Tipping elements in the Earth's climate system

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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 ≈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.,

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

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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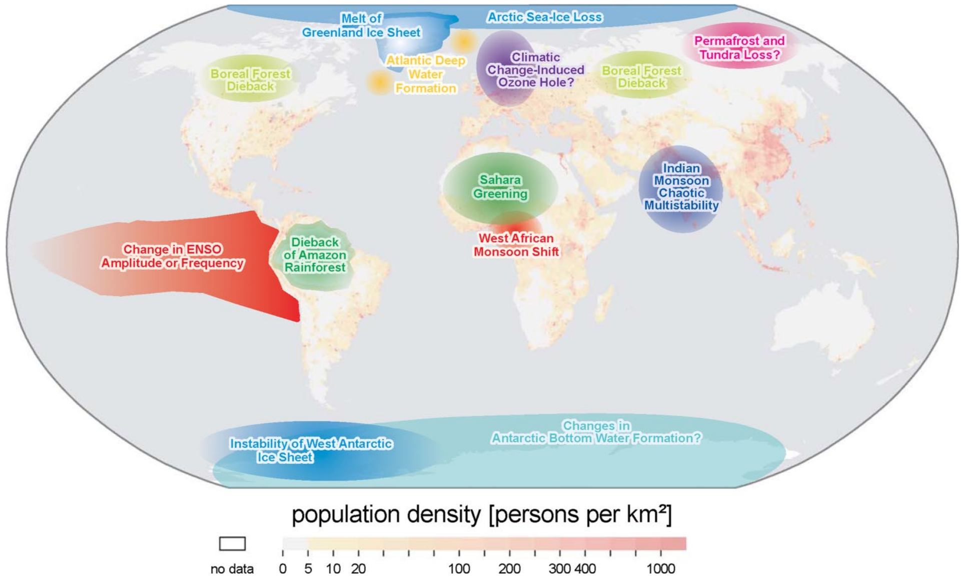

Fig. 1. Map of potential policy-relevant tipping elements in the climate system, updated from ref. 5 and overlain on global population density. Subsystems indicated could exhibit threshold-type behavior in response to anthropogenic climate forcing, where a small perturbation at a critical point qualitatively 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 $\delta\rho \to 0$, 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, $T \to T_E$).

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 ΔT_{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 (−)	$\Delta T_{permafrost}$	Missing‖	—	<100 yr (gradual)	CH_4 and CO_2 release
Marine methane hydrates*	Hydrate volume (−)	$\Delta T_{sediment}$	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 anti-symmetric 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

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

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

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

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-

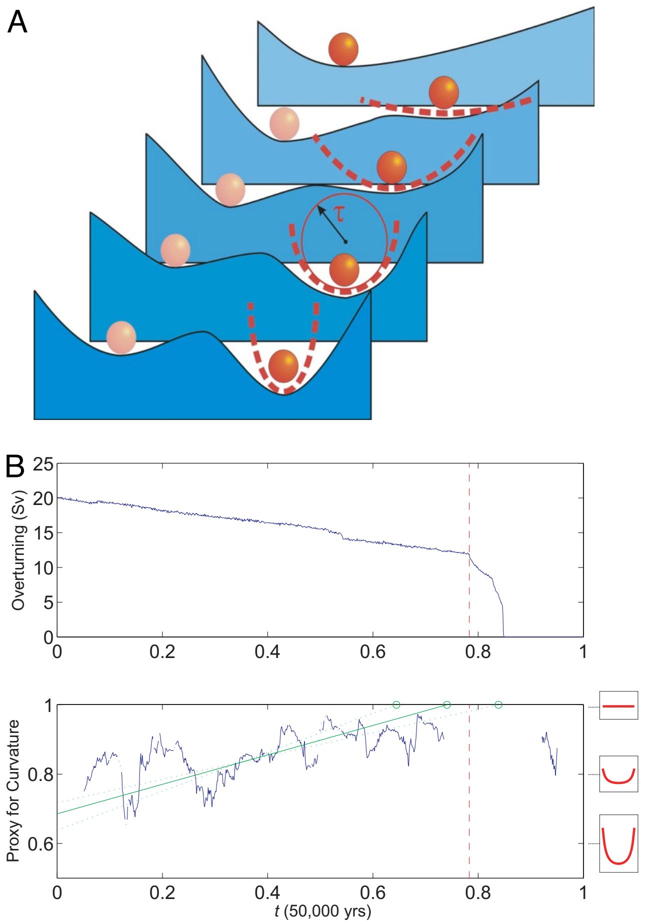

Fig. 2. Method for estimating the proximity to a tipping point. (*A*) Schematic approach: The potential wells represent stable attractors, and the ball, the state of the system. Under gradual anthropogenic forcing (progressing from dark to light blue potential), the right potential well becomes shallower 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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Integrating tipping points into climate impact assessments

