Kleiner, G. R. Leguy, W. H. Lipscomb, D. Martin, M. Morlighem, S. Nowicki, D. Pollard, S. Price, A. Quiquet, H. Seroussi, T. Schlemm, J. Sutter, R. S. W. Van De Wal, R. Winkelmann, T. Zhang, Antarctic ice sheet response to sudden and sustained ice-shelf collapse (ABUMIP). *J. Glaciol.* **66**, 891–904 (2020). doi:10.1017/jog.2020.67

143. M. Mengel, A. Levermann, Ice plug prevents irreversible discharge from east Antarctica. *Nat. Clim. Chang.* **4**, 451–455 (2014). doi:10.1038/nclimate2226

144. R. A. Bertram, D. J. Wilson, T. van de Flierdt, R. M. McKay, M. O. Patterson, F. J. Jimenez-Espejo, C. Escutia, G. C. Duke, B. I. Taylor-Silva, C. R. Riesselman, Pliocene deglacial event timelines and the biogeochemical response offshore Wilkes Subglacial Basin, East Antarctica. *Earth Planet. Sci. Lett.* **494**, 109–116 (2018). doi:10.1016/j.epsl.2018.04.054

145. C. P. Cook, T. Van De Flierdt, T. Williams, S. R. Hemming, M. Iwai, M. Kobayashi, F. J. Jimenez-Espejo, C. Escutia, J. J. González, B. K. Khim, R. M. McKay, S. Passchier, S. M. Bohaty, C. R. Riesselman, L. Tauxe, S. Sugisaki, A. L. Galindo, M. O. Patterson, F. Sangiorgi, E. L. Pierce, H. Brinkhuis, A. Klaus, A. Fehr, J. A. P. Bendle, P. K. Bijl, S. A. Carr, R. B. Dunbar, J. A. Flores, T. G. Hayden, K. Katsuki, G. S. Kong, M. Nakai, M. P. Olney, S. F. Pekar, J. Pross, U. Röhl, T. Sakai, P. K. Shrivastava, C. E. Stickley, S. Tuo, K. Welsh, M. Yamane, Dynamic behaviour of the East Antarctic ice sheet during Pliocene warmth. *Nat. Geosci.* **6**, 765–769 (2013). doi:10.1038/ngeo1889

146. R. M. Deconto, D. Pollard, P. A. Wilson, H. Pälike, C. H. Lear, M. Pagani, Thresholds for Cenozoic bipolar glaciation. *Nature* **455**, 652–656 (2008). doi:10.1038/nature07337 Medline

147. D. I. Armstrong McKay, T. Tyrrell, P. A. Wilson, Global carbon cycle perturbation across the Eocene-Oligocene climate transition. *Paleoceanography* **31**, 311–329 (2016). doi:10.1002/2015PA002818

148. D. K. Hutchinson, H. K. Coxall, D. J. Lunt, M. Steinthorsdottir, A. M. De Boer, M. Baatsen, A. von der Heydt, M. Huber, A. T. Kennedy-Asser, L. Kunzmann, J.-B. Ladant, C. H. Lear, K. Moraweck, P. N. Pearson, E. Piga, M. J. Pound, U. Salzmann, H. D. Scher, W. P. Sijp, K. K. Śliwińska, P. A. Wilson, Z. Zhang, The Eocene-Oligocene transition: a review of marine and terrestrial proxy data, models and model-data comparisons. *Clim. Past.* **17**, 269–315 (2021). doi:10.5194/cp-17-269-2021.

149. B. Marzeion, G. Kaser, F. Maussion, N. Champollion, Limited influence of climate change mitigation on short-term glacier mass loss. *Nat. Clim. Chang.* **8**, 305–308 (2018). doi:10.1038/s41558-018-0093-1

150. B. Marzeion, R. Hock, B. Anderson, A. Bliss, N. Champollion, K. Fujita, M. Huss, W. W. Immerzeel, P. Kraaijenbrink, J. H. Malles, F. Maussion, V. Radić, D. R. Rounce, A. Sakai, S. Shannon, R. van de Wal, H. Zekollari, Partitioning the Uncertainty of Ensemble Projections of Global Glacier Mass Change. *Earths Futur.* **8**, 1–25 (2020). doi:10.1029/2019EF001470

151. S. E. Chadburn, E. J. Burke, P. M. Cox, P. Friedlingstein, G. Hugelius, S. Westermann, An observation-based constraint on permafrost loss as a function of global warming. *Nat.*

*Clim. Chang.* **7**, 340–344 (2017). doi:10.1038/nclimate3262

152. D. V. Khvorostyanov, P. Ciais, G. Krinner, S. A. Zimov, Vulnerability of east Siberia's frozen carbon stores to future warming. *Geophys. Res. Lett.* **35**, 1–5 (2008). doi:10.1029/2008GL033639
153. T. Schneider von Deimling, G. Grosse, J. Strauss, L. Schirrmeister, A. Morgenstern, S. Schaphoff, M. Meinshausen, J. Boike, Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences* **12**, 3469–3488 (2015). doi:10.5194/bg-12-3469-2015
154. D. V. Khvorostyanov, P. Ciais, G. Krinner, S. A. Zimov, C. Corradi, G. Guggenberger, Vulnerability of permafrost carbon to global warming. Part II: Sensitivity of permafrost carbon stock to global warming. *Tellus B: Chem. Phys. Meteorol.* **60**, 265–275 (2008) doi:10.1111/j.1600-0889.2007.00336.x.
155. J. Obu, S. Westermann, A. Bartsch, N. Berdnikov, H. H. Christiansen, A. Dashtseren, R. Delaloye, B. Elberling, B. Etzelmüller, A. Kholodov, A. Khomutov, A. Kääb, M. O. Leibman, A. G. Lewkowicz, S. K. Panda, V. Romanovsky, R. G. Way, A. Westergaard-Nielsen, T. Wu, J. Yamkhin, D. Zou, Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km2 scale. *Earth Sci. Rev.* **193**, 299–316 (2019). doi:10.1016/j.earscirev.2019.04.023
156. FAO, ITPS, *Recarbonizing global soils – A technical manual of recommended management practices* (FAO, 2021); https://www.fao.org/documents/card/en/c/cb6378en
157. C. Schädel, E. A. G. Schuur, R. Bracho, B. Elberling, C. Knoblauch, H. Lee, Y. Luo, G. R. Shaver, M. R. Turetsky, Circumpolar assessment of permafrost C quality and its vulnerability over time using long-term incubation data. *Glob. Change Biol.* **20**, 641–652 (2014). doi:10.1111/gcb.12417 Medline
158. B. Elberling, A. Michelsen, C. Schädel, E. A. G. Schuur, H. H. Christiansen, L. Berg, M. P. Tamstorf, C. Sigsgaard, Long-term CO2 production following permafrost thaw. *Nat. Clim. Chang.* **3**, 890–894 (2013). doi:10.1038/nclimate1955
159. D. V. Khvorostyanov, G. Krinner, P. Ciais, M. Heimann, S. A. Zimov, Vulnerability of permafrost carbon to global warming. Part I: Model description and role of heat generated by organic matter decomposition. *Tellus B: Chem. Phys. Meteorol..* **60**, 250–264 (2008). doi:10.1111/j.1600-0889.2007.00333.x
160. S. Schaphoff, U. Heyder, S. Ostberg, D. Gerten, J. Heinke, W. Lucht, Contribution of permafrost soils to the global carbon budget. *Environ. Res. Lett.* **8**, 014026 (2013). doi:10.1088/1748-9326/8/1/014026
161. M. R. Turetsky, B. W. Abbott, M. C. Jones, K. Walter Anthony, D. Olefeldt, E. A. G. Schuur, C. Koven, A. D. McGuire, G. Grosse, P. Kuhry, G. Hugelius, D. M. Lawrence, C. Gibson, A. B. K. Sannel, Permafrost collapse is accelerating carbon release. *Nature* **569**, 32–34 (2019). doi:10.1038/d41586-019-01313-4 Medline
162. D. Olefeldt, S. Goswami, G. Grosse, D. Hayes, G. Hugelius, P. Kuhry, A. D. McGuire, V. E. Romanovsky, A. B. K. Sannel, E. A. G. Schuur, M. R. Turetsky, Circumpolar distribution and carbon storage of thermokarst landscapes. *Nat. Commun.* **7**, 13043 (2016). doi:10.1038/ncomms13043 Medline

163. A. Vaks, A. J. Mason, S. F. M. Breitenbach, A. M. Kononov, A. V. Osinzev, M. Rosensaft, A. Borshevsky, O. S. Gutareva, G. M. Henderson, Palaeoclimate evidence of vulnerable permafrost during times of low sea ice. *Nature* **577**, 221–225 (2020). doi:10.1038/s41586-019-1880-1 Medline

164. K. Schaefer, H. Lantuit, V. E. Romanovsky, E. A. G. Schuur, R. Witt, The impact of the permafrost carbon feedback on global climate. *Environ. Res. Lett.* **9**, 085003 (2014). doi:10.1088/1748-9326/9/8/085003

165. C. D. Koven, D. M. Lawrence, W. J. Riley, Permafrost carbon-climate feedback is sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 3752–3757 (2015). doi:10.1073/pnas.1415123112 Medline

