Tipping elements in the Earth's climate system

Timothy M. Lenton[*,†], Hermann Held[‡], Elmar Kriegler[‡,§], Jim W. Hall[¶], Wolfgang Lucht[‡], Stefan Rahmstorf[‡], and Hans Joachim Schellnhuber[†,‡,‖,]**

[*]School of Environmental Sciences, University of East Anglia, and Tyndall Centre for Climate Change Research, Norwich NR4 7TJ, United Kingdom; [‡]Potsdam Institute for Climate Impact Research, P.O. Box 60 12 03, 14412 Potsdam, Germany; [§]Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213-3890; [¶]School of Civil Engineering and Geosciences, Newcastle University, and Tyndall Centre for Climate Change Research, Newcastle NE1 7RU, United Kingdom; and [‖]Environmental Change Institute, Oxford University, and Tyndall Centre for Climate Change Research, Oxford OX1 3QY, United Kingdom

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The term "tipping point" commonly refers to a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system. Here we introduce the term "tipping element" to describe large-scale components of the Earth system that may pass a tipping point. We critically evaluate potential policy-relevant tipping elements in the climate system under anthropogenic forcing, drawing on the pertinent literature and a recent international workshop to compile a short list, and we assess where their tipping points lie. An expert elicitation is used to help rank their sensitivity to global warming and the uncertainty about the underlying physical mechanisms. Then we explain how, in principle, early warning systems could be established to detect the proximity of some tipping points.

Earth system | tipping points | climate change | large-scale impacts | climate policy

Human activities may have the potential to push components of the Earth system past critical states into qualitatively different modes of operation, implying large-scale impacts on human and ecological systems. Examples that have received recent attention include the potential collapse of the Atlantic thermohaline circulation (THC) (1), dieback of the Amazon rainforest (2), and decay of the Greenland ice sheet (3). Such phenomena have been described as "tipping points" following the popular notion that, at a particular moment in time, a small change can have large, long-term consequences for a system, i.e., "little things can make a big difference" (4).

In discussions of global change, the term tipping point has been used to describe a variety of phenomena, including the appearance of a positive feedback, reversible phase transitions, phase transitions with hysteresis effects, and bifurcations where the transition is smooth but the future path of the system depends on the noise at a critical point. We offer a formal definition, introducing the term "tipping element" to describe subsystems of the Earth system that are at least subcontinental in scale and can be switched—under certain circumstances—into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point—in forcing and a feature of the system—at which the future state of the system is qualitatively altered.

Many of the systems we consider do not yet have convincingly established tipping points. Nevertheless, increasing political demand to define and justify binding temperature targets, as well as wider societal interest in nonlinear climate changes, makes it timely to review potential tipping elements in the climate system under anthropogenic forcing (5) (Fig. 1). To this end, we organized a workshop entitled "Tipping Points in the Earth System" at the British Embassy, Berlin, which brought together 36 leading experts, and we conducted an expert elicitation that involved 52 members of the international scientific community. Here we combine a critical review of the literature with the results of the workshop to compile a short list of potential policy-relevant future tipping elements in the climate system. Results from the expert elicitation are used to rank a subset of these tipping elements in terms of their sensitivity to global warming and the associated uncertainty. Then we consider the prospects for early warning of an approaching tipping point.

Defining a Tipping Element and Its Tipping Point

Previous reviews (6–10) have defined "abrupt climate change" as occurring "when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause" (8), which is a case of bifurcation (i.e., one that focuses on equilibrium properties, implying some degree of irreversibility). We have formulated a much broader definition of a tipping element, because (*i*) we wish to include nonclimatic variables; (*ii*) there may be cases where the transition is slower than the anthropogenic forcing causing it; (*iii*) there may be no abruptness, but a slight change in control may have a qualitative impact in the future; and (*iv*) for several important phase changes, state-of-the-art models differ as to whether the transition is reversible or irreversible (in principle).

We consider "components" (Σ) of the Earth system that are associated with a specific region (or collection of regions) of the globe and are at least subcontinental in scale (length scale of order $\approx$1,000 km). A full formal definition of a tipping element is given in supporting information (SI) *Appendix 1*. For the cases considered herein, a system Σ is a tipping element if the following condition is met:

1. The parameters controlling the system can be transparently combined into a single control ρ, and there exists a critical control value ρ_{crit} from which any significant variation by $\delta\rho > 0$ leads to a qualitative change ($\hat{F}$) in a crucial system feature F, after some observation time $T > 0$, measured with respect to a reference feature at the critical value, i.e.,

$$|F(\rho \geq \rho_{crit} + \delta\rho|T) - F(\rho_{crit}|T)| \geq \hat{F} > 0. \qquad \textbf{[1]}$$

This inequality applies to forcing trajectories for which a slight deviation above a critical value that continues for some time inevitably induces a qualitative change. This change may oc-

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[†]To whom correspondence may be addressed. E-mail: t.lenton@uea.ac.uk or john@pik-potsdam.de.

