Earth System Tipping Points

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Definitions

A **tipping point** is a critical threshold at which the future state of a system can be qualitatively altered by a small change in forcing[1]. A **tipping element** is a part of the Earth system (at least sub-continental in scale) that has a tipping point[1]. Policy-relevant tipping elements are those that could be forced past a tipping point this century by human activities. **Abrupt climate change** is the subset of tipping point change which occurs faster than its cause[2]. Tipping point change also includes transitions that are slower than their cause (in both cases the rate is determined by the system itself). In either case the change in state may be reversible or irreversible. **Reversible** means that when the forcing is returned below the tipping point the system recovers its original state (either abruptly or gradually). **Irreversible** means that it does not (it takes a larger change in forcing to recover). Reversibility in principle does not mean that changes will be reversible in practice.

Tipping elements in the Earth's climate system

Previous work[1] identified a shortlist of nine potential policy-relevant tipping elements in the climate system that could pass a tipping point this century and undergo a transition this millennium under projected climate change. These are shown with some other candidates in Figure 1.

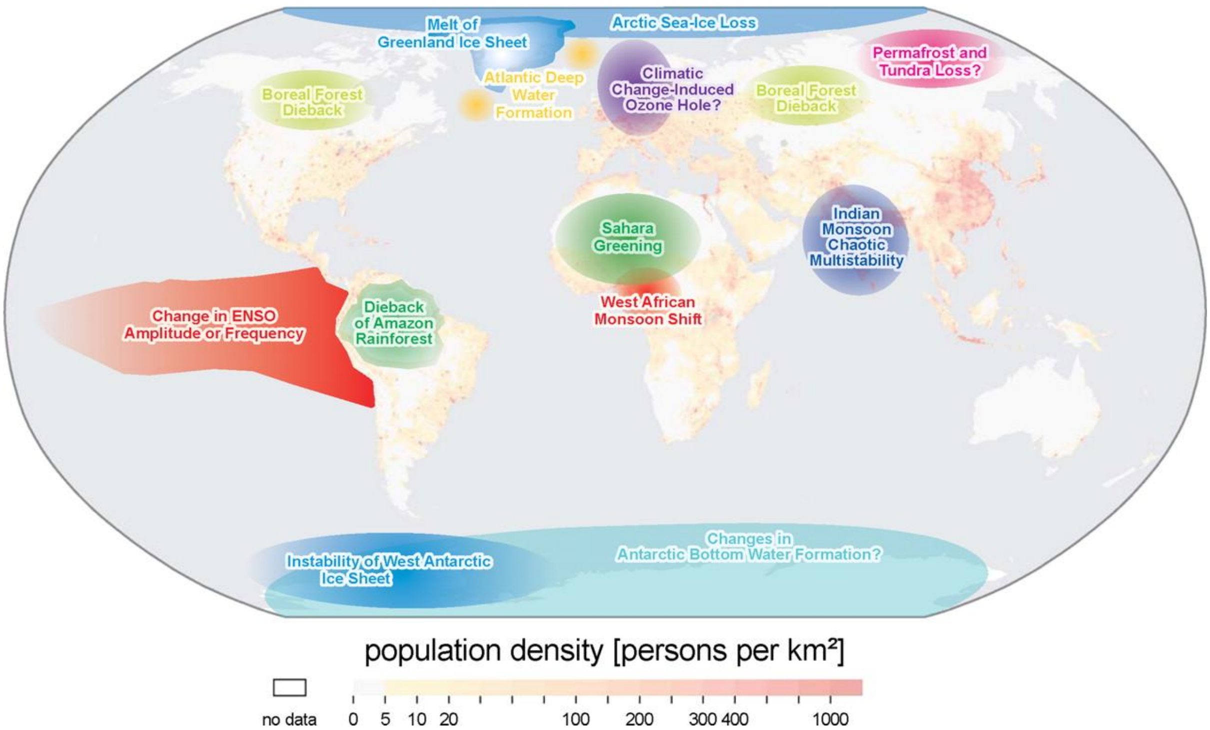

Figure 1: Map of potential policy-relevant tipping elements in the Earth's climate system overlain on population density. Question marks indicate systems whose status as tipping elements is particularly uncertain.