166. A. D. McGuire, D. M. Lawrence, C. Koven, J. S. Clein, E. Burke, G. Chen, E. Jafarov, A. H. MacDougall, S. Marchenko, D. Nicolsky, S. Peng, A. Rinke, P. Ciais, I. Gouttevin, D. J. Hayes, D. Ji, G. Krinner, J. C. Moore, V. Romanovsky, C. Schädel, K. Schaefer, E. A. G. Schuur, Q. Zhuang, Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 3882–3887 (2018). doi:10.1073/pnas.1719903115 Medline

167. A. H. MacDougall, C. A. Avis, A. J. Weaver, Significant contribution to climate warming from the permafrost carbon feedback. *Nat. Geosci.* **5**, 719–721 (2012). doi:10.1038/ngeo1573

168. F. Cheng, C. Garzione, X. Li, U. Salzmann, F. Schwarz, A. M. Haywood, J. Tindall, J. Nie, L. Li, L. Wang, B. W. Abbott, B. Elliott, W. Liu, D. Upadhyay, A. Arnold, A. Tripati, Alpine permafrost could account for a quarter of thawed carbon based on Plio-Pleistocene paleoclimate analogue. *Nat. Commun.* **13**, 1329 (2022). doi:10.1038/s41467-022-29011-2 Medline

169. R. E. Fewster, P. J. Morris, R. F. Ivanovic, G. T. Swindles, A. M. Peregon, C. J. Smith, Imminent loss of climate space for permafrost peatlands in Europe and Western Siberia. *Nat. Clim. Chang.* **12**, 373–379 (2022). doi:10.1038/s41558-022-01296-7

170. N. Chandra, P. K. Patra, J. S. H. Bisht, A. Ito, T. Umezawa, N. Saigusa, S. Morimoto, S. Aoki, G. Janssens-Maenhout, R. Fujita, M. Takigawa, S. Watanabe, N. Saitoh, J. G. Canadell, Emissions from the Oil and Gas Sectors, Coal Mining and Ruminant Farming Drive Methane Growth over the Past Three Decades. *J. Meteorol. Soc. Jpn.* **99**, 309–337 (2021). doi:10.2151/jmsj.2021-015

171. M. Saunois, A. R. Stavert, B. Poulter, P. Bousquet, J. G. Canadell, R. B. Jackson, P. A. Raymond, E. J. Dlugokencky, S. Houweling, P. K. Patra, P. Ciais, V. K. Arora, D. Bastviken, P. Bergamaschi, D. R. Blake, G. Brailsford, L. Bruhwiler, K. M. Carlson, M. Carrol, S. Castaldi, N. Chandra, C. Crevoisier, P. M. Crill, K. Covey, C. L. Curry, G. Etiope, C. Frankenberg, N. Gedney, M. I. Hegglin, L. Höglund-Isaksson, G. Hugelius, M. Ishizawa, A. Ito, G. Janssens-Maenhout, K. M. Jensen, F. Joos, T. Kleinen, P. B. Krummel, R. L. Langenfelds, G. G. Laruelle, L. Liu, T. Machida, S. Maksyutov, K. C. McDonald, J. McNorton, P. A. Miller, J. R. Melton, I. Morino, J. Müller, F. Murguia-Flores, V. Naik, Y. Niwa, S. Noce, S. O'Doherty, R. J. Parker, C. Peng, S. Peng, G. P. Peters, C. Prigent, R. Prinn, M. Ramonet, P. Regnier, W. J. Riley, J. A. Rosentreter, A. Segers, I. J. Simpson, H. Shi, S. J. Smith, L. P. Steele, B. F. Thornton, H. Tian, Y.

Tohjima, F. N. Tubiello, A. Tsuruta, N. Viovy, A. Voulgarakis, T. S. Weber, M. van Weele, G. R. van der Werf, R. F. Weiss, D. Worthy, D. Wunch, Y. Yin, Y. Yoshida, W. Zhang, Z. Zhang, Y. Zhao, B. Zheng, Q. Zhu, Q. Zhu, Q. Zhuang, The Global Methane Budget 2000–2017. *Earth Syst. Sci. Data* **12**, 1561–1623 (2020). doi:10.5194/essd-12-1561-2020

172. E. J. Burke, A. Ekici, Y. Huang, S. E. Chadburn, C. Huntingford, P. Ciais, P. Friedlingstein, S. Peng, G. Krinner, Quantifying uncertainties of permafrost carbon–climate feedbacks. *Biogeosciences* **14**, 3051–3066 (2017). doi:10.5194/bg-14-3051-2017

173. C. D. Koven, W. J. Riley, A. Stern, Analysis of Permafrost Thermal Dynamics and Response to Climate Change in the CMIP5 Earth System Models. *J. Clim.* **26**, 1877–1900 (2013). doi:10.1175/JCLI-D-12-00228.1

174. M. Meinshausen, Z. R. J. Nicholls, J. Lewis, M. J. Gidden, E. Vogel, M. Freund, U. Beyerle, C. Gessner, A. Nauels, N. Bauer, J. G. Canadell, J. S. Daniel, A. John, P. B. Krummel, G. Luderer, N. Meinshausen, S. A. Montzka, P. J. Rayner, S. Reimann, S. J. Smith, M. van den Berg, G. J. M. Velders, M. K. Vollmer, R. H. J. Wang, The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev.* **13**, 3571–3605 (2020). doi:10.5194/gmd-13-3571-2020

175. C. D. Koven, E. A. G. Schuur, C. Schädel, T. J. Bohn, E. J. Burke, G. Chen, X. Chen, P. Ciais, G. Grosse, J. W. Harden, D. J. Hayes, G. Hugelius, E. E. Jafarov, G. Krinner, P. Kuhry, D. M. Lawrence, A. H. MacDougall, S. S. Marchenko, A. D. McGuire, S. M. Natali, D. J. Nicolsky, D. Olefeldt, S. Peng, V. E. Romanovsky, K. M. Schaefer, J. Strauss, C. C. Treat, M. Turetsky, A simplified, data-constrained approach to estimate the permafrost carbon-climate feedback. *Philos. Trans. R. Soc. A* **373**, 20140423 (2015). Medline

176. K. Isaksen, Ø. Nordli, B. Ivanov, M. A. Ø. Køltzow, S. Aaboe, H. M. Gjelten, A. Mezghani, S. Eastwood, E. Førland, R. E. Benestad, I. Hanssen-Bauer, R. Brækkan, P. Sviashchennikov, V. Demin, A. Revina, T. Karandasheva, Exceptional warming over the Barents area. *Sci. Rep.* **12**, 9371 (2022). Medline

177. H. Bailey, A. Hubbard, E. S. Klein, K.-R. Mustonen, P. D. Akers, H. Marttila, J. M. Welker, Arctic sea-ice loss fuels extreme European snowfall. *Nat. Geosci.* **14**, 283–288 (2021). doi:10.1038/s41561-021-00719-y

178. P. Bakker, A. Schmittner, J. T. M. Lenaerts, A. Abe-Ouchi, D. Bi, M. R. van den Broeke, W.-L. Chan, A. Hu, R. L. Beadling, S. J. Marsland, S. H. Mernild, O. A. Saenko, D. Swingedouw, A. Sullivan, J. Yin, Fate of the Atlantic Meridional Overturning Circulation: Strong decline under continued warming and Greenland melting. *Geophys. Res. Lett.* **43**, 12,252–12,260 (2016). doi:10.1002/2016GL070457

179. J. T. M. Lenaerts, D. Le Bars, L. van Kampenhout, M. Vizcaino, E. M. Enderlin, M. R. van den Broeke, Representing Greenland ice sheet freshwater fluxes in climate models. *Geophys. Res. Lett.* **42**, 6373–6381 (2015). doi:10.1002/2015GL064738

180. L. Caesar, G. D. McCarthy, D. J. R. Thornalley, N. Cahill, S. Rahmstorf, Current Atlantic Meridional Overturning Circulation weakest in last millennium. *Nat. Geosci.* **14**, 118–120 (2021). doi:10.1038/s41561-021-00699-z

181. L. C. Jackson, A. Biastoch, M. W. Buckley, D. G. Desbruyères, E. Frajka-Williams, B. Moat, J. Robson, The evolution of the North Atlantic Meridional Overturning Circulation since 1980. *Nat. Rev. Earth Environ.* **3**, 241–254 (2022). doi:10.1038/s43017-022-00263-2

182. K. H. Kilbourne, A. D. Wanamaker, P. Moffa-Sanchez, D. J. Reynolds, D. E. Amrhein, P. G. Butler, G. Gebbie, M. Goes, M. F. Jansen, C. M. Little, M. Mette, E. Moreno-Chamarro, P. Ortega, B. L. Otto-Bliesner, T. Rossby, J. Scourse, N. M. Whitney, Atlantic circulation change still uncertain. *Nat. Geosci.* **15**, 165–167 (2022). doi:10.1038/s41561-022-00896-4

183. L. C. Jackson, R. A. Wood, Timescales of AMOC decline in response to fresh water forcing. *Clim. Dyn.* **51**, 1333–1350 (2018). doi:10.1007/s00382-017-3957-6

184. W. Liu, A. V. Fedorov, S.-P. Xie, S. Hu, Climate impacts of a weakened Atlantic Meridional Overturning Circulation in a warming climate. *Sci. Adv.* **6**, eaaz4876 (2020). doi:10.1126/sciadv.aaz4876 Medline

185. A. M. Dixon, P. M. Forster, S. F. Heron, A. M. K. Stoner, M. Beger, Future loss of local-scale thermal refugia in coral reef ecosystems. *PLOS Clim.* **1**, e0000004 (2022). doi:10.1371/journal.pclm.0000004

186. C. F. Schleussner, T. K. Lissner, E. M. Fischer, J. Wohland, M. Perrette, A. Golly, J. Rogelj, K. Childers, J. Schewe, K. Frieler, M. Mengel, W. Hare, M. Schaeffer, Differential climate impacts for policy-relevant limits to global warming: The case of 1.5 °c and 2 °c. *Earth Syst. Dyn.* **7**, 327–351 (2016). doi:10.5194/esd-7-327-2016

187. J. K. McWhorter, P. R. Halloran, G. Roff, W. J. Skirving, C. T. Perry, P. J. Mumby, The importance of 1.5°C warming for the Great Barrier Reef. *Glob. Chang. Biol*. **28**, 1332–1341 (2021) doi:10.1111/gcb.15994.

