Appendix 1: Formal Definition of a Tipping Element and Its Tipping Point

We consider sub-systems (Σ) of the Earth system that are associated with a specific region (or collection of regions) of the globe and are at least sub-continental in scale (length scale of order $\sim$1000km). We ask whether such sub-systems contain a tipping point, i.e., whether a small change in the control parameters can have large consequences for some system variable(s)? Previously, if a formal definition of tipping phenomena where 'little things make a big difference was attempted', it usually referred to equilibrium properties such as, e.g., the existence of bifurcation points [1, Box 1.1 thereof]. However, only in case of a slow forcing of the system (compared to its response time) have such definitions in terms of equilibrium properties something to say about whether at a particular moment in time a small change of controls will lead to a large change of the system in the future. In the general case of arbitrary forcing, the system response will depend on the trajectory of the control after the small change is applied. Furthermore, important systems may be controlled by the rate of a forcing in addition to the forcing itself. If tipping points in real systems depend on such forcing rates, it will generally be impossible to define them in terms of equilibrium properties. To account for all this complexity arising from the (forcing) path dependency of tipping dynamics, we ask whether maintaining a small change in control for at least some time T_{R} (to be defined) will inevitably lead to a large change of the system, i.e., independently of what might happen to the controls thereafter.

We say that a sub-system Σ is a tipping element, if the parameters controlling the system can be combined into a single control ρ, with a critical value ρ_{crit} such that a crucial system feature $F = \mathrm{Proj}(\Sigma)$ (i.e. obtained by projecting the generally high-dimensional state description Σ) qualitatively depends on whether 'ρ has exceeded ρ_{crit} by a small amount $\delta\rho$ for at least time T_{R}'. This can be formalised as follows (neglecting stochasticity in the control ρ, in which case all equations would have to be rewritten in terms of probability statements).

Σ is a tipping element if and only if there exists:

1. A time interval of interest $H_t = [t_{\mathrm{crit}}, t_0 + T_{\mathrm{E}}]$, where t_{crit} denotes a critical time at which a critical value of the control ρ is reached, t_0

signifies the present point in time ('today'), and $T_{\rm E}$ the time horizon under consideration. Note that for H_t to exist, $t_{\rm crit} - t_0 < T_{\rm E}$ is required. The future system development of interest will depend on its present state $\Sigma_0 = \Sigma(t_0)$ and the control path $\rho(\cdot)$ over $T_{\rm E}$. Here it is important to note that Σ_0 comprises at least all system properties necessary to predict a system feature $F(t)$ from the path $\rho[t_0, t]$, i.e. $F(t|\rho[t_0, t], \Sigma_0) := \mathrm{Proj}(\Sigma(\rho[t_0, t], \Sigma_0)$. In 1D systems, Σ_0 is simply $F(t_0)$.

2. A critical value $\rho_{\rm crit}$ reached with some control path $\rho^*[t_0, t_{\rm crit}]$, and an associated (sub)critical system state $\Sigma_{\rm crit} = \Sigma(\rho^*[t_0, t_{\rm crit} - \varepsilon], \Sigma_0)$ obtained just below $\rho_{\rm crit}$ with (sub)critical feature $F_{\rm crit} = \mathrm{Proj}(\Sigma_{\rm crit})$.

3. An 'exceedance time' $T_{\rm R} < t_0 + T_{\rm E} - t_{\rm crit}$.

4. A small variation in the control $\delta\rho > 0$.

5. A reference control path $\rho_{\rm ref}[t_0, t_0 + T_{\rm E}]$ with $\rho_{\rm ref}(t) < \rho_{\rm crit}$ for all $t_0 \le t \le t_0 + T_{\rm E}$, which comes close to the critical value for at least time $T_{\rm R}$, i.e., for all $t_{\rm crit} \le t \le t_{\rm crit} + T_{\rm R}$ it is $|\rho_{\rm ref}(t) - \rho_{\rm crit}| < \delta\rho/2$, and an associated reference system state at the critical time, $\Sigma_{\rm ref} = \Sigma(\rho_{\rm ref}[t_0, t_{\rm crit}], \Sigma_0)$ with reference feature $F_{\rm ref} = \mathrm{Proj}(\Sigma_{\rm ref})$.