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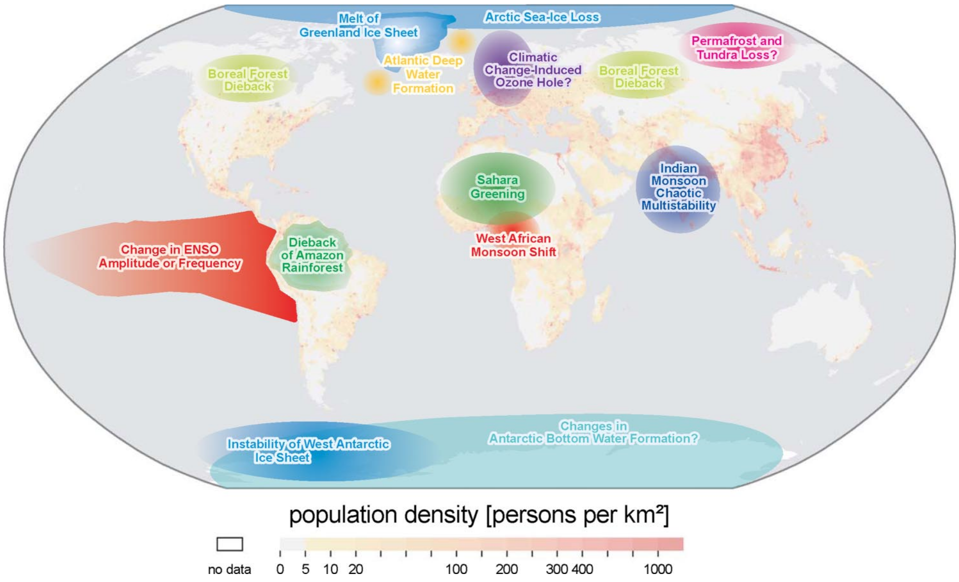

Fig. 1. Map of potential policy-relevant tipping elements in the climate system, updated from ref. 5 and overlain on global population density. Subsystems indicated could exhibit threshold-type behavior in response to anthropogenic climate forcing, where a small perturbation at a critical point qualitatively alters the future fate of the system. They could be triggered this century and would undergo a qualitative change within this millennium. We exclude from the map systems in which any threshold appears inaccessible this century (e.g., East Antarctic Ice Sheet) or the qualitative change would appear beyond this millennium (e.g., marine methane hydrates). Question marks indicate systems whose status as tipping elements is particularly uncertain.

cur immediately after the cause or much later. The definition encompasses equilibrium properties with threshold behavior as well as critical rates of forcing. In its equilibrium application, it includes all orders of phase transition and the most common bifurcations found in nature: saddle-node and Hopf bifurcations. The definition could in principle be applied at any time, e.g., in Earth's history. The feature of the system and the parameter(s) that influence it need not be climate variables. Critical conditions may be reached autonomously (without human interference), and natural variability could trigger a qualitative change.

Here we restrict ourselves to tipping elements that may be accessed by human activities and are potentially relevant to current policy. We define the subset of policy-relevant tipping elements by adding to condition 1 the following conditions:

2. Human activities are interfering with the system Σ such that decisions taken within a "political time horizon" ($T_P > 0$) can determine whether the critical value for the control ρ_{crit} is reached. This occurs at a critical time (t_{crit}) that is usually within T_P but may be later because of a commitment to further change made during T_P.
3. The time to observe a qualitative change plus the time to trigger it lie within an "ethical time horizon" (T_E); $t_{crit} + T \leq T_E$. T_E recognizes that events too far away in the future may not have the power of influencing today's decisions.
4. A significant number of people care about the fate of the component Σ, 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. A qualitative change should correspondingly be defined in terms of impacts.

Conditions 2–4 give our definition of a policy-relevant tipping element an ethical dimension, which is inevitable because a focus on policy requires the inclusion of normative judgements. These enter in the choices of the political time horizon (T_P), the ethical time horizon (T_E), and the qualitative change that fulfills condition 4. We suggest a maximum $T_P \sim 100$ years based on the human life span and our (limited) ability to consider the world we are leaving for our grandchildren, noting also the Intergovernmental Panel on Climate Change (IPCC) focus on this timescale. We suggest $T_E \sim 1{,}000$ years based on the lifetime of civilizations, noting that this is longer than the timescale of nation states and current political entities. Thus, we focus on the consequences of decisions enacted within this century that trigger a qualitative change within this millennium, and we exclude tipping elements whose fate is decided after 2100.

In the limit $\delta\rho \rightarrow 0$, condition 1 would only include vanishing equilibria and first-order phase transitions. Instead we consider that a "small" perturbation $\delta\rho$ should not exceed the magnitude of natural variability in ρ. Considering global temperature, climate variability on interannual to millennial timescales is 0.1–0.2°C. Alternatively, a popular target is to limit anthropogenic global mean temperature increase to 2°C, and we take a "small" perturbation to be 10% of this. Either way, $\delta\rho \sim 0.2$°C seems reasonable.

One useful way of classifying tipping elements is in terms of the time, T, over which a qualitative change is observed: (*i*) rapid, abrupt, or spasmodic tipping occurs if the observation time is very small compared with T_P (but $T \neq 0$); (*ii*) gradual or episodic tipping occurs if the observation time is intermediate (e.g., of order T_P); and (*iii*) slow or asymptotic tipping occurs if the observation time is very long (in particular, $T \rightarrow T_E$).

Several key questions arise. What are the potential policy-relevant tipping elements of the Earth system? And for each: What is the mechanism of tipping? What is the key feature F of interest? What are the parameter(s) projecting onto the control ρ, and their value(s) near ρ_{crit}? How long is the transition time T? What are the associated uncertainties?

Policy-Relevant Tipping Elements in the Climate System

Earth's history provides evidence of nonlinear switches in state or modes of variability of components of the climate system (6–10). Such past transitions may highlight potential tipping elements under anthropogenic forcing, but the boundary conditions under which they occurred were different from today, and anthropogenic forcing is generally more rapid and often different in pattern (11). Therefore, locating potential future tipping points requires some use of predictive models, in combination with paleodata and/or historical data.