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Abstract There is currently a huge gulf between natural scientists' understanding of climate tipping points and economists' representations of climate catastrophes in integrated assessment models (IAMs). In particular, there are multiple potential tipping points and they are not all low-probability events; at least one has a significant probability of being passed this century under mid-range (2–4 °C) global warming, and they cannot all be ruled out at low (<2 °C) warming. In contrast, the dominant framing of climate catastrophes in IAMs, and in critiques of them, is that they are associated with high (> 4 °C) or very high (> 8 °C) global warming. This discrepancy could qualitatively alter the predictions of IAMs, including estimates of the social cost of carbon. To address this discrepancy and assess the economic impact of crossing different climate tipping points, we highlight a list of scientific points that should be considered, at least in a stylised form, in simplified IAMs. For nine different tipping events, the range of expected physical climate impacts is summarised and some suggestions are made for how they may translate into socio-economic impacts on particular sectors or regions. We also consider how passing climate tipping points could affect economic growth.

1 Introduction

Climate change poses a global risk management problem. Whilst natural scientists tend to emphasise the risks associated with unchecked climate change, economists counter with the economic risks of making costly investments to tackle climate change that may turn out to be

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unnecessary (Nordhaus 1994). Attempts to strike a balance between these opposing positions are often played out through cost-benefit analysis using integrated assessment models (IAMs). However, recent critiques have highlighted that the representation of catastrophic climate risks can qualitatively alter the results of IAMs (Weitzman 2009). Furthermore, recent scientific assessments have significantly increased the likelihood of catastrophic climate events (Kriegler et al. 2009; Lenton et al. 2008; Levermann et al. 2012; Schellnhuber et al. 2006; Smith et al. 2009).

From an economic perspective a 'catastrophe' is "an event that is believed to have a very low probability of materializing but that if it does materialize will have a harm so great and sudden as to seem discontinuous with the flow of events that preceded it" (Posner 2004). Meanwhile, arguably the greatest 'reason for concern' about climate change are what the Intergovernmental Panel on Climate Change (IPCC) term 'large-scale discontinuities'. These are literal threshold responses in parts of the climate system. In their recent update of the reasons for concern, Smith et al. (2009) conclude that the risks of large-scale discontinuities become significant for even modest levels of global warming (~2.5 °C). Going into more detail, nine potential 'tipping elements' in the climate system have been identified that could pass a tipping point this century (Lenton et al. 2008), and imprecise probability assessments have been made for five of these (Kriegler et al. 2009). Each could be a potentially costly large-scale discontinuity, but corresponding economic impacts studies are largely lacking.

In contrast, existing IAMs allow for at most one pseudo-aggregate discontinuity, and they vary hugely in their assumptions about its likelihood, and in their assessment of its impacts. Catastrophic impacts estimates do dominate the overall damage estimates in some integrated assessments. For instance, in one version of the DICE model (a simplified IAM), for a 2.5 °C temperature increase, two thirds of the overall damage (of 1.5 % of global GDP) is due to the catastrophic component (Nordhaus and Boyer 2000) (their Table 4.10). Still this does not amount to an economic catastrophe (defined in that model as a 30 % reduction in global GDP), because the likelihood of the catastrophic event is assumed to be only 1.2 %.

Such IAM estimates are based on the so-called climate damage function, which usually relates global temperature change to its economic impact in terms of GDP change, and is a cornerstone in the economic analysis of climate change, e.g. (EPA 2010; Nordhaus 1992). However, there is as yet no robust empirical foundation for this function shape and its parameter values (Hanemann 2008; Weitzman 2010). In spite of these limitations, economists have estimated the social cost of carbon (SCC), the damage in monetary terms induced by an additional tonne of carbon emitted. The EPA (2010) SCC estimate from the average of three simplified IAMs is 21\$/tCO_2, at a discount rate of 3 %, and the 95th percentile SCC estimate is 65\$/t CO_2. But do such numbers adequately reflect the risks posed by climate tipping points?

Weitzman (2009; 2010) provides a penetrating critique of conventional assessments of catastrophic risks for climate policy, exploring instead the implications of a 'fat tail' to the upper end of the probability distribution of future warming. He shows that a risk averse agent should spend a large part of their income trying to avoid the low (but fat-tailed) probability of catastrophic future climate change (defined in this case as very high warming). This is qualitatively different to the results from the current generation of IAMs which assume a 'slim tail' to the distribution in which catastrophic impacts lurk, generating only a modest investment to try and avoid them. SCC estimates could be hundreds of dollars higher if fat-tailed distributions are included and the damage function is made steeper (Dietz 2011).