6. A qualitative change of a system feature $\hat{F} > 0$ that is significantly larger than the standard deviation of natural variability of F on some time scale $T_{\rm V} \ll T_{\rm E}$ of interest.

Such that:

I. Every control path in the $\delta\rho/2$-neighbourhood of $\rho_{\rm ref}[t_0, t_0 + T_{\rm E}]$ and not exceeding $\rho_{\rm crit}$ will lead to only small changes of F (averaged over $T_{\rm V}$) compared to $\hat{F}$, i.e.,

$$\forall_{t \in [t_0, t_0+T_{\rm E}]} \; |\rho(t) - \rho_{\rm ref}(t)| < \delta\rho/2 \text{ and } \rho(t) < \rho_{\rm crit} \quad \Rightarrow$$

$$\forall_{t \in [t_{\rm crit}, t_0+T_{\rm E}]} \; |\langle F\rangle(t|\rho[t_{\rm crit}, t], \Sigma_\rho(t_{\rm crit})) - \langle F\rangle(t|\rho_{\rm ref}[t_{\rm crit}, t], \Sigma_{\rm ref})| \ll \hat{F} \,,$$

where $\langle F\rangle$ denotes the $T_{\rm V}$-moving average of F.

II. Any control path $\rho(\cdot)$ that exceeds the critical value $\rho_{\rm crit}$ by a small amount $\delta\rho > 0$ for at least time $T_{\rm R}$ will lead to the observation of a qualitative change in the system equal or larger than $\hat{F}$ (within the time horizon of interest) relative to its development under the reference path $\rho_{\text{ref}}(t)$, i.e.,

$$\forall_{t\in[t_{\text{crit}},t_{\text{crit}}+T_{\text{R}}]}\ \rho(t) \geq \rho_{\text{crit}} + \delta\rho \quad \Rightarrow$$

$$\exists_{T\in[t_{\text{crit}},t_0+T_{\text{E}}]}\ |\langle F\rangle(T|\rho[t_{\text{crit}},T],\Sigma_\rho(t_{\text{crit}}))-\langle F\rangle(T|\rho_{\text{ref}}[t_{\text{crit}},T],\Sigma_{\text{ref}})| \geq \hat{F}\ ,$$

where again $\langle F\rangle$ denotes the T_{V}-moving average of F.

Requirement II constitutes the central part of our definition of a tipping element and its associated tipping point at the critical value ρ_{crit}. We note that if the 'exceedance time' T_{R}, and the time horizon of interest T_{E}, are long enough to allow the system (now assumed to be autonomous) to equilibrate within T_{R}, we recover the definition of a tipping point in terms of the equilibrium property $F_{\text{eq}}(\rho)$ of system feature F (which obviously is independent of time and initial system state). In this case, the definition simply reads:

A sub-system Σ is a tipping element if there exists a control parameter ρ with a critical value ρ_{crit}, at which a small parameter variation ($\delta\rho > 0$) leads to a qualitative change in a system feature ($\hat{F}$), i.e., $|F_{eq}(\rho_{crit}+\delta\rho) - F_{eq}(\rho_{crit})| \geq \hat{F}$.[1]

In our application to anthropogenic global change, we are interested in a policy-relevant formulation of the definition of tipping element and its associated tipping point. Therefore, we add to requirements I and II above that:

III. Decision makers are particularly interested in the consequences of decisions taken within a political time horizon of $T_P \sim$100 years, compared to longer time spans. Therefore, we focus on the subset of tipping