Here we focus on policy-relevant potential future tipping elements in the climate system. We considered a long list of candidates (Fig. 1, Table 1), and from literature review and the aforementioned workshop, we identified a short list of candidates that meet conditions 1–4 (top nine rows in Table 1). To meet condition 1, there needed to be some theoretical basis (>1 model study) for expecting a system to exhibit a critical threshold

Table 1. Policy-relevant potential future tipping elements in the climate system and (below the empty line) candidates that we considered but failed to make the short list*

Tipping element	Feature of system, F (direction of change)	Control parameter(s), ρ	Critical value(s),[†] ρ_{crit}	Global warming[†‡]	Transition timescale,[†] T	Key impacts
Arctic summer sea-ice	Areal extent (−)	Local ΔT_{air}, ocean heat transport	Unidentified[§]	+0.5–2°C	≈10 yr (rapid)	Amplified warming, ecosystem change
Greenland ice sheet (GIS)	Ice volume (−)	Local ΔT_{air}	+≈3°C	+1–2°C	>300 yr (slow)	Sea level +2–7 m
West Antarctic ice sheet (WAIS)	Ice volume (−)	Local ΔT_{air}, or less $\Delta T_{\mathrm{ocean}}$	+≈5–8°C	+3–5°C	>300 yr (slow)	Sea level +5 m
Atlantic thermohaline circulation (THC)	Overturning (−)	Freshwater input to N Atlantic	+0.1–0.5 Sv	+3–5°C	≈100 yr (gradual)	Regional cooling, sea level, ITCZ shift
El Niño–Southern Oscillation (ENSO)	Amplitude (+)	Thermocline depth, sharpness in EEP	Unidentified[§]	+3–6°C	≈100 yr (gradual)	Drought in SE Asia and elsewhere
Indian summer monsoon (ISM)	Rainfall (−)	Planetary albedo over India	0.5	N/A	≈1 yr (rapid)	Drought, decreased carrying capacity
Sahara/Sahel and West African monsoon (WAM)	Vegetation fraction (+)	Precipitation	100 mm/yr	+3–5°C	≈10 yr (rapid)	Increased carrying capacity
Amazon rainforest	Tree fraction (−)	Precipitation, dry season length	1,100 mm/yr	+3–4°C	≈50 yr (gradual)	Biodiversity loss, decreased rainfall
Boreal forest	Tree fraction (−)	Local ΔT_{air}	+≈7°C	+3–5°C	≈50 yr (gradual)	Biome switch
Antarctic Bottom Water (AABW)*	Formation (−)	Precipitation–Evaporation	+100 mm/yr	Unclear[¶]	≈100 yr (gradual)	Ocean circulation, carbon storage
Tundra*	Tree fraction (+)	Growing degree days above zero	Missing[‖]	—	≈100 yr (gradual)	Amplified warming, biome switch
Permafrost*	Volume (−)	$\Delta T_{\mathrm{permafrost}}$	Missing[‖]	—	<100 yr (gradual)	CH_4 and CO_2 release
Marine methane hydrates*	Hydrate volume (−)	$\Delta T_{\mathrm{sediment}}$	Unidentified[§]	Unclear[¶]	10^3 to 10^5 yr ($>T_E$)	Amplified global warming
Ocean anoxia*	Ocean anoxia (+)	Phosphorus input to ocean	+≈20%	Unclear[¶]	≈10^4 yr ($>T_E$)	Marine mass extinction
Arctic ozone*	Column depth (−)	Polar stratospheric cloud formation	195 K	Unclear[¶]	<1 yr (rapid)	Increased UV at surface

N, North; ITCZ, Inter-tropical Convergence Zone; EEP, East Equatorial Pacific; SE, Southeast.

*See *SI Appendix 2* for more details about the tipping elements that failed to make the short list.

[†] Numbers given are preliminary and derive from assessments by the experts at the workshop, aggregation of their opinions at the workshop, and review of the literature.

[‡] Global mean temperature change above present (1980–1999) that corresponds to critical value of control, where this can be meaningfully related to global temperature.

[§] Meaning theory, model results, or paleo-data suggest the existence of a critical threshold but a numerical value is lacking in the literature.

[¶] Meaning either a corresponding global warming range is not established or global warming is not the only or the dominant forcing.

[‖] Meaning no subcontinental scale critical threshold could be identified, even though a local geographical threshold may exist.

(ρ_{crit}) at a subcontinental scale, and/or past evidence of threshold behavior. Where the proposed ρ_{crit} could be meaningfully related to temperature, condition 2 was evaluated based on an "accessible neighborhood" of global temperatures from the IPCC (12) of 1.1–6.4°C above 1980–1999 that could be committed to over the next $T_P \sim 100$ years, and on recognition that transient warming is generally greater toward the poles and greater on land than in the ocean. Condition 3 was evaluated on the basis of model projections, known shortcomings of the models, and paleodata. Our collective judgement was used to evaluate condition 4.

Our short list differs from that of the IPCC (ref. 12, chapter 10, especially p. 775 ff, p. 818 ff) because our definition and criteria differ from, and are more explicit than, the IPCC notion of abrupt climate change. The evidence base we use is also slightly different because it encompasses some more recent studies. The authors of this paper and the workshop participants are a smaller group of scientists than the IPCC members, the groups are only partially overlapping, and our analysis was undertaken largely in parallel. We seek to add value to the IPCC overview by injecting a more precise definition and undertaking a complementary, in-depth evaluation.

We now discuss the entries that made our short list and seek to explain significant discrepancies from the IPCC where they arise. Those candidates that did not make the short list (and why) are discussed in *SI Appendix 2*.