This article critically reviews modelling of tipping point impacts in the economics of climate change literature and, specifically, in the simplified IAMs. Section 2 summarises recent advances in the natural science understanding of tipping points, with a view to their possible implementation into IAMs. Section 3 reviews the modelling of catastrophic climate impacts in IAMs. Section 4 proposes an idealised stylised framework to bridge the gap between recent developments in Earth system science and economics. There we try to systematise the current understanding about how climate catastrophes could affect the economic system. For that purpose, a general equilibrium (GE) framework is taken as reference, mapping the physical consequences of tipping points to their possible associated economic impacts. Section 5 concludes, and the Supplementary Information provides additional discussion and links to the primary literature on climate tipping points and their impacts.

2 Tipping points: what is known from Earth system science

Several 'tipping elements' in the climate system have been identified that could pass a tipping point this century, leading to a qualitative change in their future state (Lenton et al. 2008; Schellnhuber 2009). Leading candidates are: abrupt loss of Arctic summer sea-ice, irreversible meltdown of the Greenland ice sheet (GIS), disintegration of the West Antarctic ice sheet (WAIS), reorganisation of the Atlantic thermohaline circulation (THC), increased amplitude of the El Niño Southern Oscillation (ENSO), disruption of the Indian summer monsoon (ISM), collapse of the West African monsoon (WAM), dieback of the Amazon rainforest, and dieback of boreal forests. Abrupt changes in Antarctic bottom water formation, tundra, permafrost, marine methane hydrates, ocean anoxia and Arctic ozone have also been considered, but either lacked evidence for a large-scale threshold or were deemed to have a threshold that is inaccessible this century (Lenton et al. 2008). Subsequent work has identified the Yedoma region of permafrost and the North Atlantic sub-polar gyre as potential tipping elements, and has considered several other candidates, including aridification of southwest North America (Lenton 2012; Lenton et al. 2009; Levermann et al. 2012). A new class of tipping point dependent only on the rate of climate change has also been suggested, with the example of self-sustaining breakdown of soils rich in carbon (Wieczorek et al. 2011).

The existence of a threshold is uncertain for some of these systems (see Supplementary Information), but the salient point here is not whether all of these systems exhibit tipping points—but rather that the list of potential tipping points is a long one! Even if further research eliminates some of the candidates, it seems unlikely that the list will reduce to a single large-scale discontinuity. Thus, we should consider the possibility of multiple tipping points in the climate system, which are unlikely to all occur at the same time or level of e.g. global temperature rise.

In fact, the causes of tipping are different for different elements, and cannot always be related to global warming or CO_2 (Lenton 2011a, b). In particular, the Indian summer monsoon is weakened by localised aerosol pollution, both cooling sulphate and warming black carbon aerosols, which form 'atmospheric brown clouds'. The Amazon rainforest and the Sahel are also sensitive to sulphate aerosol pollution, but in opposite directions. Cooling sulphate aerosol pollution has been biased to the Northern Hemisphere and tended to promote drought in the Sahel but protected the Amazon from drought (because of an overall southward shift in the Inter-Tropical Convergence Zone). In the Arctic region, declining sulphate aerosols and increasing black carbon aerosols probably make the largest contribution to warming, followed by the greenhouse gases methane and (short-lived) ozone. Thus, to fully capture the likelihood of all the different tipping different elements in an IAM, one would need to include short-lived, regionally-explicit radiative forcing agents.

In the meantime, some progress can be made by considering the subset of tipping elements where a threshold can be meaningfully (if imperfectly) related to global temperature change, via regional changes in temperature or precipitation (Giorgi 2008). So, where do those tipping points lie? Initial assessments based on literature review and a workshop (‘Tipping Points in the Earth System’ at the British Embassy in Berlin, 5–6 October 2005) suggested the Arctic sea-ice and the Greenland ice sheet have the nearest tipping points, in the range 0.5–2 °C of global warming (above 1980–99). Most of the remaining thresholds could lie somewhere in the range 3–5 °C of global warming. An independent synthesis is broadly consistent with this, suggesting that the risk of large scale discontinuities becomes significant around 1 °C global warming and starts to become severe at 2.5 °C global warming (Smith et al. 2009).

Expert elicitation (Kriegler et al. 2009) has obtained more detail in the form of imprecise probability statements for tipping of five elements (GIS, WAIS, THC, ENSO, Amazon) under three different future temperature corridors out to the year 2200 (low=0.5–2 °C, medium=2–4 °C, and high >4 °C). In the results, if the upper probability bound was <0.1 it was considered “remote”, if the lower probability bound ≥0.1 it was considered “significant” and if it was ≥0.5 it was considered “large”. The only remote probabilities were for two elements (the THC and ENSO) under the low warming scenario. Under medium warming, the majority of experts gave a significant probability of tipping Greenland and the Amazon, and half the experts gave a large probability of tipping Greenland. Under high warming, all tipping points were given significant probability, and tipping of Greenland and the Amazon were given large probability. Aggregating these results, even under the most conservative assumptions, gives a >16 % probability of tipping at least one of five elements under medium warming, which rises to >56 % probability (i.e. more likely than not) under high warming.