188. S. I. Seneviratne, J. Rogelj, R. Séférian, R. Wartenburger, M. R. Allen, M. Cain, R. J. Millar, K. L. Ebi, N. Ellis, O. Hoegh-Guldberg, A. J. Payne, C. F. Schleussner, P. Tschakert, R. F. Warren, The many possible climates from the Paris Agreement’s aim of 1.5 °C warming. *Nature* **558**, 41–49 (2018). doi:10.1038/s41586-018-0181-4 Medline

189. S. Bathiany, M. Claussen, V. Brovkin, CO2-induced sahel greening in three CMIP5 earth system models. *J. Clim.* **27**, 7163–7184 (2014). doi:10.1175/JCLI-D-13-00528.1

190. P. Chang, R. Zhang, W. Hazeleger, C. Wen, X. Wan, L. Ji, R. J. Haarsma, W.-P. Breugem, H. Seidel, Oceanic link between abrupt changes in the North Atlantic Ocean and the African monsoon. *Nat. Geosci.* **1**, 444–448 (2008). doi:10.1038/ngeo218

191. K. H. Cook, E. K. Vizy, Coupled Model Simulations of the West African Monsoon System: Twentieth- and Twenty-First-Century Simulations. *J. Clim.* **19**, 3681–3703 (2006). doi:10.1175/JCLI3814.1

192. J. Raj, H. K. Bangalath, G. Stenchikov, West African Monsoon: Current state and future projections in a high-resolution AGCM. *Clim. Dyn.* **52**, 6441–6461 (2019). doi:10.1007/s00382-018-4522-7

193. M. Biasutti, Forced Sahel rainfall trends in the CMIP5 archive. *J. Geophys. Res. Atmos.* **118**, 1613–1623 (2013). doi:10.1002/jgrd.50206

194. T. M. Shanahan, N. P. Mckay, K. A. Hughen, J. T. Overpeck, B. Otto-Bliesner, C. W. Heil, J. King, C. A. Scholz, J. Peck, The time-transgressive termination of the African humid period. *Nat. Geosci.* **8**, 140–144 (2015). doi:10.1038/ngeo2329

195. F. S. R. Pausata, G. Messori, Q. Zhang, Impacts of dust reduction on the northward expansion of the African monsoon during the Green Sahara period. *Earth Planet. Sci. Lett.* **434**, 298–307 (2016). doi:10.1016/j.epsl.2015.11.049

196. D. Chandan, W. R. Peltier, African Humid Period Precipitation Sustained by Robust Vegetation, Soil, and Lake Feedbacks. *Geophys. Res. Lett.* **47**, 1–12 (2020). doi:10.1029/2020GL088728

197. J. A. Collins, M. Prange, T. Caley, L. Gimeno, B. Beckmann, S. Mulitza, C. Skonieczny, D. Roche, E. Schefuß, Rapid termination of the African Humid Period triggered by northern high-latitude cooling. *Nat. Commun.* **8**, 1372 (2017). doi:10.1038/s41467-017-01454-y Medline

198. D. Gerten, H. Hoff, J. Rockström, J. Jägermeyr, M. Kummu, A. V. Pastor, Towards a revised planetary boundary for consumptive freshwater use: Role of environmental flow requirements. *Curr. Opin. Environ. Sustain.* **5**, 551–558 (2013). doi:10.1016/j.cosust.2013.11.001

199. W. Lucht, S. Schaphoff, T. Erbrecht, U. Heyder, W. Cramer, Terrestrial vegetation redistribution and carbon balance under climate change. *Carbon Balance Manag.* **1**, 6 (2006). doi:10.1186/1750-0680-1-6 Medline

200. A. J. Winkler, R. B. Myneni, A. Hannart, S. Sitch, V. Haverd, D. Lombardozzi, V. K. Arora, J. Pongratz, J. E. M. S. Nabel, D. S. Goll, E. Kato, H. Tian, A. Arneth, P. Friedlingstein, A. K. Jain, S. Zaehle, V. Brovkin, Slowdown of the greening trend in natural vegetation with further rise in atmospheric $CO_2$. *Biogeosciences* **18**, 4985–5010 (2021). doi:10.5194/bg-18-4985-2021

201. Y. Pan, R. A. Birdsey, J. Fang, R. Houghton, P. E. Kauppi, W. A. Kurz, O. L. Phillips, A. Shvidenko, S. L. Lewis, J. G. Canadell, P. Ciais, R. B. Jackson, S. W. Pacala, A. D. McGuire, S. Piao, A. Rautiainen, S. Sitch, D. Hayes, A Large and Persistent Carbon Sink in the World's Forests. *Science* **333**, 988–993 (2011). doi:10.1126/science.1201609

202. C. J. A. Bradshaw, I. G. Warkentin, Global estimates of boreal forest carbon stocks and flux. *Global Planet. Change* **128**, 24–30 (2015). doi:10.1016/j.gloplacha.2015.02.004

203. M. Thurner, C. Beer, M. Santoro, N. Carvalhais, T. Wutzler, D. Schepaschenko, A. Shvidenko, E. Kompter, B. Ahrens, S. R. Levick, C. Schmullius, Carbon stock and density of northern boreal and temperate forests. *Glob. Ecol. Biogeogr.* **23**, 297–310 (2014). doi:10.1111/geb.12125

204. S. Bathiany, M. Claussen, V. Brovkin, T. Raddatz, V. Gayler, Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI earth system model. *Biogeosciences* **7**, 1383–1399 (2010). doi:10.5194/bg-7-1383-2010

205. D. Lawrence, M. Coe, W. Walker, L. Verchot, K. Vandecar, The Unseen Effects of Deforestation: Biophysical Effects on Climate. *Front. For. Glob. Chang.* **5**, ffgc.2022.756115 (2022). doi:10.3389/ffgc.2022.756115

206. G. B. Bonan, Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science* **320**, 1444–1450 (2008). doi:10.1126/science.1155121

207. B. Abis, V. Brovkin, Alternative tree-cover states of the boreal ecosystem: A conceptual model. *Glob. Ecol. Biogeogr.* **28**, 612–627 (2019). doi:10.1111/geb.12880

208. R. G. Pearson, S. J. Phillips, M. M. Loranty, P. S. A. Beck, T. Damoulas, S. J. Knight, S. J. Goetz, Shifts in Arctic vegetation and associated feedbacks under climate change. *Nat. Clim. Chang.* **3**, 673–677 (2013). doi:10.1038/nclimate1858

209. W. Zhang, P. A. Miller, B. Smith, R. Wania, T. Koenigk, R. Döscher, Tundra shrubification and tree-line advance amplify arctic climate warming: Results from an individual-based dynamic vegetation model. *Environ. Res. Lett.* **8**, 034023 (2013). doi:10.1088/1748-9326/8/3/034023

210. O. A. Carpino, A. A. Berg, W. L. Quinton, J. R. Adams, Climate change and permafrost thaw-induced boreal forest loss in northwestern Canada. *Environ. Res. Lett.* **13**, 084018 (2018). doi:10.1088/1748-9326/aad74e

211. K. D. Dearborn, C. A. Wallace, R. Patankar, J. L. Baltzer, Permafrost thaw in boreal peatlands is rapidly altering forest community composition. *J. Ecol.* **109**, 1452–1467 (2021). doi:10.1111/1365-2745.13569

212. G. Grosse, S. Goetz, A. D. McGuire, V. E. Romanovsky, E. A. G. Schuur, Changing permafrost in a warming world and feedbacks to the Earth system. *Environ. Res. Lett.* **11**, 040201 (2016). doi:10.1088/1748-9326/11/4/040201

213. M. Williams, Y. Zhang, C. Estop-Aragonés, J. P. Fisher, G. Xenakis, D. J. Charman, I. P. Hartley, J. B. Murton, G. K. Phoenix, Boreal permafrost thaw amplified by fire disturbance and precipitation increases. *Environ. Res. Lett.* **15**, 114050 (2020). doi:10.1088/1748-9326/abbeb8

214. C. M. Gibson, L. E. Chasmer, D. K. Thompson, W. L. Quinton, M. D. Flannigan, D. Olefeldt, Wildfire as a major driver of recent permafrost thaw in boreal peatlands. *Nat. Commun.* **9**, 3041 (2018). doi:10.1038/s41467-018-05457-1 Medline

215. M. Hirota, M. Holmgren, E. H. Van Nes, M. Scheffer, Global Resilience of Tropical Forest and Savanna to Critical Transitions. *Science* **334**, 232–235 (2011). doi:10.1126/science.1210657

216. I. Parry, P. Ritchie, P. Cox, Evidence of Amazon rainforest dieback in CMIP6 models. *EGUsphere* egusphere-2022-82 [Preprint] (2022); https://egusphere.copernicus.org/preprints/2022/egusphere-2022-82/.