Arctic Sea-Ice. As sea-ice melts, it exposes a much darker ocean surface, which absorbs more radiation–amplifying the warming. Energy-balance models suggest that this ice-albedo positive feedback can give rise to multiple stable states of sea-ice (and land snow) cover, including finite ice cap and ice-free states, with ice caps smaller than a certain size being unstable (13). This small ice-cap instability is also found in some atmospheric general circulation models (AGCMs), but it can be largely eliminated by noise due to natural variability (14). The instability is not expected to be relevant to Southern Ocean sea-ice because the Antarctic continent covers the region over which it would be expected to arise (15). Different stable states for the flow rate through the narrow outlets that drain parts of the Arctic basin have also been found in a recent model (16). For both summer and winter Arctic sea-ice, the area coverage is declining at present (with summer sea-ice declining more markedly; ref. 17), and the ice has thinned significantly over a large area. Positive ice-albedo feedback dominates external forcing in causing the thinning and shrinkage since 1988, indicating strong nonlinearity and leading some to suggest that this system may already have passed a tipping point (18), although others disagree (19). In IPCC projections with ocean-atmosphere general circulation models (OAGCMs) (12), half of the models become ice-free in September during this century (19), at a polar temperature of −9°C (9°C above present) (20). The transition has nonlinear steps in many of the models, but a common critical threshold has yet to be identified (19). Thinning of the winter sea-ice increases the efficiency of formation of open water in summer, and abrupt retreat occurs when ocean heat transport to the Arctic increases rapidly (19). Only two IPCC models (12) exhibit a complete loss of annual sea-ice cover under extreme forcing (20). One shows a nonlinear transition to a new stable state in <10 years when polar temperature rises above −5°C (13°C above present), whereas the other shows a more linear transition. We conclude that a critical threshold for summer Arctic sea-ice loss may exist, whereas a further threshold for year-round ice loss is more uncertain and less accessible this century. Given that the IPCC models significantly underestimate the observed rate of Arctic sea-ice decline (17), a summer ice-loss threshold, if not already passed, may be very close and a transition could occur well within this century.

Greenland Ice Sheet (GIS). Ice-sheet models typically exhibit multiple stable states and nonlinear transitions between them (21). In some simulations with the GIS removed, summer melting prevents its reestablishment (22), indicating bistability, although others disagree (23). Regardless of whether there is bistability, in deglaciation, warming at the periphery lowers ice altitude, increasing surface temperature and causing a positive feedback that is expected to exhibit a critical threshold beyond which there is ongoing net mass loss and the GIS shrinks radically or eventually disappears. During the last interglacial (the Eemian), there was a 4- to 6-m higher sea level that must have come from Greenland and/or Antarctica. Increased Arctic summer insolation caused an estimated <3.5°C summertime warming of Greenland, and shrinkage of the GIS contributed an estimated 1.9–3.0 m to sea level, although a widespread ice cap remained (24). Broadly consistent with this, future projections suggest a GIS threshold for negative surface mass balance resides at ≥≈3°C local warming (above preindustrial) (3, 25). Uncertainties are such that IPCC (12) put the threshold at ≈1.9–4.6°C global warming (above preindustrial), which is clearly accessible this century. We give a closer and narrower range (above present) because amplification of warming over Greenland may be greater (26) than assumed (12, 25) because of more rapid sea-ice decline than modeled (17). Also, recent observations show the surface mass balance is declining (12) and contributing to net mass loss from the GIS (27, 28) that is accelerating (28, 29). Finally, existing ice-sheet models are unable to explain the speed of recent changes. These changes include melting and thinning of the coastal margins (30) and surging of outlet glaciers (29, 31), which may be contributed to by the intrusion of warming ocean waters (32). This is partly compensated by some mass gain in the interior (33). There is a lack of knowledge of natural GIS variability, and Greenland temperature changes have differed from the global trend (26), so interpretation of recent observations remains uncertain. If a threshold is passed, the IPCC (12) gives a >1,000-year timescale for GIS collapse. However, given the acknowledged (12) lack of processes that could accelerate collapse in current models, and their inability to simulate the rapid disappearance of continental ice at the end of the last ice age, a lower limit of 300 years is conceivable (34).

West Antarctic Ice Sheet (WAIS). Most of the WAIS is grounded below sea level and has the potential to collapse if grounding-line retreat triggers a strong positive feedback whereby ocean water undercuts the ice sheet and triggers further separation from the bedrock (35–37). The WAIS has retreated at least once during the Pleistocene (38), but the full extent of retreat is not known, nor is whether it occurred in the Eemian or the long, warm interglacial MIS-11 ≈400 ka. Approximately 1–4 m of the Eemian sea-level rise may have come from Antarctica, but some could have been from parts of the East Antarctic Ice Sheet grounded below sea level (and currently thinning at a rapid rate). WAIS collapse may be preceded by the disintegration of ice shelves and the acceleration of ice streams. Ice shelf collapse could be triggered by the intrusion of warming ocean water beneath them or by surface melting. It requires ≈5°C of local warming for surface atmospheric temperatures to exceed the melting point in summer on the major (Ross and Fischner-Ronne) ice shelves (12, 37). The threshold for ocean warming is estimated to be lower (37). The WAIS itself requires ≈8°C of local warming of the surface atmosphere at 75–80°S to reach the melting point in summer (37). Although the IPCC (12) declines to give a threshold, we estimate a range that is clearly accessible this century. Concern is raised by recent inferences from gravity measurements that the WAIS is losing mass (39), and observations that glaciers draining into the Amundsen Sea are losing 60% more ice than they are gaining and hence contributing to sea-level rise (40). They drain a region containing ≈1.3 m of a total ≈5 m of global sea-level rise contained in the WAIS. Although the timescale is highly uncertain, a qualitative WAIS change could occur within this millennium, with collapse within 300 years being a worst-case scenario. Rapid sea-level rise (>1 m per century) is more likely to come from the WAIS than from the GIS.