[1] This can be derived from requirements I and II as follows:

$$|F_{\text{eq}}(\rho_{\text{crit}}+\delta\rho) - F_{\text{eq}}(\rho_{\text{crit}})| \geq |F_{\text{eq}}(\rho_{\text{crit}}+\delta\rho) - F_{\text{eq}}(\rho_{\text{ref}})| - |F_{\text{eq}}(\rho_{\text{crit}}) - F_{\text{eq}}(\rho_{\text{ref}})| \sim |F_{\text{eq}}(\rho_{\text{crit}}+\delta\rho) - F_{\text{eq}}(\rho_{\text{ref}})| \geq \hat{F}\ ;$$

furthermore $F_{\text{eq}}(\rho_{\text{crit}})$ may either be interpreted as obtained in the limit $\rho \to \rho_{\text{crit}}$ from below, or obtained at a near-critical forcing slightly below ρ_{crit} where F is well-defined. Hence, the distance of $F_{\text{eq}}(\rho_{\text{crit}})$ to the reference feature needs to fulfil requirement I.

elements for which the development of $\rho(\cdot)$ within the political time horizon (and driven by human interference) decides on whether a critical state is reached at some point within T_{E}. This may either be the case if the critical state is reached already within the political horizon, or if it would be reached at a later point in time in the absence of policies enacted during the political horizon to prevent the system from reaching its critical state.

IV. A qualitative change $\hat{F}$ of a system feature is large enough so that it could significantly affect human welfare on at least a sub-continental scale, or could compromise the overall mode of operation of the Earth system, or would entail the loss of a unique value of the biosphere.

We now compare our general definition of tipping element (requirements I-IV) with the definition we have given in the main paper (conditions 1-4). Obviously, requirements III and IV are equivalent to conditions (2) and (4), respectively. Condition (3) is already included in the specification of a time interval of interest H_t above, if we identify T_{E} as the 'ethical time horizon'. Condition (1) basically represents II in compact notation.[2]

For applying our definition of a tipping element to the response of Earth system components to anthropogenic interference, it remains to fix the time scales T_{V}, T_{E}, and the values of a small exceedance $\delta\rho$ and a large change in system feature $\hat{F}$. A reasonable choice for the time scale to filter variability in the system feature F is $T_{\mathrm{V}} \sim 10$ years, assuming that higher-frequency variations of F are not relevant for the assessment whether or not a qualitative change $\hat{F}$ has occurred. Our choice of values for the other quantities is motivated in the main paper, and is only repeated here for completeness. $\delta\rho$ should be on the order of natural variability in the control parameter, and for the particular case of annual global mean temperature $\delta\rho \sim 0.2$°C seems reasonable. $\hat{F}$ should be determined by considering associated impacts that fulfil requirement IV. For the ethical time horizon, we suggest $T_{\mathrm{E}} \sim 1000$ years beyond which changes in the Earth system may not matter for current policy considerations.

Humankind can influence the future development of the control path $\rho(\cdot)$

[2] In precise analogy to the argument outlined in the previous footnote we can replace the reference path by ρ_{crit} as it was assumed under requirement I that small deviations from the reference path would only induce small changes in the system feature.

by policies to mitigate climate change. As far as global mean temperature (GMT) increase is concerned, stringent emissions reduction measures are likely to affect the GMT trajectory on a time scale of approximately 30-60 years given the inertia in the energy and climate system. Geo-engineering options such as injecting reflective aerosols into the stratosphere [2] can affect GMT on a somewhat shorter time scale (potentially two decades including preparation and deployment of the technology) and thus increase the leverage of humankind on the control path $\rho(\cdot)$. However, there may be serious side-effects to any type of geo-engineering option, and it remains doubtful whether we can indeed notice the approach of a tipping point in a timely manner to deploy such methods effectively as a 'last resort'. Therefore, we suggest that anticipatory emissions reduction measures are the most viable option to avoid crossing a tipping point.

Appendix 2: Evaluation of Other Potential Policy-Relevant Tipping Elements

Here we evaluate some suggested policy relevant tipping elements that are included in Table 1 of the main paper but not discussed there because they did not convincingly meet all the conditions (1)-(4) given in the main paper. If conditions (2)-(4) are met the potential tipping element is included in Figure 1 of the main paper, where a question mark denotes systems for which the existence of a critical threshold (condition (1)) is particularly uncertain. We also discuss here some candidate tipping elements not in Figure 1 because any threshold appears inaccessible this century (condition (2)) or a qualitative change would appear beyond this millennium (condition (3)). In some cases, the link to climate is also unclear or indirect.