217. C. Jones, J. Lowe, S. Liddicoat, R. Betts, Committed terrestrial ecosystem changes due to climate change. *Nat. Geosci.* **2**, 484–487 (2009). doi:10.1038/ngeo555

218. J. D. Anadón, O. E. Sala, F. T. Maestre, Climate change will increase savannas at the expense of forests and treeless vegetation in tropical and subtropical Americas. *J. Ecol.* **102**, 1363–1373 (2014). doi:10.1111/1365-2745.12325

219. P. M. Brando, B. Soares-Filho, L. Rodrigues, A. Assunção, D. Morton, D. Tuchschneider, E. C. M. Fernandes, M. N. Macedo, U. Oliveira, M. T. Coe, The gathering firestorm in southern Amazonia. *Sci. Adv.* **6**, eaay1632 (2020). doi:10.1126/sciadv.aay1632 Medline

220. R. A. Betts, N. W. Arnell, P. M. Boorman, S. E. Cornell, J. I. House, N. R. Kaye, M. P. McCarthy, D. J. McNeall, M. G. Sanderson, A. J. Wiltshire, in *Understanding the Earth System*, S. Cornell, I. C. Prentice, J. House, C. Downy, Eds. (Cambridge Univ. Press, 2012; doi:10.1017/CBO9780511921155.009, pp. 160–201.

221. L. F. Salazar, C. A. Nobre, Climate change and thresholds of biome shifts in Amazonia. *Geophys. Res. Lett.* **37**, 2010GL043538 (2010). doi:10.1029/2010GL043538

222. P. Zelazowski, Y. Malhi, C. Huntingford, S. Sitch, J. B. Fisher, Changes in the potential distribution of humid tropical forests on a warmer planet. *Philos. Trans. R. Soc. A* **369**, 137–160 (2011). Medline

223. C. A. Boulton, B. B. B. Booth, P. Good, Exploring uncertainty of Amazon dieback in a perturbed parameter Earth system ensemble. *Glob. Change Biol.* **23**, 5032–5044 (2017). doi:10.1111/gcb.13733 Medline

224. C. Lyon, E. E. Saupe, C. J. Smith, D. J. Hill, A. P. Beckerman, L. C. Stringer, R. Marchant, J. McKay, A. Burke, P. O'Higgins, A. M. Dunhill, B. J. Allen, J. Riel-Salvatore, T. Aze, Climate change research and action must look beyond 2100. *Glob. Chang. Biol.* **28**, 349–361 (2021). doi:10.1111/gcb.15871

225. C. A. Boulton, P. Good, T. M. Lenton, Early warning signals of simulated Amazon rainforest dieback. *Theor. Ecol.* **6**, 373–384 (2013). doi:10.1007/s12080-013-0191-7

226. M. J. P. Sullivan, S. L. Lewis, K. Affum-Baffoe, C. Castilho, F. Costa, A. C. Sanchez, C. E. N. Ewango, W. Hubau, B. Marimon, A. Monteagudo-Mendoza, L. Qie, B. Sonké, R. V. Martinez, T. R. Baker, R. J. W. Brienen, T. R. Feldpausch, D. Galbraith, M. Gloor, Y. Malhi, S.-I. Aiba, M. N. Alexiades, E. C. Almeida, E. A. de Oliveira, E. Á. Dávila, P. A. Loayza, A. Andrade, S. A. Vieira, L. E. O. C. Aragão, A. Araujo-Murakami, E. J. M. M. Arets, L. Arroyo, P. Ashton, G. Aymard C, F. B. Baccaro, L. F. Banin, C. Baraloto, P. B. Camargo, J. Barlow, J. Barroso, J.-F. Bastin, S. A. Batterman, H. Beeckman, S. K. Begne, A. C. Bennett, E. Berenguer, N. Berry, L. Blanc, P. Boeckx, J. Bogaert, D. Bonal, F. Bongers, M. Bradford, F. Q. Brearley, T. Brncic, F. Brown, B. Burban, J. L. Camargo, W. Castro, C. Céron, S. C. Ribeiro, V. C. Moscoso, J. Chave, E. Chezeaux, C. J. Clark, F. C. de Souza, M. Collins, J. A. Comiskey, F. C. Valverde, M. C. Medina, L. da Costa, M. Dančák, G. C. Dargie, S. Davies, N. D. Cardozo, T. de Haulleville, M. B. de Medeiros, J. del Aguila Pasquel, G. Derroire, A. Di Fiore, J.-L. Doucet, A. Dourdain, V. Droissart, L. F. Duque, R. Ekoungoulou, F. Elias, T. Erwin, A. Esquivel-Muelbert, S. Fauset, J. Ferreira, G. F. Llampazo, E. Foli, A. Ford, M. Gilpin, J. S. Hall, K. C. Hamer, A. C. Hamilton, D. J. Harris, T. B. Hart, R. Hédl, B. Herault, R. Herrera, N. Higuchi, A. Hladik, E. H. Coronado, I. Huamantupa-Chuquimaco, W. H. Huasco, K. J. Jeffery, E. Jimenez-Rojas, M. Kalamandeen, M. N. K. Djuikouo, E. Kearsley, R. K. Umetsu, L. K. Kho, T. Killeen, K. Kitayama, B. Klitgaard, A. Koch, N. Labrière, W. Laurance, S. Laurance, M. E. Leal, A. Levesley, A. J. N. Lima, J. Lisingo, A. P. Lopes, G. Lopez-Gonzalez, T. Lovejoy, J. C. Lovett, R. Lowe, W. E. Magnusson, J. Malumbres-Olarte, Â. G. Manzatto, B. H. Marimon, A. R. Marshall, T. Marthews, S. M. de Almeida Reis, C. Maycock, K. Melgaço, C. Mendoza, F. Metali, V. Mihindou, W. Milliken, E. T. A. Mitchard, P. S. Morandi, H. L. Mossman, L. Nagy, H. Nascimento, D. Neill, R. Nilus, P. N. Vargas, W. Palacios, N. P. Camacho, J. Peacock, C. Pendry, M. C. Peñuela Mora, G. C. Pickavance, J. Pipoly, N. Pitman, M. Playfair, L. Poorter, J. R. Poulsen, A. D. Poulsen,

R. Preziosi, A. Prieto, R. B. Primack, H. Ramírez-Angulo, J. Reitsma, M. Réjou-Méchain, Z. R. Correa, T. R. de Sousa, L. R. Bayona, A. Roopsind, A. Rudas, E. Rutishauser, K. Abu Salim, R. P. Salomão, J. Schietti, D. Sheil, R. C. Silva, J. S. Espejo, C. S. Valeria, M. Silveira, M. Simo-Droissart, M. F. Simon, J. Singh, Y. C. Soto Shareva, C. Stahl, J. Stropp, R. Sukri, T. Sunderland, M. Svátek, M. D. Swaine, V. Swamy, H. Taedoumg, J. Talbot, J. Taplin, D. Taylor, H. ter Steege, J. Terborgh, R. Thomas, S. C. Thomas, A. Torres-Lezama, P. Umunay, L. V. Gamarra, G. van der Heijden, P. van der Hout, P. van der Meer, M. van Nieuwstadt, H. Verbeeck, R. Vernimmen, A. Vicentini, I. C. G. Vieira, E. V. Torre, J. Vleminckx, V. Vos, O. Wang, L. J. T. White, S. Willcock, J. T. Woods, V. Wortel, K. Young, R. Zagt, L. Zemagho, P. A. Zuidema, J. A. Zwerts, O. L. Phillips, Long-term thermal sensitivity of Earth's tropical forests. *Science* **368**, 869–874 (2020). doi:10.1126/science.aaw7578

227. G. Sampaio, M. H. Shimizu, C. A. Guimarães-Júnior, F. Alexandre, M. Guatura, M. Cardoso, T. F. Domingues, A. Rammig, C. von Randow, L. F. C. Rezende, D. M. Lapola, $CO_2$ physiological effect can cause rainfall decrease as strong as large-scale deforestation in the Amazon. *Biogeosciences* **18**, 2511–2525 (2021). doi:10.5194/bg-18-2511-2021