Atlantic Thermohaline Circulation (THC). A shutoff in North Atlantic Deep Water formation and the associated Atlantic THC can occur if sufficient freshwater (and/or heat) enters the North Atlantic to halt density-driven North Atlantic Deep Water formation (41). Such THC reorganizations play an important part in rapid climate changes recorded in Greenland during the last glacial cycle (42, 43). Hysteresis of the THC has been found in all models that have been systematically tested thus far (44), from conceptual "box" representations of the ocean (45) to OAGCMs (46). The most complex models have yet to be systematically tested because of excessive computational cost. Under sufficient North Atlantic freshwater forcing, all models exhibit a collapse of convection. In some experiments, this collapse is reversible (47) (after the forcing is removed, convection resumes), whereas in others, it is irreversible (48)—indicating bistability. In either case, a tipping point has been passed according to condition 1. The proximity of the present climate to this tipping point varies considerably between models, corresponding to an additional North Atlantic freshwater input of 0.1–0.5 Sv (44). The sensitivity of North Atlantic freshwater input to anthropogenic forcing is also poorly known, but regional precipitation is predicted to increase (12) and the GIS could contribute significantly (e.g., GIS melt over 1,000 years is equivalent to 0.1 Sv). The North Atlantic is observed to be freshening (49), and estimates of recent increases in freshwater input yield 0.014 Sv from melting sea ice (18), 0.007 Sv from Greenland (29), and 0.005 Sv from Eurasian rivers (50), totaling 0.026 Sv, without considering precipitation over the oceans or Canadian river runoff. The IPCC (12) argues that an abrupt transition of the THC is "very unlikely" (probability <10%) to occur before 2100 and that any transition is likely to take a century or more. Our definition encompasses gradual transitions that appear continuous across the tipping point; hence, some of the IPCC runs (ref. 12, p. 773 ff) may yet meet our criteria (but would need to be run for longer to see if they reach a qualitatively different state). Furthermore, the IPCC does not include freshwater runoff from GIS melt. Subsequent OAGCM simulations clearly pass a THC tipping point this century and undergo a qualitative change before the next millennium (48). Both the timescale and the magnitude of forcing are important (51), because a more rapid forcing to a given level can more readily overwhelm the negative feedback that redistributes salt in a manner that maintains whatever is the current circulation state.

El Niño–Southern Oscillation (ENSO). Gradual anthropogenic forcing is expected, on theoretical grounds, to interact with natural modes of climate variability by altering the relative amount of time that the climate system spends in different states (52). ENSO is the most significant ocean-atmosphere mode, and its variability is controlled by (at least) three factors: zonal mean thermocline depth, thermocline sharpness in the EEP, and the strength of the annual cycle and hence the meridional temperature gradient across the equator (53, 54). Increased ocean heat uptake could cause a permanent deepening of the thermocline in the EEP and a consequent shift from present day ENSO variability to greater amplitude and/or more frequent El Niños (55). However, a contradictory theory postulates sustained La Niña conditions due to stronger warming of the West Equatorial Pacific than the East, causing enhanced easterly winds and reinforcing the up-welling of cold water in the EEP (56). The mid-Holocene had a reduction in ENSO amplitude related to a stronger zonal temperature gradient (57, 58). The globally ≈3°C warmer early Pliocene is characterized by some as having persistent El Niño conditions (59), whereas others disagree (60). Under future forcing, the first OAGCM studies showed a shift from the current ENSO variability to more persistent or frequent El Niño-like conditions. Now that numerous OAGCMs have been intercompared, there is no consistent trend in their transient response and only a small collective probability of a shift toward more persistent or frequent El Niño conditions (61, 62). However, in response to a warmer stabilized climate, the most realistic models simulate increased El Niño amplitude (with no clear change in frequency) (54). This would have large-scale impacts, and even if the transition is smooth and gradual, a tipping point may exist by condition 1. Given also that past climate changes have been accompanied by changes in ENSO, we differ from IPCC (12) and consider there to be a significant probability of a future increase in ENSO amplitude. The required warming can be accessed this century (54) with the transition happening within a millennium, but the existence and location of any threshold is particularly uncertain.

Indian Summer Monsoon (ISM). The land-to-ocean pressure gradient, which drives the monsoon circulation is reinforced by the moisture the monsoon itself carries from the adjacent Indian Ocean (moisture-advection feedback) (63). Consequently, any perturbation that tends to weaken the driving pressure gradient has the potential to destabilize the monsoon circulation. Greenhouse warming that is stronger over land and in the Northern Hemisphere tends to strengthen the monsoon, but increases in planetary albedo over the continent due to aerosol forcing and/or land-use change tend to weaken it. The ISM exhibited rapid changes in variability during the last ice age (64) and the Holocene (65), with an increased strength during recent centuries consistent with Northern Hemisphere warming (66). Recent time series display strongly nonlinear characteristics, from the intraseasonal via the interannual and the decadal to the centennial timescale (67), with the interannual variations lag correlated with the phases of ENSO, although this may be increasingly masked by anthropogenic forcing (68). A simple model (63) predicts collapse of the ISM if regional planetary albedo exceeds ≈0.5, whereas increasing CO_2 stabilizes the monsoon. IPCC projections do not show obvious threshold behavior this century (12), but they do agree that sulfate aerosols would dampen the strength of ISM precipitation, whereas increased greenhouse gases increase the interannual variability of daily precipitation (69). We differ from IPCC (12) on the basis of past apparent threshold behavior of the ISM and because brown haze and land-use-change forcing are poorly captured in the models. Furthermore, conceptual work on the potentially chaotic nature of the ISM (70) has been developed (V. Petoukhov, K. Zickfeld, and H.J.S., unpublished work) to suggest that under some plausible decadal-scale scenarios of land use and greenhouse gas and aerosol forcing, switches occur between two highly nonlinear metastable regimes of the chaotic oscillations corresponding to the "active" and "weak" monsoon phases, on the intraseasonal and interannual timescales. Sporadic bifurcation transitions may also happen from regimes of chaotic oscillations to regimes with highly deterministic oscillations, or to regimes with very weak oscillations.