The key point here is that the portrayal of climate tipping points as ‘high impact-low probability’ events no longer seems justified if future global warming is >2 °C, and certainly not if warming exceeds 4 °C. One might counter that the greater the warming, the less likely it is to occur, but we need to think in terms of a probability distribution of warming, where very low warming is also unlikely. If we look at ‘business-as-usual’ type emissions scenarios with a mid-range climate sensitivity they readily produce around 4 °C warming at the end of this century (New et al. 2011), and staying under 2 °C warming is looking less likely than exceeding it. Ideally we should then work out (joint) probability distributions for tipping each element, which combine the likelihood of different levels of warming with the likelihood of tipping that element as a function of warming. However, it seems obvious that the result will be a significant (i.e. ≥0.1) probability of passing at least one tipping point this century or next.

This is a key point, because it is at odds with the definition of a ‘catastrophe’ as used in the economics literature. Passing one or more climate tipping points in the next century or so is already well beyond “very low probability” (Posner 2004). So, either the recent studies leading to this conclusion are wrong (and climate tipping points can indeed be treated as high-impact low probability events) or the current treatment of climate tipping points in IAMs is wrong. Is there a way that this qualitative discrepancy between Earth system science and economics can be reconciled?

Well there might be, if the impacts of passing particular tipping points are not so catastrophic. At least three factors are crucial to determining these impacts. First is the time it takes (having passed a tipping point), for a qualitative change to occur. This varies widely between the different tipping elements, ranging over at least 1–1,000 years (whereas IAMs tend to assume that all of the impacts happen immediately a tipping point is passed). At the quick end of the scale are shifts in monsoonal systems that could occur from one year to the next. At the slow end of the scale are the loss of large ice sheets that could take a millennium or more. Second is how widely distributed the impacts of passing a tipping point will be. Many tipping elements are regionally-focused and the impacts of tipping them will be unevenly distributed (Table 1). However, even with regional systems, e.g. monsoons, there is usually the possibility for knock-on effects elsewhere in the world, because we live in a coupled Earth system, and a globalised economic system. Third is the (ir)reversibility of passing particular tipping points. Not all tipping points are points of no return leading to irreversible change. Integrated over time, if a tipping point is subsequently reversed it would have less impact than if it were irreversible. However, it will be extremely difficult to reduce future global warming without geoengineering the climate (Solomon et al. 2009), meaning that for current practical purposes, climate tipping points can be viewed as irreversible.

An example of widespread, irreversible but relatively slow onset impacts is the disintegration of large ice sheets contributing to sea-level rise. The two key tipping elements in this regard are Greenland and West Antarctica. Greenland can contribute ~7 m (if melted completely) and the parts of West Antarctica grounded below sea-level ~3 m (Bamber et al. 2009) to global average sea level, or ~10 m in total. Parts of the East Antarctic ice sheet grounded below sea level may also be vulnerable to abrupt shrinkage, and in the past, over multi-millennial timescales, sea level has shown a high sensitivity to temperature of order ~10 $m°C^{-1}$ (Rohling et al. 2009). In the long-run therefore, there is a significant probability of sea level rise >10 m. But timescale is crucial here, as the impacts of sea-level rise depend strongly on the rate at which it occurs (as well as the eventual magnitude). Once a tipping point is passed e.g. committing Greenland to irreversible meltdown, the amount by which it is passed will still affect the rate of melt and hence sea-level rise (Huybrechts and De Wolde 1999). Even if tens of metres of sea level rise are destined to occur millennia hence, this may never be "so great and sudden as to seem discontinuous with the flow of events that preceded it" (Posner 2004). Thus, not all climate tipping points necessarily translate into clear tipping points in impacts.

What about the impacts of tipping the other elements? Several studies have looked at the impacts of a collapse of the Atlantic thermohaline circulation (Arnell et al. 2005; Kuhlbrodt et al. 2009; Lenton et al. 2009; Link and Tol 2011; Link and Tol 2004; Schwartz and Randall 2003), which is typically viewed as catastrophic (Nordhaus 1994) although at least one study has argued it could have a net economic benefit (Link and Tol 2004). Alas, targeted studies of the impacts of passing other tipping points are in short supply. Initial assessment of the effects of Amazon rainforest dieback, disruption of the Indian summer monsoon, or abrupt aridification of Southwest North America all suggest high damages (Lenton et al. 2009). However, there are some tipping elements for which the impacts may not be catastrophic, e.g. dieback of boreal forests would be a regional and ecological catastrophe, but it is unclear whether it ranks as a global catastrophe.