Antarctic Bottom Water (AABW): AABW formation and corresponding outflow into the deep ocean shuts off under a business-as-usual tripling of CO_2 in one AOGCM [3]. An increase in precipitation minus evaporation over the Southern Ocean and decreased export of sea-ice cause freshening of surface waters such that they become less dense than deep water and this prevents deep convection. The resulting state is only transiently stable under sustained forcing, because the deep ocean gradually warms up and becomes less dense, eventually allowing convection to resume. More model studies are required to establish whether AABW collapse is a robust feature, and if so, assess the threshold.

Tundra: At its northern boundary, encroachment of the boreal forest into the tundra, which occurs when regions exceed ∼1000 growing degree days (GDD) above zero, initiates a positive feedback whereby the trees obscure snow thus amplifying warming, as happened in the early Holocene [4]. Already, lengthening of the snow-free season has contributed significantly to recent Arctic summer warming trends and is encouraging shrub growth in the tundra [5] and greening of the boreal forest [6]. However, models [7, 8, 9] suggest the transition from tundra to boreal forest will be a continuous process without strong nonlinearity or threshold behaviour. Hence it is not a tipping element.

Permafrost: Recent permafrost melt in Siberia has been described in the popular media as a tipping point because it is accompanied by increased fluxes of methane and carbon dioxide that contribute to the greenhouse effect. However, existing future projections of permafrost melt, although substantial, are quasi-linear and do not exhibit threshold behaviour [10, 11]. These projections ignore the positive feedback from methane emissions, but it is estimated to be weak [12] at the global scale and hence cannot promote a strongly non-linear regional response. The inclusion of an estimated ∼400 PgC of methane stored in frozen hydrate reservoirs under the boreal permafrost could strengthen the feedback somewhat. However, no studies to date convincingly demonstrate that it is a tipping element by our definition.

Marine methane hydrates: A much larger methane hydrate reservoir estimated at up to ∼10,000 PgC resides under marine continental shelf and slope sediment. 1500-4500 PgC of methane (comparable with known conventional fossil fuel reserves of ∼4000-5000 PgC) are thought to have been degassed from methane hydrates at the Paleocene-Eocene Thermal Maximum (PETM) 55.5 Ma. This has led to concern that anthropogenic forcing might trigger a massive, catastrophic release of methane. The timescale of the forcing in this case is at least ∼1000 years because it takes that long for the thermal perturbation to propagate into the sediment column to the depth of the hydrate deposits [13]. Existing models [13, 14] encapsulate local scale tipping points for methane release and under anthropogenic forcing there is a progressive release on $10^3 - 10^5$ year timescales of 1-2 times the amount of fossil fuel carbon emitted [13]. Although the anthropogenic greenhouse forcing may be stabilised, once methane release events start, each adds to the warming promoting further release events. Eventually, the reservoir of methane hydrates is essentially drained – a qualitative change. If no evidence is found for a large perturbation as the trigger of the PETM event, this would support the interpretation that marine methane hydrates are a tipping element. However, it is unlikely a qualitative change can occur within this millennium ($t_{\text{crit}} + T > T_{\text{E}}$).

Ocean anoxia: The existence of past mass extinction events in the marine fossil record is suggestive of tipping point dynamics unless a massive external perturbation can be invoked for all of them. Such a kill agent may not be necessary given that some models of ecological networks exhibit self-organised criticality and undergo internally-generated extinction events of all sizes. Different past mass extinctions in marine ecosystems have been linked to warming, ocean acidification, and ocean anoxia. Of these, ocean anoxia is the most likely tipping element, with models [15, 16] that include positive feedback between anoxia, phosphorus recycling from sediments and marine productivity, exhibiting critical thresholds. In one model [16], a sustained increase in phosphorus input to the ocean triggers a Hopf bifurcation that starts self-sustaining oscillations between an oxic and an anoxic ocean. Phosphorus input to the ocean has been greatly increased by human agricultural fertilizer application, and global warming is also expected to accelerate weathering processes which release phosphorus. If maintained, this could trigger widespread anoxia, which would first appear in coastal and shelf-seas. However, for the global deep ocean to switch to an anoxic state requires strong recycling of phosphorus from sediments under anoxic conditions and will take $\sim 10^4$ years due to the long response time of deep ocean phosphorus ($t_{\text{crit}} + T > T_{\text{E}}$). Despite this, it should be assessed whether a qualitative change in coastal and shelf-seas could occur within the ethical time horizon.