Sahara/Sahel and West African Monsoon (WAM). Past greening of the Sahara occurred in the mid-Holocene (71–73) and may have happened rapidly in the earlier Bölling-Allerod warming. Collapse of vegetation in the Sahara ≈5,000 years ago occurred more rapidly than orbital forcing (71, 72). The system has been modeled and conceptualized in terms of bistable states that are maintained by vegetation–climate feedback (71, 74). However, it is intimately tied to the WAM circulation, which in turn is affected by sea surface temperatures (SSTs), particularly antisymmetric patterns between the Hemispheres. Greenhouse gas forcing is expected to increase the interhemispheric SST gradient and thereby increase Sahel rainfall; hence, the recent Sahel drought has been attributed to increased aerosol loading cooling the Northern Hemisphere (75). Future 21st century projections differ (75, 76); in two AOGCMs, the WAM collapses, but in one this leads to further drying of the Sahel, whereas in the other it causes wetting due to increased inflow from the West. The latter response is more mechanistically reasonable, but it requires a ≈3°C warming of SSTs in the Gulf of Guinea (76). A third AOGCM with the most realistic present-day WAM predicts no large trend in mean rainfall but a doubling of the number of anomalously dry years by the end of the century (76). If the WAM is disrupted such that there is increased inflow from the West (76), the resulting moisture will wet the Sahel and support greening of the Sahara, as is seen in mid-Holocene simulations (73). Indeed, in an intermediate complexity model, increasing atmospheric CO_2 has been predicted to cause future expansion of grasslands into up to 45% of the Sahara, at a rate of up to 10% of Saharan area per decade (11). In the Sahel, shrub vegetation may also increase due to increased water use efficiency (stomatal closure) under higher atmospheric CO_2 (77). Such greening of the Sahara/Sahel is a rare example of a beneficial potential tipping element.

Amazon Rainforest. A large fraction of precipitation in the Amazon basin is recycled, and, therefore, simulations of Amazon deforestation typically generate ≈20–30% reductions in precipitation (78), lengthening of the dry season, and increases in summer temperatures (79) that would make it difficult for the forest to reestablish, and suggest the system may exhibit bistability. Dieback of the Amazon rainforest has been predicted (2, 80) to occur under ≈3–4°C global warming because of a more persistent El Niño state that leads to drying over much of the Amazon basin (81). Different vegetation models driven with similar climate projections also show Amazon dieback (82), but other global climate models (83) project smaller reductions (or increases) of precipitation and, therefore, do not produce dieback (84). A regional climate model (85) predicts Amazon dieback due to widespread reductions in precipitation and lengthening of the dry season. Changes in fire frequency probably contribute to bistability and will be amplified by forest fragmentation due to human activity. Indeed land-use change alone could potentially bring forest cover to a critical threshold. Thus, the fate of the Amazon may be determined by a complex interplay between direct land-use change and the response of regional precipitation and ENSO to global forcing.

Boreal Forest. The boreal system exhibits a complex interplay between tree physiology, permafrost, and fire. Under climate change, increased water stress, increased peak summer heat stress causing increased mortality, vulnerability to disease and subsequent fire, as well as decreased reproduction rates could lead to large-scale dieback of the boreal forests (77, 86), with transitions to open woodlands or grasslands. In interior boreal regions, temperate tree species will remain excluded from succession due to frost damage in still very cold winters. Continental steppe grasslands will expand at the expense of boreal forest where soil moisture along the arid timberline ecotone declines further (87), amplified through concurrent increases in the frequency of fires. Newly unfrozen soils that regionally drain well, and reductions in the amount of snow, also support drying, more fire and hence less biomass. In contrast, increased thaw depth and increased water-use efficiency under elevated CO_2 will tend to increase available soil moisture, decreasing fire frequency and increasing woody biomass. Studies suggest a threshold for boreal forest dieback of ≈3°C global warming (77, 86), but limitations in existing models and physiological understanding make this highly uncertain.

Others. We remind the reader that we considered other candidate tipping elements, which are not listed here because they did not meet conditions 2–4 for policy relevance. Some are listed in Table 1 and discussed in *SI Appendix 2*.

Ranking the Threat

Given our identification of policy-relevant tipping elements in the climate system, how do we decide which pose the greatest threat to society and, therefore, need the greatest attention? The first step is to asses the sensitivity of each tipping element to global warming and the associated uncertainties, including the confidence of the community in the argument for tipping element status. Our workshop and systematic review of the literature addressed this. In addition, formal elicitations of expert beliefs have frequently been used to bring current understanding of model studies, empirical evidence, and theoretical considerations to bear on policy-relevant variables (88). From a natural science perspective, a general criticism is that expert beliefs carry subjective biases and, moreover, do not add to the body of scientific knowledge unless verified by data or theory. Nonetheless, expert elicitations, based on rigorous protocols from statistics (89–91) and risk analysis (91, 92), have proved to be a very valuable source of information in public policymaking (93). It is increasingly recognized that they can also play a valuable role for informing climate policy decisions (94). In the field of climate change, formal expert elicitations have been conducted, e.g., on climate sensitivity (95), forest ecosystems (96), the WAIS (97), radiative forcing of aerosols (98), and the THC (99).