This highlights a more general need to comprehensively map out the potential physical consequences of different tipping events. So, in Table 1 (and the Supplementary Information) we make a start at this for the nine tipping elements identified previously (Lenton et al. 2008). For each tipping event, we consider potential impacts on precipitation, atmospheric and ocean circulation, as well as on temperature and sea level. We also consider how they may alter climate variability, including the distribution of shorter-term extreme events that impact people. Such connections have only begun to be mapped out in climate models, but they could be critical to determining the impacts of tipping points, and if so they should ultimately be captured in IAMs. There are also potential causal couplings between tipping events (e.g. as mapped out in Figure 2 of Kriegler et al. 2009).

Table 1 Potential physical impacts of passing different climate tipping points (see the Supplementary Information for references)

Tipping event	Temperature	Sea level	Precipitation	Atmospheric circulation	Ocean circulation	Biogeochemical cycles	Modes of variability	Extreme events
Arctic summer sea-ice loss	↑Arctic & N. Hem. warming	(minimal effect)	Local shift from snowfall to rainfall	↓polar vortex, shift in storm track	Intrusion of warm Atlantic waters	↑Permafrost thawing, ↑CO_2, CH_4	Shift in NAO centre of action	Cold winters in Europe
Greenland ice sheet meltdown	Local ↑	≤7 m global ≤0.5 m/century uneven	Local shift to rainfall	Less jet stream deflection?	↓THC, loss of Irminger Sea convection	Flooding of permafrost, ↑CO_2, CH_4	?	Storm surges, icebergs
West Antarctic ice sheet collapse	Local ↑	≤3.3 m abrupt ≤1 m/century uneven	Local shift	Uneven polar vortex?	↓or↑THC, Archipelago created	Flooding of permafrost, ↑CO_2, CH_4	?	Storm surges, icebergs
Atlantic thermohaline circulation (THC) shutdown	↓N. Atlantic ↑S. Hem.	Regional shifts ↑0.5 m in parts of N. Atlantic	Drying of Sahel, collapse of WAM, wetting Amazonia	Southward shift of ITCZ, Atlantic storm track shift	Fundamental reorganisation	↑CO_2, biome changes	AMO ceases, ↑ENSO	Cold winters in Europe, hurricanes shift south?
ENSO increase in amplitude	↑S Asia, S Australia…↓in NZ	Regional effects	↓SE Asia, E Australia, Amazon…	Walker circulation change	↑THC, warming Ross, Amundsen seas	↑CO_2, reduced land C storage	Coupled changes to PDO, AMO	Droughts, floods
Indian summer monsoon (ISM) weakening	Local ↑summer	–	↓ in India	[inherent]	?	?	Coupling to SO?	Drought in India, heatwaves
West African monsoon (WAM) collapse	↑in Sahel ↓coastal W. Africa	–	Sahel wetting/drying? (uncertain)	Inflow of moist air from Atlantic to W?	?	Possible greening of Sahel/Sahara	Coupling to THC?	Source region for Atlantic hurricanes
Amazon rainforest dieback	↑regional	–	↓regional	Walker circulation?	–	↑CO_2	Feedback to ENSO?	Droughts, fires, biodiversity loss
Boreal forest dieback	↓winter ↑summer	–	↓regional?	Regional effects?	–	↑CO_2	–	Fires, insect pests, biome loss

NAO North Atlantic Oscillation, *AMO* Atlantic Multidecadal Oscillation, *PDO* Pacific Decadal Oscillation, *SO* Southern Oscillation

Several insights emerge from this discussion that should be considered (at least in a stylised form) in simplified IAMs: (1) There are multiple tipping points. (2) They occur at different levels of forcing. (3) Some can be meaningfully related to global temperature change (although indirectly). (4) Others are sensitive to localised climate forcing agents (especially aerosols). (5) Some may depend on the rate of climate forcing. (6) The precise tipping points are uncertain. (7) They are not all ‘low’ probability events, some should be considered significant (>0.1) or even large (>0.5) probability events. (8) Tipping points are mostly irreversible in practice (even though some are reversible in principle). (9) The time for their full impact to be realised varies (over 1–1,000 yr). (10) The spatial extent of their impacts varies (from regional, i.e. ~1,000 km, to global scale). (11) Impacts can still depend on the extent to which a tipping point is exceeded.

3 Tipping points in IAMs

The preceding discussion indicates that economic impacts would vary widely between tipping points, affecting different sectors and regions. This section reviews the modelling of catastrophic impacts in the simplified IAMs used in the EPA (2010) assessment of the social cost of carbon; the DICE, PAGE and FUND models.