We should be most concerned about those tipping points that are nearest (least avoidable) and those that have the largest negative impacts. Generally, the more rapid and less reversible a transition is, the greater its impacts. Additionally, any positive feedback to global climate change may increase concern, as can interactions whereby tipping one element encourages tipping another. The proximity of some tipping points has been assessed through expert elicitation[1,3]. Proximity, rate and reversibility have been also assessed through literature review[1], but there is a need for more detailed consideration of impacts[4]. The following are some of the most concerning tipping elements:

The **Greenland ice sheet** (GIS) may be nearing a tipping point where it is committed to shrink[1,3]. Striking amplification of seasonal melt was observed in summer 2007 associated with record Arctic sea-ice loss[5]. Once underway the transition to a smaller ice cap will have low reversibility, although it is likely to take several centuries (and is therefore not abrupt). The impacts via sea level rise will ultimately be large and global, but will depend on the rate of ice sheet shrinkage. Latest work suggests there may be several stable states for ice volume, with the first transition involving retreat of the ice sheet onto land and around 1.5 m of sea level rise[6].

The **West Antarctic ice sheet** (WAIS) is currently assessed to be further from a tipping point than the GIS, but this is more uncertain[1,3]. Recent work has shown that multiple stable states can exist for the grounding line of the WAIS, and that it has collapsed repeatedly in the past. It has the potential for more rapid change and hence greater impacts than the GIS.

The **Amazon rainforest** experienced widespread drought in 2005 turning the region from a sink to a source (0.6-0.8 PgC yr^{-1}) of carbon[7]. If anthropogenic-forced[8] lengthening of the dry season continues, and droughts increase in frequency or severity[9], the rainforest could reach a tipping point resulting in dieback of up to ~80% of the rainforest[10-13], and its replacement by savannah. This could take a few decades, would have low reversibility, large regional impacts, and knock-on effects far away. Widespread dieback is expected in a >4 °C warmer world[3], and it could be committed to at a lower global temperature, long before it begins to be observed[14].

The **Sahel and West African Monsoon** (WAM) have experienced rapid but reversible changes in the past, including devastating drought from the late 1960s through the 1980s. Forecast future weakening of the Atlantic thermohaline circulation contributing to 'Atlantic Niño' conditions, including strong warming in the Gulf of Guinea[15], could disrupt the seasonal onset of the WAM[16] and its later 'jump' northwards[17] into the Sahel. Whilst this might be expected to dry the Sahel, current global models give conflicting results. In one, if the WAM circulation collapses, this leads to wetting of parts of the Sahel as moist air is drawn in from the Atlantic to the West[15,18], greening the region in what would be a rare example of a positive tipping point.

The **Indian Summer Monsoon** (ISM) is probably already being disrupted[19,20] by an atmospheric brown cloud (ABC) haze that sits over the sub-continent and, to a lesser degree, the Indian Ocean. The ABC haze is comprised of a mixture of soot, which absorbs sunlight, and some reflecting sulfate. It causes heating of the atmosphere rather than the land surface, weakening the seasonal establishment of a land-ocean temperature gradient which is critical in triggering monsoon onset[19]. Conversely, greenhouse gas forcing is acting to strengthen the monsoon as it warms the northern land masses faster than the ocean to the south. In some future projections, ABC forcing could double the drought frequency within a decade[19] with large impacts, although it should be highly reversible.

Estimation of likelihood under different scenarios

If we pass climate tipping points due to human activities (which in IPCC language are called "large scale discontinuities"[21]), then this would qualify as dangerous anthropogenic interference (DAI) in the climate system. Relating actual regional tipping points to e.g. global mean temperature change is always indirect, often difficult and sometimes not meaningful. Recent efforts suggest that 1 °C global warming (above 1980-1999) could be dangerous as there are "moderately significant"[21] risks of large scale discontinuities, and Arctic sea-ice and possibly the Greenland ice sheet would be threatened[1,22]. 3 °C is clearly dangerous as risks of large scale discontinuities are "substantial or severe"[21], and several tipping elements could be threatened[1]. Under a 2-4 °C committed warming, expert elicitation[3] gives a >16% probability of crossing at least 1 of 5 tipping points, which rises to >56% for a >4 °C committed warming. Considering a longer list of 9 potential tipping elements, Figure 2 summarizes recent information on the likelihood of tipping them under the IPCC range of projected global warming this century.