On the basis of previous experience (99), we used the aforementioned workshop to initiate an elicitation of expert opinions on, among other things, six potential tipping elements listed in Table 1: reorganization of the Atlantic THC, melt of the GIS, disintegration of the WAIS, Amazon rainforest dieback, dieback of boreal forests, and shift of the ENSO regime to an El Niño-like mean state. The elicitation was based on a computer-based interactive questionnaire that was completed individually by participating experts. Following a pilot phase at the workshop, the questionnaire was distributed to 193 international scientists in October and November 2005; 52 experts returned a completed questionnaire (among them 16 workshop participants and 22 contributors to the IPCC Fourth Assessment Report). Although participation inevitably involved a self-selection process, we assembled a heterogeneous group covering a wide range of expertise (see *SI Appendix 3*). The full results will be presented separately (E.K., J.W.H., H.H., R. Dawson, and H.J.S., unpublished work). Here we report a subset that reflect the range of scientific perspectives to supplement our own assessment of the tipping elements.

In the questionnaire, experts were asked for a pairwise comparison of tipping elements in terms of (*i*) their sensitivity to global mean temperature increase and (*ii*) the uncertainty about the underlying physical mechanisms. The exact questions posed to participants and the breakdown of their responses are described in *SI Appendix 3*. We have identified partial rankings of tipping elements from the collection of expert responses. Because the number of experts commenting on individual pairs of tipping elements varied widely, those rankings could not be established with equal credibility. We highlight the difference in expert consensus by using the symbols ≫ and > for strong and weak consensus upon the ordering, respectively, and by providing the number x that agreed with the direction of the ordering compared with the number y of experts who commented on the pair [given as $x(y)$]. For sensitivity to global mean warming, we find

$$\text{GIS}\ \overset{8(10)\ \text{to WAIS}}{\underset{7(7)\ \text{to THC}}{\gg}}\ \begin{array}{c} \text{WAIS}\ \overset{2(3)}{>} \\ \\ \text{Amazon rainforest}\ \underset{2(2)}{>} \end{array}\ \text{THC},$$

where the more sensitive tipping element is to the left. Owing to the close link between ENSO and the Amazon rainforest, both were judged of similar sensitivity to warming, but experts were divided as to whether ENSO would be more sensitive than the THC. Boreal forests were only compared with the Amazon rainforest, and three out of five experts judged the former to be more sensitive to global mean warming. Concerning the uncertainty about the physical mechanisms that may give rise to tipping points, we find

$$\begin{array}{c} \text{WAIS}\ \overset{3(4)\ \text{to THC}}{\underset{6(9)\ \text{to GIS}}{\gg}} \\ \\ \text{Amazon rainforest}\ \overset{2(2)\ \text{to THC}}{\underset{1(1)\ \text{to GIS}}{>}} \\ \\ \text{ENSO}\ \overset{3+2(6)\ \text{to THC}}{\underset{2(2)\ \text{to GIS}}{\geq}} \end{array}\ \text{THC}\ \overset{6(8)}{\gg}\ \text{GIS},$$

where the more uncertain tipping element is to the left. We display a greater or equal uncertainty about the ENSO compared with the THC, because three and two out of six experts believed the ENSO to be more and similarly uncertain, respectively. In addition, five out of six experts judged the uncertainty about the response of boreal forests to be larger than for the Amazon rainforest.

Taking into account our own analysis of the literature (summarized in the previous section and Table 1) and the expert elicitation (summarized above), the potential tipping elements in the climate system may be grouped into three clusters: (*i*) high sensitivity with smallest uncertainty: GIS and Arctic sea-ice; (*ii*) intermediate sensitivity with largest uncertainty: WAIS, Boreal forest, Amazon rainforest, ENSO, and WAM; (*iii*) low sensitivity with intermediate uncertainty: THC. ISM is not included in the clustering because its forcing differs, but it clearly has large uncertainty. We conclude that the greatest (and clearest) threat is to the Arctic with summer sea-ice loss likely to occur long before (and potentially contribute to) GIS melt. Tipping elements in the tropics, the boreal zone, and West Antarctica are surrounded by large uncertainty and, given their potential sensitivity, constitute candidates for surprising society. The archetypal example of a tipping element, the THC appears to be a less immediate threat, but the long-term fate of the THC under significant warming remains a source of concern (99).

The Prospects for Early Warning

Establishing early warning systems for various tipping elements would clearly be desirable, but can ρ_{crit} be anticipated before we reach it? In principle, an incipient bifurcation in a dynamical system could be anticipated (100), by looking at the spectral properties of time series data (101), in particular, extracting the longest system-immanent timescale (τ) from the response of the system to natural variability (102). Systems theory reveals (Fig. 2*A*) (*i*) that those tipping points that represent a bifurcation are universally characterized by $\tau \rightarrow \infty$ at the threshold, and (*ii*) that in principle τ could be reconstructed through methods of time series analysis. Hence a ''degenerate fingerprinting'' method has been developed for anticipating a threshold in a spatially extended system and applied to the detection of a threshold in the Atlantic THC, by using time series output from a model of intermediate complexity (102) (Fig. 2*B*).