3.1 DICE

The damage function of the current DICE2007 model (used in the EPA assessment), mainly based on the DICE1997 model (Nordhaus and Boyer 2000), has non-catastrophic and catastrophic components. The catastrophic damage estimates are based on a survey of 19 experts (Nordhaus 1994) and combine four elements (Nordhaus and Boyer 2000): Firstly, a high consequence climate catastrophe is defined as one that could lead to a permanent loss of 25 % of global GDP, comparable to the cumulative loss over several years after the 1929 Great Depression. (For comparison the 2008 Great Recession led to an approximately 5 % annual GDP loss in 2009.) The catastrophe is assumed to have asymmetric effects across countries, e.g. affecting the EU twice as much as to the US (because it is based on a collapse of the thermohaline circulation). Secondly, experts were asked to assess the likelihood of that climate catastrophe for two global temperature increase scenarios: 2.5 °C in 2090 and 6 °C in 2175. There was high variability among the experts and, particularly, across disciplines. The mean probability was 4.8 % for the 2.5 °C scenario and 12.1 % for the 6 °C case. Thirdly, both the estimated GDP loss and the probabilities were increased in order to take into account new evidence by the end of the 1990s about the effects and likelihood of the collapse or slow down of the thermohaline circulation (Nordhaus and Boyer 2000). The probabilities were doubled and the GDP loss increased to 30 %. Note, however, that the probabilities actually implemented in DICE are only 0.6 % for the 2.5 °C scenario and 3.4 % for the 6 °C scenario (Nordhaus and Boyer 2000). Finally, it is assumed that agents are averse to catastrophic risk, and they are willing to pay to avoid it (following a rate of risk aversion of 4 and an income elasticity of 0.1). The willingness to pay to avoid the catastrophe for the 2.5 °C scenario is 1 % of global GDP and 7 % for the 6 °C scenario.

3.2 PAGE

Dietz et al. (2007) describe the way the PAGE2002 model (Hope 2006) used in the Stern review (Stern 2006) considers catastrophic impacts. PAGE models the impact of a climate catastrophe or discontinuity in probabilistic terms, when global temperature is above a certain threshold. The threshold follows a triangular distribution (as with all random parameters and exogenous variables in PAGE) with mode of 5 °C, minimum of 2 °C and maximum of 8 °C. The probability of discontinuity then starts to rise from zero by 10 % per °C above the threshold (i.e. with a mode of +5 °C). The mode of the immediate GDP loss is 10 %, with a minimum of 5 % and a maximum of 20 %. This specification of the discontinuity damage function means that for a global temperature increase of 6 °C the mode of the GDP loss would be 1 % (six times lower than under the DICE model), for 7 °C it would be 4 % of GDP, and 9 % for 8 °C. Notably, despite these modest catastrophe-derived damages, Stern (2006) still came to the conclusion that climate protection pays off.

In the updated PAGE2009 model (Hope 2011), the GDP losses due to the discontinuity does not occur immediately, but along a transition period. Note that while in DICE GDP is endogenously computed, and therefore accounts for the GDP loss because of climate change, in the PAGE models, GDP is exogenously driven. This lead to a certain underestimation of climate damages on GDP in the PAGE model, compared to DICE, other things being equal.

3.3 FUND

FUND 2.8n has been used to assess the economic impacts of a collapse of the West Antarctic ice sheet (Nicholls et al. 2008), and of a shutdown of the thermohaline circulation (Link and Tol 2011; Link and Tol 2004), on a country-by-country basis.

The WAIS collapse scenarios (Nicholls et al. 2008) involve a globally-uniform 5 metre rise in sea level, starting in 2030 and taking from 100 to 1,000 years, i.e. contributions to sea-level rise of 0.5–5 m/century. The 100 year collapse scenario (5 m/century) with a nearby tipping point is presented as an extreme scenario but one that cannot be completely ruled out. Only the impacts of sea level rise on coastal zones are considered, excluding storms and sea flood risk. The model assumes perfect (i.e. optimal) adaptation action based on cost-benefit analysis. High levels of coastal protection are predicted around low-lying population centres, which massively reduces the number of people exposed to flooding to around 2–3 % of the 400 million that live within 5 m of sea level. This comes at considerable cost, but one that is less than the cost of abandonment. Meanwhile large (but thinly populated) areas of agricultural land, boreal forest, and tundra are abandoned to rising seas. However, case studies of the Netherlands and the Thames Estuary with the same 5 m/century driving scenario, suggest that imperfect adaptation, e.g. due to delays in policy implementation, makes abandonment a more likely outcome (Lonsdale et al. 2008; Olsthoorn et al. 2008).

There are also some scientific weaknesses in the driving scenarios. First, the fastest WAIS collapse yet simulated by models takes around 1,000 years (Pollard and DeConto 2009). Second, the fraction of the WAIS vulnerable to abrupt collapse is equivalent to around 3.3 m rather than 5 m of eustatic sea level rise (Bamber et al. 2009). Third, the sea-level contribution from WAIS collapse would not be globally uniform, exceeding the mean along e.g. the eastern seaboard of the US (Mitrovica et al. 2009). Finally, the loss of the WAIS and attendant sea level rise would have other impacts that are not considered (Table 1), for example, encouraging retreat of the Greenland ice sheet (Kriegler et al. 2009), and releasing methane and carbon dioxide from the flooding of tundra and boreal forests in the Arctic.