228. Science Panel for the Amazon (SPA), "Amazon Assessment Report 2021" Nobre C, Encalada A, Anderson E, Roca Alcazar FH, Bustamante M, Mena C, Peña-Claros M, Poveda G, Rodriguez JP, Saleska S, Trumbore S, Val AL, Villa Nova L, Abramovay R, Alencar A, Rodríguez Alzza C, Armenteras D, Artaxo P, Athayde S, Barretto Filho HT, Barlow J, Berenguer E, Bortolotto F, Costa FA, Costa MH, Cuvi N, Fearnside PM, Ferreira J, Flores BM, Frieri S, Gatti LV, Guayasamin JM, Hecht S, Hirota M, Hoorn C, Josse C, Lapola DM, Larrea C, Larrea-Alcazar DM, Lehm Ardaya Z, Malhi Y, Marengo JA, Melack J, Moraes R M, Moutinho P, Murmis MR, Neves EG, Paez B, Painter L, Ramos A, Rosero-Peña MC, Schmink M, Sist P, ter Steege H, Val P, van der Voort H, Varese M, Zapata-Ríos G, Eds. (United Nations Sustainable Development Solutions Network, 2021); https://www.theamazonwewant.org/spa-reports/. DOI: 10.55161/RWSX6527

229. L. V. Gatti, L. S. Basso, J. B. Miller, M. Gloor, L. Gatti Domingues, H. L. G. Cassol, G. Tejada, L. E. O. C. Aragão, C. Nobre, W. Peters, L. Marani, E. Arai, A. H. Sanches, S. M. Corrêa, L. Anderson, C. Von Randow, C. S. C. Correia, S. P. Crispim, R. A. L. Neves, Amazonia as a carbon source linked to deforestation and climate change. *Nature* **595**, 388–393 (2021). doi:10.1038/s41586-021-03629-6 Medline

230. R. J. W. Brienen, O. L. Phillips, T. R. Feldpausch, E. Gloor, T. R. Baker, J. Lloyd, G. Lopez-Gonzalez, A. Monteagudo-Mendoza, Y. Malhi, S. L. Lewis, R. Vásquez Martinez, M. Alexiades, E. Álvarez Dávila, P. Alvarez-Loayza, A. Andrade, L. E. O. C. Aragão, A. Araujo-Murakami, E. J. M. M. Arets, L. Arroyo, G. Aymard C, O. S. Bánki, C. Baraloto, J. Barroso, D. Bonal, R. G. A. Boot, J. L. C. Camargo, C. V. Castilho, V. Chama, K. J. Chao, J. Chave, J. A. Comiskey, F. Cornejo Valverde, L. da Costa, E. A. de Oliveira, A. Di Fiore, T. L. Erwin, S. Fauset, M. Forsthofer, D. R. Galbraith, E. S. Grahame, N. Groot, B. Hérault, N. Higuchi, E. N. Honorio Coronado, H. Keeling, T. J. Killeen, W. F. Laurance, S. Laurance, J. Licona, W. E. Magnussen, B. S. Marimon, B. H. Marimon-Junior, C. Mendoza, D. A. Neill, E. M. Nogueira, P. Núñez, N. C. Pallqui Camacho, A. Parada, G. Pardo-Molina, J. Peacock, M. Peña-Claros, G. C. Pickavance, N. C. A. Pitman, L. Poorter, A. Prieto, C. A. Quesada, F. Ramírez, H. Ramírez-Angulo, Z.

Restrepo, A. Roopsind, A. Rudas, R. P. Salomão, M. Schwarz, N. Silva, J. E. Silva-Espejo, M. Silveira, J. Stropp, J. Talbot, H. ter Steege, J. Teran-Aguilar, J. Terborgh, R. Thomas-Caesar, M. Toledo, M. Torello-Raventos, R. K. Umetsu, G. M. F. van der Heijden, P. van der Hout, I. C. Guimarães Vieira, S. A. Vieira, E. Vilanova, V. A. Vos, R. J. Zagt, Long-term decline of the Amazon carbon sink. *Nature* **519**, 344–348 (2015). doi:10.1038/nature14283 Medline

231. A. Esquivel-Muelbert, T. R. Baker, K. G. Dexter, S. L. Lewis, R. J. W. Brienen, T. R. Feldpausch, J. Lloyd, A. Monteagudo-Mendoza, L. Arroyo, E. Álvarez-Dávila, N. Higuchi, B. S. Marimon, B. H. Marimon-Junior, M. Silveira, E. Vilanova, E. Gloor, Y. Malhi, J. Chave, J. Barlow, D. Bonal, N. Davila Cardozo, T. Erwin, S. Fauset, B. Hérault, S. Laurance, L. Poorter, L. Qie, C. Stahl, M. J. P. Sullivan, H. ter Steege, V. A. Vos, P. A. Zuidema, E. Almeida, E. Almeida de Oliveira, A. Andrade, S. A. Vieira, L. Aragão, A. Araujo-Murakami, E. Arets, G. A. Aymard C, C. Baraloto, P. B. Camargo, J. G. Barroso, F. Bongers, R. Boot, J. L. Camargo, W. Castro, V. Chama Moscoso, J. Comiskey, F. Cornejo Valverde, A. C. Lola da Costa, J. del Aguila Pasquel, A. Di Fiore, L. Fernanda Duque, F. Elias, J. Engel, G. Flores Llampazo, D. Galbraith, R. Herrera Fernández, E. Honorio Coronado, W. Hubau, E. Jimenez-Rojas, A. J. N. Lima, R. K. Umetsu, W. Laurance, G. Lopez-Gonzalez, T. Lovejoy, O. Aurelio Melo Cruz, P. S. Morandi, D. Neill, P. Núñez Vargas, N. C. Pallqui Camacho, A. Parada Gutierrez, G. Pardo, J. Peacock, M. Peña-Claros, M. C. Peñuela-Mora, P. Petronelli, G. C. Pickavance, N. Pitman, A. Prieto, C. Quesada, H. Ramírez-Angulo, M. Réjou-Méchain, Z. Restrepo Correa, A. Roopsind, A. Rudas, R. Salomão, N. Silva, J. Silva Espejo, J. Singh, J. Stropp, J. Terborgh, R. Thomas, M. Toledo, A. Torres-Lezama, L. Valenzuela Gamarra, P. J. van de Meer, G. van der Heijden, P. van der Hout, R. Vasquez Martinez, C. Vela, I. C. G. Vieira, O. L. Phillips, Compositional response of Amazon forests to climate change. *Glob. Change Biol.* **25**, 39–56 (2019). doi:10.1111/gcb.14413

232. A. Esquivel-Muelbert, O. L. Phillips, R. J. W. Brienen, S. Fauset, M. J. P. Sullivan, T. R. Baker, K. J. Chao, T. R. Feldpausch, E. Gloor, N. Higuchi, J. Houwing-Duistermaat, J. Lloyd, H. Liu, Y. Malhi, B. Marimon, B. H. Marimon Junior, A. Monteagudo-Mendoza, L. Poorter, M. Silveira, E. V. Torre, E. A. Dávila, J. Del Aguila Pasquel, E. Almeida, P. A. Loayza, A. Andrade, L. E. O. C. Aragão, A. Araujo-Murakami, E. Arets, L. Arroyo, G. A. Aymard C, M. Baisie, C. Baraloto, P. B. Camargo, J. Barroso, L. Blanc, D. Bonal, F. Bongers, R. Boot, F. Brown, B. Burban, J. L. Camargo, W. Castro, V. C. Moscoso, J. Chave, J. Comiskey, F. C. Valverde, A. L. da Costa, N. D. Cardozo, A. Di Fiore, A. Dourdain, T. Erwin, G. F. Llampazo, I. C. G. Vieira, R. Herrera, E. Honorio Coronado, I. Huamantupa-Chuquimaco, E. Jimenez-Rojas, T. Killeen, S. Laurance, W. Laurance, A. Levesley, S. L. Lewis, K. L. L. M. Ladvocat, G. Lopez-Gonzalez, T. Lovejoy, P. Meir, C. Mendoza, P. Morandi, D. Neill, A. J. Nogueira Lima, P. N. Vargas, E. A. de Oliveira, N. P. Camacho, G. Pardo, J. Peacock, M. Peña-Claros, M. C. Peñuela-Mora, G. Pickavance, J. Pipoly, N. Pitman, A. Prieto, T. A. M. Pugh, C. Quesada, H. Ramirez-Angulo, S. M. de Almeida Reis, M. Rejou-Machain, Z. R. Correa, L. R. Bayona, A. Rudas, R. Salomão, J. Serrano, J. S. Espejo, N. Silva, J. Singh, C. Stahl, J. Stropp, V. Swamy, J. Talbot, H. Ter Steege, J. Terborgh, R. Thomas, M. Toledo, A. Torres-Lezama, L. V. Gamarra, G. van der Heijden, P. van der Meer, P. van der Hout, R. V. Martinez, S. A. Vieira, J. V. Cayo, V. Vos, R. Zagt, P. Zuidema, D. Galbraith, Tree mode of death and mortality risk factors across Amazon forests. *Nat. Commun.* **11**, 5515 (2020). doi:10.1038/s41467-020-18996-3