Arctic ozone: The Antarctic ozone hole is a tipping element that has already been tipped by human activity. It is widely believed that the stratospheric ozone layer has been saved by the Montreal protocol. However, Europe in particular could face a climate change-induced ozone hole [17, 18]. Global warming implies global cooling of the stratosphere that supports formation of ice clouds, which in turn provide a catalyst for stratospheric ozone destruction. Furthermore, there exists a strong coupling between the troposphere and the stratosphere in the Northern Annular Mode (NAM) and strong synergistic interactions between stratospheric ozone depletion and greenhouse warming are possible [19]. However, more studies are required to assess whether this is a potential tipping element.

Appendix 3: Expert Elicitation: Method and Results

A computer-based interactive questionnaire was designed to elicit expert beliefs on seven events of passing a potential tipping point. Six events are related to the tipping elements discussed in the present paper, and we focus the discussion on these. An overview of the elicitation and the results from the other parts of the questionnaire will be presented in a separate article (Kriegler E, Hall JW, Held H, Dawson R, Schellnhuber HJ, unpublished work). We focus our exposition here on the methodology for obtaining the results presented in the main text. The exact definitions that were used in the questionnaire are as follows:

Reorganisation of the Atlantic meridional overturning circulation (THC): A reorganisation of the Atlantic meridional overturning circulation that involves a permanent shutdown of convection in the Labrador Sea AND a drastic reduction in deep water overflow across the Greenland-Scotland ridge by at least 80%.

Melt of the Greenland ice sheet (GIS): An alternative state that is largely ice-free. Such conditions may have existed during a previous interglacial period, or may not have existed since before the original formation of the ice sheet. Deglaciation would proceed by warming at the perhiphery followed by lowering of the ice altitude, causing a positive feedback. Dynamical responses may occur that reduces deglaciation timescale. For sufficient warming, the increase in ice melting and discharge would exceed the increase in accumulation over the ice sheet, causing an eventual transition to a nearly ice-free state.

Disintegration of the West Antarctic ice sheet (WAIS): An alternative state, in which West Antarctica becomes an archipelago when discharge exceeds accumulation for warmer temperatures. This could occur at relatively large warming due to melting and ice altitude-temperature feedback. Alternatively, for moderate warming, formation of pond water or basal melting of ice shelves due to contact with warm ocean waters could lead to ice shelf collapse. Then ice streams may accelerate, also leading to deglaciation.

Dieback of the Amazon rainforest (Amaz): A dieback of the Amazon rainforest, in which at least half of its current area is converted to raingreen forest, savannah or grassland. Besides climate change, a second driver for a potential dieback of the Amazon rainforest is land use change from human activity. Here, we ask you to factor out this driver by assuming that the current rate of deforestation (up to 1 percent of rainforest area per year) will be kept in check so that not more than 20 percent of the current rainforest will be deforested by human activity in the long run. This implies that at least 30 percent of rainforest needs to be lost through climate change related factors, if the overall reduction of the Amazon rainforest shall be qualified as dieback in the sense above.

Dieback of boreal forests (BoFo): A dieback of boreal forests, in which their global area, including potential additions from northward migration in a warming climate, is at least cut in half due to widespread conversion of boreal forests to open woodlands or grasslands.

Shift to a persistent El Niño regime (ENSO): A shift in the ENSO mean state towards El-Niño like conditions. (This definition was changed from its original text in the final phase of the elicitation during which participants were allowed to revise their statements.)