The THC shutdown scenario (Link and Tol 2011) is superimposed on an underlying business-as-usual climate change scenario, with weakening of the THC starting in 2070 and shutdown completing in 2100. This is a rapid shutdown when compared to many models, though not when compared to paleo-data. Crucially, only the resultant temperature changes are considered, with a few countries (e.g. Iceland, Ireland) experiencing net cooling, many in the Northern Hemisphere experiencing less warming than they otherwise would, and many in the Southern Hemisphere experiencing more warming than they otherwise would. Overall the economic impact is negative but limited to at most around 0.3 % of global GDP (adding to around 1 % reduction in GDP due to climate change alone, late this century). There are larger negative effects in some countries and sectors, counterbalanced by benefits elsewhere.

However, effects on other climate variables (Table 1) that are not considered, could arguably have much larger impacts. A THC shutdown would impact precipitation (e.g. through southward shift of the Inter-Tropical Convergence Zone), would have dynamic effects on sea-level, would alter seasonality and the distribution of extreme events in the North Atlantic region, and would have knock-effects for other tipping elements such as the Indian monsoon.

In the version of FUND used in the EPA (2010) assessment, the total damages (not just the catastrophic component) actually slow down as warming passes 5 °C and at 8 °C above pre-industrial they are only ~7 % of GDP.

4 Proposals for integrated assessment modelling of climate tipping points

The preceding sections highlight qualitative discrepancies between current understanding of climate tipping points and their treatment in IAMs. Here we address how tipping points could be better captured in a stylised way in IAMs. Then we consider how the magnitude, time and space scales of their impacts could be better captured. Finally, we consider more broadly how they could impact the economy.

4.1 Representation of tipping points

Current IAMs if they consider a tipping point at all have only one of them, perhaps because it is assumed to be catastrophic. However, natural science suggests including multiple tipping points, of differing (but uncertain) proximity, and expert elicitation (Kriegler et al. 2009) suggests at least one of them is a lot closer than considered in existing studies with DICE or PAGE. This could be addressed in an IAM by introducing several tipping points each at a different level of global temperature change (with some associated uncertainty range). To examine the qualitative effects, one could proceed without worrying about the precise identity of each tipping point; several could be scattered across e.g. the range 1–6 °C global warming, with differing magnitudes of impacts and timescales for impacts to be realised.

To make it more realistic, IAMs should consider the whole set of tipping points (Table 1) and draw on recent assessments of the proximity of specific thresholds (summarised in Section 2), rather than the outdated information they seem to be using at present. For example, irreversible meltdown of the Greenland ice sheet is a good candidate for a potentially nearby tipping point, with e.g. a best guess threshold of 2 °C (above 1980–99). Uncertainties about threshold location can be captured with likelihood functions, e.g. for Greenland a lower limit of 0.5 °C and an upper limit of around 5 °C.

Ideally, as information becomes available, thresholds should be redefined in terms of radiative forcing, which has the advantage that one can circumvent the uncertain climate sensitivity (Lenton 2011a, b). To capture those tipping points that are sensitive to regional forcing factors IAMs will need to capture regional radiative forcing and its various contributors. This sounds challenging, but even simplified IAMs break the economy down into regions (or even countries), and often distinguish regional from global temperatures. For parity, we suggest they consider regional sources and concentrations of short-lived radiative forcing agents. Ideally regions should be associated with particular tipping elements (e.g. Amazonia, West Africa, Greenland, West Antarctica) not just players in the global economy.

Where a tipping point is believed to respond to the rate of (regional) climate change, then this needs to be brought into the mathematics of an IAM, which should not be prohibitively difficult in that time and forcing are already variables in the model.

4.2 Capturing the impacts of passing tipping points

IAMs typically translate passing a tipping point into an immediate and significant loss of GDP. This is the ‘sharpest’ form of discontinuity—akin to a first-order phase transition in physics, or a discontinuity in the graph of a function in mathematics. Whilst this might be appropriate for a sudden shift in a monsoon system (e.g. India, China) from one year to the next, it is clearly not appropriate for many other tipping elements where the impacts will accrue over time. In the past, there have indeed been very abrupt changes in climate, of the order of 5 °C in a decade, linked to abrupt shifts of the Atlantic thermohaline circulation, coupled to sea-ice and atmospheric circulation. Yet in future model projections where the THC collapses, it typically takes the order of a century. Ice sheet collapse is even slower, taking several centuries at least. Thus, the impacts of crossing some climate tipping point may be better described as a discontinuity in the gradient (first derivative) of a function. For example, a sudden change in the rate of sea-level rise (rather than a jump in its magnitude) due to passing a tipping point for West Antarctic ice sheet collapse.