Medline

233. K. Yu, P. Ciais, S. I. Seneviratne, Z. Liu, H. Y. H. Chen, J. Barichivich, C. D. Allen, H. Yang, Y. Huang, A. P. Ballantyne, Field-based tree mortality constraint reduces estimates of model-projected forest carbon sinks. *Nat. Commun.* **13**, 2094 (2022). doi:10.1038/s41467-022-29619-4 Medline

234. M. Baudena, O. A. Tuinenburg, P. A. Ferdinand, A. Staal, Effects of land-use change in the Amazon on precipitation are likely underestimated. *Glob. Change Biol.* **27**, 5580–5587 (2021). doi:10.1111/gcb.15810 Medline

235. Y. Chai, G. Martins, C. Nobre, C. von Randow, T. Chen, H. Dolman, Constraining Amazonian land surface temperature sensitivity to precipitation and the probability of forest dieback. *NPJ Clim. Atmos. Sci.* **4**, 6 (2021). doi:10.1038/s41612-021-00162-1

236. C. Huntingford, P. Zelazowski, D. Galbraith, L. M. Mercado, S. Sitch, R. Fisher, M. Lomas, A. P. Walker, C. D. Jones, B. B. B. Booth, Y. Malhi, D. Hemming, G. Kay, P. Good, S. L. Lewis, O. L. Phillips, O. K. Atkin, J. Lloyd, E. Gloor, J. Zaragoza-Castells, P. Meir, R. Betts, P. P. Harris, C. Nobre, J. Marengo, P. M. Cox, Simulated resilience of tropical rainforests to CO2 -induced climate change. *Nat. Geosci.* **6**, 268–273 (2013). doi:10.1038/ngeo1741

237. S. S. Saatchi, N. L. Harris, S. Brown, M. Lefsky, E. T. A. Mitchard, W. Salas, B. R. Zutta, W. Buermann, S. L. Lewis, S. Hagen, S. Petrova, L. White, M. Silman, A. Morel, Benchmark map of forest carbon stocks in tropical regions across three continents. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 9899–9904 (2011). doi:10.1073/pnas.1019576108 Medline

238. E. M. Nogueira, A. M. Yanai, F. O. R. Fonseca, P. M. Fearnside, Carbon stock loss from deforestation through 2013 in Brazilian Amazonia. *Glob. Change Biol.* **21**, 1271–1292 (2015). doi:10.1111/gcb.12798 Medline

239. V. H. A. Heinrich, R. Dalagnol, H. L. G. Cassol, T. M. Rosan, C. T. de Almeida, C. H. L. Silva Junior, W. A. Campanharo, J. I. House, S. Sitch, T. C. Hales, M. Adami, L. O. Anderson, L. E. O. C. Aragão, Large carbon sink potential of secondary forests in the Brazilian Amazon to mitigate climate change. *Nat. Commun.* **12**, 1785 (2021). doi:10.1038/s41467-021-22050-1 Medline

240. B. Zimbres, P. Rodríguez-Veiga, J. Z. Shimbo, P. da Conceição Bispo, H. Balzter, M. Bustamante, I. Roitman, R. Haidar, S. Miranda, L. Gomes, F. Alvim Carvalho, E. Lenza, L. Maracahipes-Santos, A. C. Abadia, J. A. do Prado Júnior, E. L. Mendonça Machado, A. P. Dias Gonzaga, M. de Castro Nunes Santos Terra, J. M. de Mello, J. R. Soares Scolforo, J. R. Rodrigues Pinto, A. Alencar, Mapping the stock and spatial distribution of aboveground woody biomass in the native vegetation of the Brazilian Cerrado biome. *For. Ecol. Manage.* **499**, 119615 (2021). doi:10.1016/j.foreco.2021.119615

241. P. S. Morandi, B. S. Marimon, B. H. Marimon-Junior, J. A. Ratter, T. R. Feldpausch, G. R. Colli, C. B. R. Munhoz, M. C. da Silva Júnior, E. de Souza Lima, R. F. Haidar, L. Arroyo, A. A. Murakami, F. de Góis Aquino, B. M. T. Walter, J. F. Ribeiro, R. Françoso, F. Elias, E. A. de Oliveira, S. M. Reis, B. de Oliveira, E. C. das Neves, D. S. Nogueira, H. S. Lima, T. P. de Carvalho, S. A. Rodrigues, D. Villarroel, J. M. Felfili, O. L. Phillips, E. C. das Neves, D. S. Nogueira, H. S. Lima, T. P. de Carvalho, S. A. Rodrigues, D. Villarroel, J. M. Felfili, O. L. Phillips, Tree diversity and above-ground biomass in the

South America Cerrado biome and their conservation implications. *Biodivers. Conserv.* **29**, 1519–1536 (2020). doi:10.1007/s10531-018-1589-8

242. H. S. Barros, P. M. Fearnside, Soil carbon stock changes due to edge effects in central Amazon forest fragments. *For. Ecol. Manage.* **379**, 30–36 (2016). doi:10.1016/j.foreco.2016.08.002

243. A. C. Staver, S. Archibald, S. A. Levin, The Global Extent and Determinants of Savanna and Forest as Alternative Biome States. *Science* **334**, 230–232 (2011). doi:10.1126/science.1210465

244. Y. Malhi, L. E. O. C. Aragão, D. Galbraith, C. Huntingford, R. Fisher, P. Zelazowski, S. Sitch, C. McSweeney, P. Meir, Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 20610–20615 (2009). doi:10.1073/pnas.0804619106 Medline

245. M. Drüke, W. von Bloh, B. Sakschewski, N. Wunderling, S. Petri, M. Cardoso, H. M. J. Barbosa, K. Thonicke, Climate-induced hysteresis of the tropical forest in a fire-enabled Earth system model. *Eur. Phys. J. Spec. Top.* **230**, 3153–3162 (2021). doi:10.1140/epjs/s11734-021-00157-2

246. C. Ciemer, N. Boers, M. Hirota, J. Kurths, F. Müller-Hansen, R. S. Oliveira, R. Winkelmann, Higher resilience to climatic disturbances in tropical vegetation exposed to more variable rainfall. *Nat. Geosci.* **12**, 174–179 (2019). doi:10.1038/s41561-019-0312-z

247. T. Kukla, A. Ahlström, S. Y. Maezumi, M. Chevalier, Z. Lu, M. J. Winnick, C. P. Chamberlain, The resilience of Amazon tree cover to past and present drying. *Global Planet. Change* **202**, 103520 (2021). doi:10.1016/j.gloplacha.2021.103520

248. A. Levermann, J. Schewe, V. Petoukhov, H. Held, Basic mechanism for abrupt monsoon transitions. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 20572–20577 (2009). doi:10.1073/pnas.0901414106 Medline

249. K. Zickfeld, B. Knopf, V. Petoukhov, H. J. Schellnhuber, Is the Indian summer monsoon stable against global change? *Geophys. Res. Lett.* **32**, 2005GL022771 (2005). doi:10.1029/2005GL022771

250. A. Levermann, V. Petoukhov, J. Schewe, H. J. Schellnhuber, Abrupt monsoon transitions as seen in paleorecords can be explained by moisture-advection feedback. *Proc. Natl. Acad. Sci. U.S.A.* **113**, E2348–E2349 (2016). doi:10.1073/pnas.1603130113 Medline

251. W. R. Boos, T. Storelvmo, Reply to Levermann et al.: Linear scaling for monsoons based on well-verified balance between adiabatic cooling and latent heat release. *Proc. Natl. Acad. Sci. U.S.A.* **113**, E2350–E2351 (2016). doi:10.1073/pnas.1603626113 Medline

252. A. Katzenberger, J. Schewe, J. Pongratz, A. Levermann, Robust increase of Indian monsoon rainfall and its variability under future warming in CMIP-6 models. *Earth Syst. Dyn.*, **12**, 367–386 (2021). doi:10.5194/esd-12-367-2021

253. A. J. Watson, T. M. Lenton, B. J. W. Mills, Ocean deoxygenation, the global phosphorus cycle and the possibility of human-caused large-scale ocean anoxia. *Philos. Trans. R. Soc. A* **375**, 20160318 (2017). Medline

254. H. C. Jenkyns, Geochemistry of oceanic anoxic events. *Geochem. Geophys. Geosyst.* **11**,

2009GC002788 (2010). doi:10.1029/2009GC002788

255. T. P. Kemena, A. Landolfi, A. Oschlies, K. Wallmann, A. W. Dale, Ocean phosphorus inventory: Large uncertainties in future projections on millennial timescales and their consequences for ocean deoxygenation. *Earth Syst. Dyn.* **10**, 539–553 (2019). doi:10.5194/esd-10-539-2019

256. D. Niemeyer, T. P. Kemena, K. J. Meissner, A. Oschlies, A model study of warming-induced phosphorus-oxygen feedbacks in open-ocean oxygen minimum zones on millennial timescales. *Earth Syst. Dyn.* **8**, 357–367 (2017). doi:10.5194/esd-8-357-2017

257. V. Lago, M. H. England, Projected Slowdown of Antarctic Bottom Water Formation in Response to Amplified Meltwater Contributions. *J. Clim.* **32**, 6319–6335 (2019). doi:10.1175/JCLI-D-18-0622.1