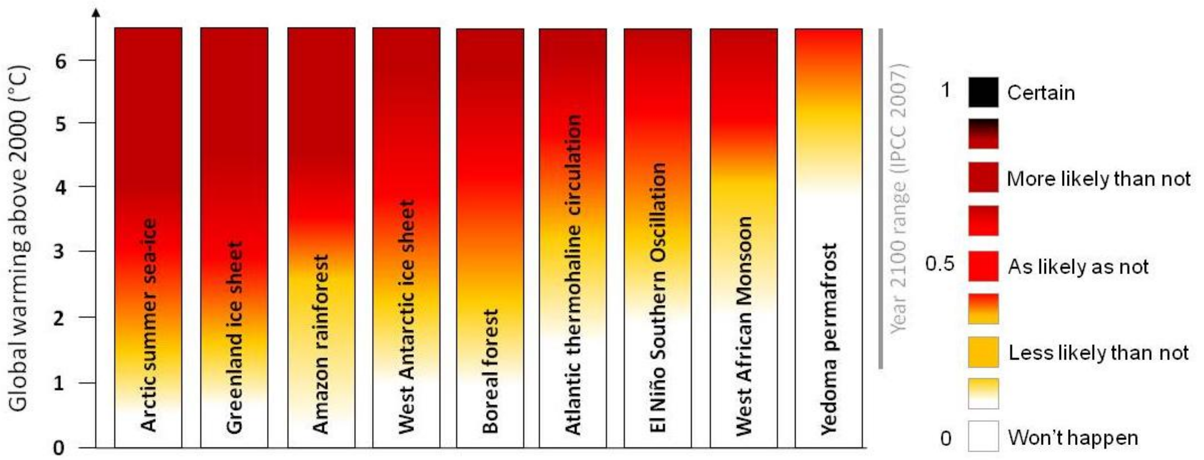

Figure 2: Burning embers diagram for the likelihood of tipping different elements under different degrees of global warming[23] – updated, based on expert elicitation results[3] and recent literature.

Early warning prospects

An alternative approach to assessing the likelihood of tipping different elements is to try and directly extract some information on their present stability (or otherwise). Recent progress has been made in identifying and testing generic potential early warning indicators of an approaching tipping point[1,24-27]. Slowing down in response to perturbation is a nearly universal property of systems approaching various types of tipping point[25,27]. This has been successfully detected in past climate records approaching different transitions[24,25], and in model experiments[24-26]. Other early warning indicators that have been explored for ecological tipping points[28], include increasing variance[28], skewed responses[28,29] and their spatial equivalents[30]. These are beginning to be applied to anticipating climate tipping points. For climate sub-systems subject to a high degree of short timescale variability ('noise'), flickering between states may occur prior to a more permanent transition[31]. For such cases, we have recently developed a method of deducing the number of states (or 'modes') being sampled by a system, their relative stability (or otherwise), and changes in these properties over time[32].

Applying these methods to observational and reconstructed climate indices leading up to the present, we find that the Atlantic Multi-decadal Oscillation (AMO) index, which is believed to reflect fluctuations in the underlying strength of the thermohaline circulation, is showing signs of slowing down (i.e. decreasing stability) and of the appearance of a second state (or mode of behavior). On interrogating the underlying sea surface temperature data (used to construct the index), we find that recent significant changes are localized in the northernmost North Atlantic, and are investigating the possible relationship with changes in Arctic sea-ice cover. Meanwhile, some other climate indices, e.g. the Pacific Decadal Oscillation (PDO) show signs of increasing stability.

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