The questionnaire was tested and refined at the Tipping Point Workshop at the British Embassy, Berlin (5-6 October 2005) and subsequently distributed electronically to 193 international scientists. Among them were 22 workshop participants with expertise on the tipping elements addressed in the questionnaire. 52 scientists, among them 16 workshop participants, returned a completed questionnaires during November 2005 - February 2006. Table 1 provides a breakdown of the participants according to country of affiliation and field of research. It can be seen that we attracted a hetero-

Table 1: Composition of the group of participating experts

Country of affiliation	No. of experts	Research field	No. of experts
Australia	1	Glaciology	10
Belgium	2	Ice sheet modelling	3
Canada	1	Ecology	4
France	1	Ecosystem modelling	7
Germany	13	Marine biosphere modelling	4
Japan	1	Oceanography	9
Netherlands	1	Climate Modelling	15
UK	16		
USA	16		

geneous group of experts coming from various world regions and covering a wide range of expertise. The response of the 52 experts was compiled and fed back to participants. At this stage, they were given the opportunity to revise their statements if they wished to. The elicitation process concluded in April 2006.

The questionnaire contained four parts. In the first part, participants were asked to select those tipping events they wished to comment upon and to provide a self-assessment of their expertise on the corresponding tipping elements. Participants were encouraged to remain in their area of expertise. In the second part, experts who selected more than one tipping event were asked to compare them pair-wise in terms of their sensitivity to global mean warming and uncertainty about the physical mechanisms underlying their response to a changing climate. Participating experts were presented with two questions for each pair of tipping points A, B they selected to comment upon. The following are quotes from the questionnaire. Note that the term "triggering (the crossing of) a tipping point" was used to imply that the events do not have to have occurred at a given point, but rather must have become unavoidable there (see our discussion in Supporting Information 1).

1. *Please compare the tipping points pairwise in terms of their sensitivity to future global mean warming, i.e. how great does an increase in global mean temperature need to be to trigger the tipping points. ... Your options for comparing two tipping points A and B:*

   - *$A > B$: A more sensitive to global mean warming than B,*

- *$A < B$: A less sensitive to global mean warming than B,*
- *$A = B$: A and B similarly sensitive to global mean warming, or,*
- ***U:** I am unable/unwilling to rank the sensitivity of A and B in terms of magnitude.*

2. *Please compare the tipping points pairwise in terms of the uncertainty that exists around the underlying physical mechanisms. ... Your options for comparing two tipping points A and B:*

    - *$A > B$: A more uncertain than B,*
    - *$A < B$: A less uncertain than B,*
    - *$A = B$: A and B are similarly uncertain, or,*
    - ***U:** I am unable/unwilling to rank the uncertainty from A and B in terms of magnitude.*

Since participants could only be asked to compare tipping events if they selected more than one, only a fraction of experts provided responses in Part 2 of the questionnaire. For the six tipping events under consideration, we nevertheless could obtain 38 (on sensitivity) and 42 (on uncertainty) pairwise comparisons from 25 experts. In each of the two cases, 10 out of 15 possible combinations of tipping events were covered by at least one expert. Table 2 breaks down the ranking relations that experts provided for the sensitivity of tipping events to global mean warming. Table 3 provides the analogous information for the uncertainty about tipping points. We used the collection of expert responses to identify a partial ranking of tipping elements given in the main paper.

Table 2: Ranking of sensitivity to global mean warming

	>	=	<
THC - GIS	–	–	7
THC - WAIS	–	1	2
THC - Amaz	–	–	2
THC - ENSO	2	–	3
GIS - WAIS	8	2	–
GIS - Amaz	1	–	–
GIS - ENSO	1	–	–
WAIS - Amaz	–	–	1
Amaz - BoFo	1	1	3
Amaz - ENSO	–	3	–

Table 3: Ranking of uncertainty in sensitivity to global mean warming

	>	=	<
THC - GIS	6	1	1
THC - WAIS	1	–	3
THC - Amaz	–	–	2
THC - ENSO	1	2	3
GIS - WAIS	2	1	6
GIS - Amaz	–	–	1
GIS - ENSO	–	–	2
WAIS - Amaz	1	–	–
Amaz - BoFo	–	1	5
Amaz - ENSO	2	1	–

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