The magnitude of GDP loss (or perhaps in one or two cases, gain) associated with particular tipping points clearly merits further research. Current stylised approaches disagree widely (Section 3). In a spirit of qualitative enquiry, one could randomly assign a range of impacts magnitudes (and timescales) to a scattering of tipping points in a simple IAM to see if and how it can qualitatively alter results.

Beyond that there is a need for detailed research on the impacts of individual tipping point scenarios, which should use high-resolution impacts models, e.g. (Higgins and Vellinga 2004). The details at the regional and spatial scales do matter as aggregate estimates hide results relevant both for society and policymakers. For instance, even if the aggregated effect on global GDP due to the impacts in the agriculture sector appear relatively low (e.g. <0.5 %), for specific countries and concrete social groups, the consequences can be very significant in terms of hunger risk (Parry et al. 1999).

Once assessed, the differing spatial distribution of impacts from different tipping points can be brought into IAMs that distinguish different regions. Of interest are tipping points whose major impacts will be quite localised, e.g. dieback of the Amazon rainforest, or disruption of the Indian summer monsoon (Table 1). They warrant targeted studies looking at how these very-disproportionate impact events play out in a globalised economy.

Natural modes of climate variability, notably ENSO, could also be incorporated into simplified IAMs. Known impacts on e.g. agriculture and health, could then be used to help parameterise e.g. the impact of a sudden increase in the magnitude of ENSO variability. Ultimately, one might picture an IAM that captures a series of principal components describing the dominant patterns of climate variability, how they are coupled together, and how they are affected by particular tipping points, e.g. loss of Arctic sea-ice cover.

Table 2 Mapping between sectoral impacts and economic variables

		Economic variables			
		Household Welfare	Production	Capital stock	Labour
Sectoral impacts	Agriculture		Change in land productivity		
	Coastal areas	Forced migration reducing welfare	Production losses due to sea floods	Capital losses due to sea floods	
	River floods		Production losses due to river floods	Capital losses due to river floods	
	Tourism		Change in tourism expenditures		
	Human health	Change in mortality	Change in morbidity		Lower productivity due to higher temperature

4.3 How tipping points could affect the economy

Usually only global GDP is considered as the variable in the left-hand side of the catastrophic damage function in IAMs. While this has simplicity on its side, it hides the specific sectors and regional areas to be affected. Yet that information is relevant and necessary for policymakers, and important for raising awareness of the climate change problem.

Ideally any assessment of climate change impacts should look not only at the effects on economic production (GDP) in a certain year, but also at the dynamic effects over time. Fankhauser and Tol (2005) discuss how climate change could affect economic growth, via four categories of economic variables: household welfare (mainly related to non-market impacts), production (mainly related to productive or market activities), capital stock (which might affect economic growth prospects) and labour productivity (also affecting growth as it would affect real wages and, therefore, savings due to the impact on consumption). How those economic variables are affected by climate change can be analysed in a consistent way within a general equilibrium setup. For instance, following Ciscar et al. (2011), Table 2 represents how impacts on key sectors would affect the noted variables.

This information could be combined with the kind of sectoral effects induced by the different tipping points. That would be a major exercise beyond the scope of this article, but e.g., using qualitative information from existing studies (Arnell et al. 2005; Lenton et al. 2009), one could derive a first tentative mapping between tipping points and affected sectors for Europe.

There remains a clear methodological difficulty in translating the biophysical impacts associated with climate catastrophes into economic impacts, because the transmission mechanisms between the biophysical and economic systems are relatively poorly understood. Expert elicitation could help in this, but large-scale modelling is the preferred option.

5 Conclusions

The economic analysis of climate impacts, including estimates of the social cost of carbon (SCC), is usually made with simplified Integrated Assessment Models (IAMs). However, these appear to have some fundamental flaws in their representation of climate catastrophes. In particular, whilst current IAMs consider at most one climate tipping point and assume it is associated with very high global warming, recent scientific assessments have identified multiple potential tipping points, which could be passed under mid-range or even low global warming. This discrepancy could qualitatively alter the predictions of IAMs, leading one to question the robustness of their current advice to policy. To improve assessment of the economic impact of crossing different climate tipping points, we have highlighted a list of scientific points that should be considered, at least in a stylised form, in simplified IAMs. For nine different tipping events, the range of expected physical climate impacts has been summarised, and some suggestions made for how to translate these into socio-economic impacts on particular sectors or regions. A series of modifications to the specification of the catastrophic damage function have been proposed, elaborating it to look at specific tipping points. We also suggest that a general equilibrium economic framework could be used to analyse the effects of tipping points on human welfare, economic production and the two main drivers of economic growth (capital accumulation and labour).

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