258. J. Bjordal, T. Storelvmo, K. Alterskjær, T. Carlsen, Equilibrium climate sensitivity above 5 °C plausible due to state-dependent cloud feedback. *Nat. Geosci.* **13**, 718–721 (2020). doi:10.1038/s41561-020-00649-1

259. I. Tan, T. Storelvmo, M. D. Zelinka, Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science* **352**, 224–227 (2016). doi:10.1126/science.aad5300

260. J. Zhu, C. J. Poulsen, On the Increase of Climate Sensitivity and Cloud Feedback With Warming in the Community Atmosphere Models. *Geophys. Res. Lett.* **47**, 1–10 (2020). doi:10.1029/2020GL089143

261. G. V. Cesana, A. D. Del Genio, Observational constraint on cloud feedbacks suggests moderate climate sensitivity. *Nat. Clim. Chang.* **11**, 213–218 (2021). doi:10.1038/s41558-020-00970-y

262. J. Zhu, C. J. Poulsen, B. L. Otto-Bliesner, High climate sensitivity in CMIP6 model not supported by paleoclimate. *Nat. Clim. Chang.* **10**, 378–379 (2020). doi:10.1038/s41558-020-0764-6

263. C. Senf, R. Seidl, Mapping the forest disturbance regimes of Europe. *Nat. Sustain.* **4**, 63–70 (2021). doi:10.1038/s41893-020-00609-y

264. S. Netherer, B. Panassiti, J. Pennerstorfer, B. Matthews, Acute Drought Is an Important Driver of Bark Beetle Infestation in Austrian Norway Spruce Stands. *Front. For. Glob. Chang.* **2**, ffgc.2019.00039 (2019). doi:10.3389/ffgc.2019.00039

265. G. Forzieri, M. Girardello, G. Ceccherini, J. Spinoni, L. Feyen, H. Hartmann, P. S. A. Beck, G. Camps-Valls, G. Chirici, A. Mauri, A. Cescatti, Emergent vulnerability to climate-driven disturbances in European forests. *Nat. Commun.* **12**, 1081 (2021). doi:10.1038/s41467-021-21399-7 Medline

266. C. Senf, A. Buras, C. S. Zang, A. Rammig, R. Seidl, Excess forest mortality is consistently linked to drought across Europe. *Nat. Commun.* **11**, 6200 (2020). doi:10.1038/s41467-020-19924-1 Medline

267. C. Senf, J. Sebald, R. Seidl, Increasing canopy mortality affects the future demographic structure of Europe's forests. *One Earth* **4**, 749–755 (2021). doi:10.1016/j.oneear.2021.04.008

268. B. Schuldt, A. Buras, M. Arend, Y. Vitasse, C. Beierkuhnlein, A. Damm, M. Gharun, T. E. E. Grams, M. Hauck, P. Hajek, H. Hartmann, E. Hiltbrunner, G. Hoch, M. Holloway-Phillips, C. Körner, E. Larysch, T. Lübbe, D. B. Nelson, A. Rammig, A. Rigling, L. Rose, N. K. Ruehr, K. Schumann, F. Weiser, C. Werner, T. Wohlgemuth, C. S. Zang, A. Kahmen, A first assessment of the impact of the extreme 2018 summer drought on Central European forests. *Basic Appl. Ecol.* **45**, 86–103 (2020). doi:10.1016/j.baae.2020.04.003

269. A. Buras, A. Rammig, C. S. Zang, Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. *Biogeosciences* **17**, 1655–1672 (2020). doi:10.5194/bg-17-1655-2020

270. W. Peters, A. Bastos, P. Ciais, A. Vermeulen, A historical, geographical and ecological perspective on the 2018 European summer drought. *Philos. Trans. R. Soc. B.* **375**, 20190505 (2020). doi:10.1098/rstb.2019.0505 Medline

271. K. Albrich, W. Rammer, R. Seidl, Climate change causes critical transitions and irreversible alterations of mountain forests. *Glob. Change Biol.* **26**, 4013–4027 (2020). doi:10.1111/gcb.15118 Medline

272. E. M. Lansu, C. C. van Heerwaarden, A. I. Stegehuis, A. J. Teuling, Atmospheric Aridity and Apparent Soil Moisture Drought in European Forest During Heat Waves. *Geophys. Res. Lett.* **47**, (2020). doi:10.1029/2020GL087091

273. S. Wang, Y. Zhang, W. Ju, A. Porcar-Castell, S. Ye, Z. Zhang, C. Brümmer, M. Urbaniak, I. Mammarella, R. Juszczak, K. Folkert Boersma, Warmer spring alleviated the impacts of 2018 European summer heatwave and drought on vegetation photosynthesis. *Agric. For. Meteorol.* **295**, 108195 (2020). doi:10.1016/j.agrformet.2020.108195

274. A. J. Teuling, A hot future for European droughts. *Nat. Clim. Chang.* **8**, 364–365 (2018). doi:10.1038/s41558-018-0154-5

275. L. Samaniego, S. Thober, R. Kumar, N. Wanders, O. Rakovec, M. Pan, M. Zink, J. Sheffield, E. F. Wood, A. Marx, Anthropogenic warming exacerbates European soil moisture droughts. *Nat. Clim. Chang.* **8**, 421–426 (2018). doi:10.1038/s41558-018-0138-5

276. C. Gohr, J. S. Blumröder, D. Sheil, P. L. Ibisch, Quantifying the mitigation of temperature extremes by forests and wetlands in a temperate landscape. *Ecol. Inform.* **66**, 101442 (2021). doi:10.1016/j.ecoinf.2021.101442

277. G. Lasslop, V. Brovkin, C. H. Reick, S. Bathiany, S. Kloster, Multiple stable states of tree cover in a global land surface model due to a fire-vegetation feedback. *Geophys. Res. Lett.* **43**, 6324–6331 (2016). doi:10.1002/2016GL069365

278. P. Zhang, J. H. Jeong, J. H. Yoon, H. Kim, S. Y. Simon Wang, H. W. Linderholm, K. Fang, X. Wu, D. Chen, Abrupt shift to hotter and drier climate over inner East Asia beyond the tipping point. *Science* **370**, 1095–1099 (2020). doi:10.1126/science.abb3368

279. Y. van der Velde, A. J. A. M. Temme, J. J. Nijp, M. C. Braakhekke, G. A. K. van Voorn, S. C. Dekker, A. J. Dolman, J. Wallinga, K. J. Devito, N. Kettridge, C. A. Mendoza, L. Kooistra, M. B. Soons, A. J. Teuling, Emerging forest-peatland bistability and resilience of European peatland carbon stores. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2101742118

(2021). doi:10.1073/pnas.2101742118 Medline

280. R. M. Varney, S. E. Chadburn, P. Friedlingstein, E. J. Burke, C. D. Koven, G. Hugelius, P. M. Cox, A spatial emergent constraint on the sensitivity of soil carbon turnover to global warming. *Nat. Commun.* **11**, 5544 (2020). doi:10.1038/s41467-020-19208-8 Medline

281. D. T. Shindell, D. Rind, P. Lonergan, Increased polar stratospheric ozone losses and delayed eventual recovery owing to increasing greenhouse-gas concentrations. *Nature* **392**, 589–592 (1998). doi:10.1038/33385

282. D. L. Hartmann, J. M. Wallace, V. Limpasuvan, D. W. J. Thompson, J. R. Holton, Can ozone depletion and global warming interact to produce rapid climate change? *Proc. Natl. Acad. Sci. U.S.A.* **97**, 1412–1417 (2000). doi:10.1073/pnas.97.4.1412 Medline

283. J. Austin, D. Shindell, S. R. Beagley, C. Brühl, M. Dameris, E. Manzini, T. Nagashima, P. Newman, S. Pawson, G. Pitari, E. Rozanov, C. Schnadt, T. G. Shepherd, Uncertainties and assessments of chemistry-climate models of the stratosphere. *Atmos. Chem. Phys.* **3**, 1–27 (2003). doi:10.5194/acp-3-1-2003

284. B. Weatherhead, A. Tanskanen, A. Stevermer, S. B. Andersen, A. Arola, J. Austin, G. Bernhard, H. Browman, V. Fioletov, V. Grewe, J. Herman, W. Josefsson, A. Kylling, E. Kyrö, A. Lindfors, D. Shindell, P. Taalas, D. Tarasick, in "Arctic Climate Impact Assessment Report" C. Symon, L. Arris, B. Heal, Eds. (Cambridge Univ. Press, 2005; http://www.acia.uaf.edu/pages/scientific.html), pp. 151–182.

285. V. Eyring, N. P. Gillett, K. M. A. Rao, R. Barimalala, M. Barreiro Parrillo, N. Bellouin, C. Cassou, P. J. Durack, Y. Kosaka, S. McGregor, S. Min, O. Morgenstern, Y. Sun, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou, Eds. (Cambridge Univ. Press, 2021); https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_03.pdf

286. J. A. Francis, S. J. Vavrus, Evidence for a wavier jet stream in response to rapid Arctic warming. *Environ. Res. Lett.* **10**, 014005 (2015). doi:10.1088/1748-9326/10/1/014005

287. R. Blackport, J. A. Screen, Weakened evidence for mid-latitude impacts of Arctic warming. *Nat. Clim. Chang.* **10**, 1065–1066 (2020). doi:10.1038/s41558-020-00954-y

288. F. J. Doblas-Reyes, A. A. Sörensson, M. Almazroui, A. Dosio, W. J. Gutowski, R. Haarsma, R. Hamdi, B. Hewitson, W.-T. Kwon, B. L. Lamptey, D. Maraun, T. S. Stephenson, I. Takayabu, L. Terray, A. Turner, Z. Zuo, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou, Eds. (Cambridge Univ. Press, 2020).