These studies reveal that if a system is forced slowly (keeping it in quasi-equilibrium), proximity to a threshold may be inferred in a model-independent way. However, if the system is forced faster (as is probably the case for the THC today), a dynamical model will also be needed. Even if there is no bifurcation, determining τ is still worthwhile because it determines the system's linear response characteristics to external forcing, and transitions that are not strictly bifurcations are expected to resemble bifurcation-type behavior to a certain degree. For strongly resource-limited ecosystems that show self-organized patchiness, their observable macrostructure may also provide an indication of their proximity to state changes (103).

If a forewarning system for approaching thresholds is to become workable, then real-time observation systems need to be improved (e.g., building on the Atlantic THC monitoring at 26.5°N). For slow transition systems, notably ocean and ice sheets, observation records also need to be extended further back in time (e.g., for the Atlantic beyond the ≈150-year SST record). Analysis of extended time series data could then be used to improve models (104), e.g., an effort to determine the Atlantic's τ and assimilate it into ocean models could reduce the vast intra- and intermodel (44) spread regarding the proximity to a tipping point (102).

Conclusion

Society may be lulled into a false sense of security by smooth projections of global change. Our synthesis of present knowledge suggests that a variety of tipping elements could reach their critical point within this century under anthropogenic climate change. The greatest threats are tipping the Arctic sea-ice and the Greenland ice sheet, and at least five other elements could surprise us by exhibiting a nearby tipping point. This knowledge should influence climate policy, but a full assessment of policy relevance would require that, for each potential tipping element, we answer the following questions: Mitigation: Can we stay clear of ρ_{crit}? Adaptation: Can $\hat{F}$ be tolerated?

The IPCC provides a thorough overview of mitigation (105) and adaptation (106) work upon which such a policy assessment of tipping elements could be built. Given the scale of potential impacts from tipping elements, we anticipate that they will shift the balance toward stronger mitigation and demand adaptation concepts beyond incremental approaches (107, 108). Policy analysis and implementation will be extremely challenging given the nonconvexities in the human-environment system (109) that will be enhanced by tipping elements, as well as the need to handle intergenerational justice and interpersonal equity over long periods and under conditions of uncertainty (110). A rigorous study of potential tipping elements in human socioeconomic systems would also be welcome, especially to address whether and how a rapid societal transition toward sustainability could be triggered, given that some models suggest there exists a tipping point for the transition to a low-carbon-energy system (111).

It seems wise to assume that we have not yet identified all potential policy-relevant tipping elements. Hence, a systematic search for further tipping elements should be undertaken, drawing on both paleodata and multimodel ensemble studies. Given the large uncertainty that remains about tipping ele-

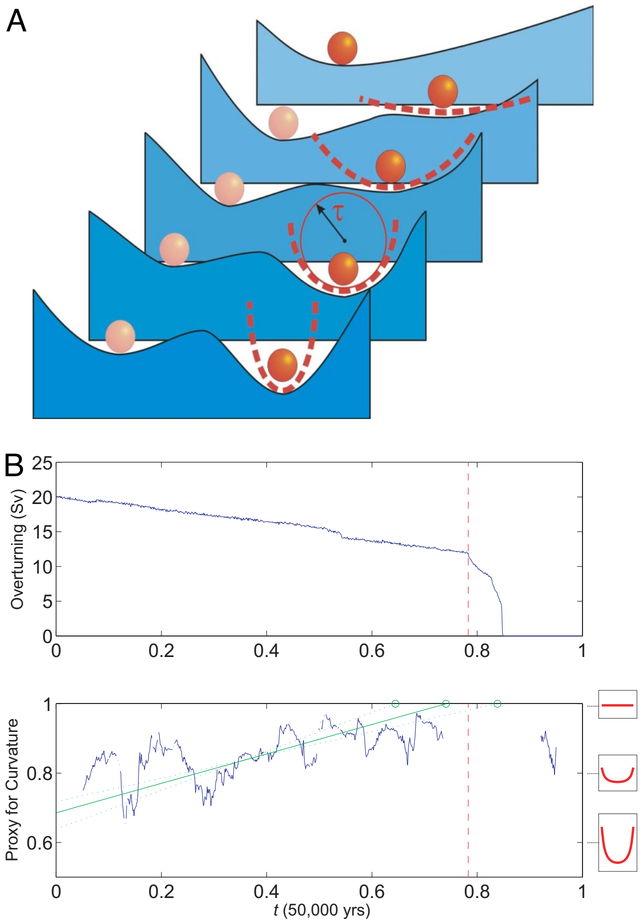

Fig. 2. Method for estimating the proximity to a tipping point. (*A*) Schematic approach: The potential wells represent stable attractors, and the ball, the state of the system. Under gradual anthropogenic forcing (progressing from dark to light blue potential), the right potential well becomes shallower and finally vanishes (threshold), causing the ball to abruptly roll to the left. The curvature of the well is inversely proportional to the system's response time τ to small perturbations. ''Degenerate fingerprinting'' (102) extracts τ from the system's noisy, multivariate time series and forecasts the vanishing of local curvature. (*B*) Degenerate fingerprinting ''in action'': Shown is an example for the Atlantic meridional overturning circulation. (*Upper*) Overturning strength under a 4-fold linear increase of atmospheric CO_2 over 50,000 years in the CLIMBER-2 model with weak, stochastic freshwater forcing. Eventually, the circulation collapses without early warning. (*Lower*) Overturning replaced by a proxy of the shape of the potential (as in *A*). Although the signal is noisier in *Lower* than it is in *Upper*, it allows forecasting of the location of the threshold (data taken from ref. 102). The solid green line is a linear fit, and the dashed green lines are 95% error bars.

ments, there is an urgent need to improve our understanding of the underlying physical mechanisms determining their behavior, so that policy makers are able ''to avoid the unmanageable, and to manage the unavoidable'' (112).

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