289. D. Archer, B. Buffett, V. Brovkin, Ocean methane hydrates as a slow tipping point in the global carbon cycle. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 20596–20601 (2009).

doi:10.1073/pnas.0800885105 Medline

290. G. R. Dickens, Down the Rabbit Hole: Toward appropriate discussion of methane release from gas hydrate systems during the Paleocene-Eocene thermal maximum and other past hyperthermal events. *Clim. Past* **7**, 831–846 (2011). doi:10.5194/cp-7-831-2011

291. G. R. Dickens, J. R. O. Neil, D. K. Rea, R. M. Owen, Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene. *Paleoceanography* **10**, 965–971 (1995). doi:10.1029/95PA02087

292. T. A. Minshull, H. Marín-Moreno, D. I. Armstrong McKay, P. A. Wilson, Mechanistic insights into a hydrate contribution to the Paleocene-Eocene carbon cycle perturbation from coupled thermohydraulic simulations. *Geophys. Res. Lett.* **43**, 8637–8644 (2016). doi:10.1002/2016GL069676

293. D. J. Lunt, A. Ridgwell, A. Sluijs, J. Zachos, S. Hunter, A. Haywood, A model for orbital pacing of methane hydrate destabilization during the Palaeogene. *Nat. Geosci.* **4**, 775–778 (2011). doi:10.1038/ngeo1266

294. D. I. Armstrong McKay, T. M. Lenton, Reduced carbon cycle resilience across the Palaeocene–Eocene Thermal Maximum. *Clim. Past* **14**, 1515–1527 (2018). doi:10.5194/cp-14-1515-2018

295. J. C. Zachos, G. R. Dickens, R. E. Zeebe, An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. *Nature* **451**, 279–283 (2008). doi:10.1038/nature06588 Medline

296. S. Kender, K. Bogus, G. K. Pedersen, K. Dybkjær, T. A. Mather, E. Mariani, A. Ridgwell, J. B. Riding, T. Wagner, S. P. Hesselbo, M. J. Leng, Paleocene/Eocene carbon feedbacks triggered by volcanic activity. *Nat. Commun.* **12**, 5186 (2021). doi:10.1038/s41467-021-25536-0 Medline

297. M. Gutjahr, A. Ridgwell, P. F. Sexton, E. Anagnostou, P. N. Pearson, H. Pälike, R. D. Norris, E. Thomas, G. L. Foster, Very large release of mostly volcanic carbon during the Palaeocene-Eocene Thermal Maximum. *Nature* **548**, 573–577 (2017). doi:10.1038/nature23646 Medline

298. H. Marín-Moreno, T. A. Minshull, G. K. Westbrook, B. Sinha, S. Sarkar, The response of methane hydrate beneath the seabed offshore Svalbard to ocean warming during the next three centuries. *Geophys. Res. Lett.* **40**, 5159–5163 (2013). doi:10.1002/grl.50985

299. E. J. Burke, C. D. Jones, C. D. Koven, Estimating the Permafrost-Carbon Climate Response in the CMIP5 Climate Models Using a Simplified Approach. *J. Clim.* **26**, 4897–4909 (2013). doi:10.1175/JCLI-D-12-00550.1

300. P. de Vrese, T. Stacke, T. Kleinen, V. Brovkin, Diverging responses of high-latitude $CO_2$ and $CH_4$ emissions in idealized climate change scenarios. *Cryosphere* **15**, 1097–1130 (2021). doi:10.5194/tc-15-1097-2021

301. P. Friedlingstein, M. W. Jones, M. O'Sullivan, R. M. Andrew, J. Hauck, G. P. Peters, W. Peters, J. Pongratz, S. Sitch, C. Le Quéré, D. C. E. Bakker, J. G. Canadell, P. Ciais, R. B. Jackson, P. Anthoni, L. Barbero, A. Bastos, V. Bastrikov, M. Becker, L. Bopp, E. Buitenhuis, N. Chandra, F. Chevallier, L. P. Chini, K. I. Currie, R. A. Feely, M. Gehlen,

D. Gilfillan, T. Gkritzalis, D. S. Goll, N. Gruber, S. Gutekunst, I. Harris, V. Haverd, R. A. Houghton, G. Hurtt, T. Ilyina, A. K. Jain, E. Joetzjer, J. O. Kaplan, E. Kato, K. Klein Goldewijk, J. I. Korsbakken, P. Landschützer, S. K. Lauvset, N. Lefèvre, A. Lenton, S. Lienert, D. Lombardozzi, G. Marland, P. C. McGuire, J. R. Melton, N. Metzl, D. R. Munro, J. E. M. S. Nabel, S.-I. Nakaoka, C. Neill, A. M. Omar, T. Ono, A. Peregon, D. Pierrot, B. Poulter, G. Rehder, L. Resplandy, E. Robertson, C. Rödenbeck, R. Séférian, J. Schwinger, N. Smith, P. P. Tans, H. Tian, B. Tilbrook, F. N. Tubiello, G. R. van der Werf, A. J. Wiltshire, S. Zaehle, Global carbon budget 2019. *Earth Syst. Sci. Data* **11**, 1783–1838 (2019). doi:10.5194/essd-11-1783-2019

302. W. S. Broecker, T.-H. Peng, Lamont-Doherty Geological Observatory, *Tracers in the Sea* (Eldigio Press, 1982).

303. J. Segschneider, J. Bendtsen, Temperature-dependent remineralization in a warming ocean increases surface pCO2 through changes in marine ecosystem composition. *Global Biogeochem. Cycles* **27**, 1214–1225 (2013). doi:10.1002/2013GB004684

304. D. I. Armstrong McKay, S. E. Cornell, K. Richardson, J. Rockström, Resolving ecological feedbacks on the ocean carbon sink in Earth system models. *Earth Syst. Dyn.* **12**, 797–818 (2021). doi:10.5194/esd-12-797-2021

305. C. Heinze, T. Blenckner, H. Martins, D. Rusiecka, R. Döscher, M. Gehlen, N. Gruber, E. Holland, Ø. Hov, F. Joos, J. B. R. Matthews, R. Rødven, S. Wilson, The quiet crossing of ocean tipping points. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2008478118 (2021). doi:10.1073/pnas.2008478118 Medline

306. D. H. Rothman, Thresholds of catastrophe in the Earth system. *Sci. Adv.* **3**, e1700906 (2017). doi:10.1126/sciadv.1700906 Medline

307. D. H. Rothman, Characteristic disruptions of an excitable carbon cycle. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 14813–14822 (2019). doi:10.1073/pnas.1905164116 Medline

308. T. Smith, D. Traxl, N. Boers, Empirical evidence for recent global shifts in vegetation resilience. *Nat. Clim. Chang.* **12**, 477–484 (2022). doi:10.1038/s41558-022-01352-2

309. S. Wang, Y. Zhang, W. Ju, J. M. Chen, P. Ciais, A. Cescatti, J. Sardans, I. A. Janssens, M. Wu, J. A. Berry, E. Campbell, M. Fernández-Martínez, R. Alkama, S. Sitch, P. Friedlingstein, W. K. Smith, W. Yuan, W. He, D. Lombardozzi, M. Kautz, D. Zhu, S. Lienert, E. Kato, B. Poulter, T. G. M. Sanders, I. Krüger, R. Wang, N. Zeng, H. Tian, N. Vuichard, A. K. Jain, A. Wiltshire, V. Haverd, D. S. Goll, J. Peñuelas, Recent global decline of CO2 fertilization effects on vegetation photosynthesis. *Science* **370**, 1295–1300 (2020). doi:10.1126/science.abb7772

310. A. J. Winkler, R. B. Myneni, G. A. Alexandrov, V. Brovkin, Earth system models underestimate carbon fixation by plants in the high latitudes. *Nat. Commun.* **10**, 885 (2019). doi:10.1038/s41467-019-08633-z Medline

311. T. Tagesson, G. Schurgers, S. Horion, P. Ciais, F. Tian, M. Brandt, A. Ahlström, J. P. Wigneron, J. Ardö, S. Olin, L. Fan, Z. Wu, R. Fensholt, Recent divergence in the contributions of tropical and boreal forests to the terrestrial carbon sink. *Nat. Ecol. Evol.* **4**, 202–209 (2020). doi:10.1038/s41559-019-1090-0 Medline

312. K. A. Duffy, C. R. Schwalm, V. L. Arcus, G. W. Koch, L. L. Liang, L. A. Schipper, How

close are we to the temperature tipping point of the terrestrial biosphere? *Sci. Adv.* **7**, eaay1052 (2021). doi:10.1126/sciadv.aay1052 Medline