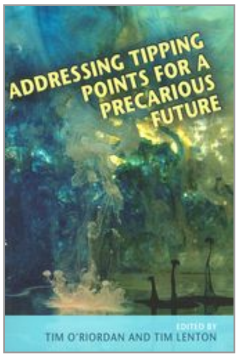

Addressing Tipping Points for a Precarious Future

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Tipping Elements from a Global Perspective

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[−] Abstract and Keywords

Several tipping points in the Earth system could be crossed this century, due to our collective impact on the planet interacting with its natural patterns of variability. This chapter summarizes existing information on the likelihood and impacts of tipping different elements of the Earth system, and uses that information to produce a tentative assessment of the relative risks that they pose. It then considers the prospects for early warning of approaching tipping points, as a means of helping manage the risks. The chapter is structured around a series of simple questions about Earth system tipping points: What are they? Where are they? How close are they? Which carry the greatest impacts? What is the worst-case scenario? What early warning signs should we be looking for? When can we get reliable predictions? How should we respond?

Keywords: tipping points, tipping elements, abrupt climate change, risk assessment, early warning

The aim of this chapter is to provide an overview of potential tipping points in the Earth system, which we may cross this century, due to our collective impact on the planet interacting with its natural patterns of variability. I take a risk-assessment approach, summarizing existing information on the likelihood and impacts of tipping different elements of the Earth system, and using that information to produce a tentative assessment of the relative risks that they pose. Then I consider the prospects for early warning of approaching tipping points, as a means of helping manage the risks. The chapter is structured around a series of simple questions about Earth system tipping points: What are they? Where are they? How close are they? Which carry the greatest impacts? What is the worst case scenario? What early warning signs should we be looking for? When can we get reliable predictions? How should we respond?

At the start let me pin my colours to the mast, and defend my use of the term 'tipping point'. Distaste regarding it seems to stem from two main concerns. One is the over-liberal or uncritical application of such physical science concepts to social systems, containing actors with an element of both free will and reflection, who continually shape and reshape the systems of which they are a part. I can sidestep this, because my primary focus here is on our planet and its physical sub-systems, and I have no qualms about applying physical theories there. The definition I propose below is intended for physical systems, and I do not claim that it can be applied to social ones.

The second concern is psychological; talking about damaging tipping points is perceived as alarmist and likely to breed hedonism, despair or other maladaptive responses in the population. This line of argument I find morally challenging, because as a scientist I am trained to 'tell it like it is', **(p.24)** as clearly as I can. The argument that the evidence and modelling I will discuss carry distasteful messages, and therefore their presentation should be adjusted, is not one I can accept. (That said, I realize we live in an era of 'post-normal' science, in which the objective and the subjective are always entwined (Stirling 2003).)

What and where are tipping points?

Little things can (sometimes) make a big difference, as Malcolm Gladwell's book that popularized societal tipping points argues (Gladwell 2000). Mathematicians, with their concept of a bifurcation point, have known this for centuries, as have physicists fascinated by phase changes of matter. More recently ecologists have borrowed from bifurcation theory to describe 'regime shifts' in ecosystems. Gladwell takes his cues from epidemiology, and the theory of infection spread, which has different underlying mathematics. Dynamical systems theory encompasses these and other classes of physical phenomena, which all share a common feature: a small change within, or from outside, a system can cause a large change in its future state. It seems natural to me to use the term 'tipping point' to describe this group of phenomena, and to communicate about them to non-scientists.

Thus, 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 (Lenton *et al*. 2008). Tipping points can conceivably occur in any spatial scale of system which has strong non-linearity in its internal dynamics. Here I focus on large-scale tipping points in the physical, chemical, and biological make-up of our planet. A *tipping element* is a part of the Earth system (at least sub-continental in scale) that has a tipping point (Lenton *et al*. 2008). Policy-relevant tipping elements are those that could be forced past a tipping point this century by human activities. In the language of the Intergovernmental Panel on Climate Change (IPCC), they are called 'large-scale discontinuities' (Smith *et al*. 2009), and are one type of dangerous anthropogenic interference in the climate system. *Abrupt climate change* is a subset of tipping point change which occurs faster than its cause (Rahmstorf 2001). 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 **(p.25)** 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.

Previous work (Lenton *et al*. 2008) has 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 2.1, where the tipping elements are grouped into those that involve ice melting, those that involve changes in the circulation of the ocean or atmosphere, and those that involve the loss of major biomes.

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 amplification of global climate change may increase concern, as can interactions whereby tipping one element encourages tipping another, potentially leading to 'domino dynamics'. The leading candidates are now briefly summarized, with an emphasis on recent behaviour, and what the nature of the underlying mechanisms means for the reversibility and rapidity of any future transitions (for more details, see recent reviews (Lenton *et al*. 2008; Lenton 2012)). In later sections, the proximity of individual tipping points and their impacts are expanded upon.

Ice melting

The *Arctic sea-ice* underwent a new record summer loss of area in 2012, breaking the previous record set in 2007 and reaching around half of the area it had in the summers of the late 1970s, when the satellite record began. Projections are for the complete loss of ice in summer within decades. Whether this will involve an underlying bifurcation is debated (Abbot *et al*. 2011; Eisenman and Wettlaufer 2009) because ice re-grows in each dark polar winter, i.e. the loss is reversible in principle (Notz 2009). But already the changing ice cover is changing atmospheric circulation patterns (Overland and Wang 2010; Wu and Zhang 2010), with knock-on effects that extend to mid-latitudes, including contributing to cold winter extremes over Europe (Petoukhov and Semenov 2010).

The *Greenland ice sheet* (GIS) may be nearing a tipping point where it is committed to shrink (Kriegler *et al*. 2009; Lenton *et al*. 2008). Record seasonal melting occurred in summer 2012, probably associated with record **(p.26)**

(p.27) Arctic sea-ice loss, as it was in 2007 (Mote 2007). Extraordinary warmth around 12 July 2012 saw thawing across almost the entire ice sheet surface, which would have lowered the albedo (reflectivity), further amplifying the melt (Box *et al*. 2012). 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 (around 7 m) and global, but will depend on the rate of ice sheet shrinkage. There may be several stable states for ice volume, with the first transition involving retreat of the ice sheet on to land and around 1.5 m of sea-level rise (Ridley *et al*. 2010), up to 50 cm of which could occur this century (Pfeffer *et al*. 2008).

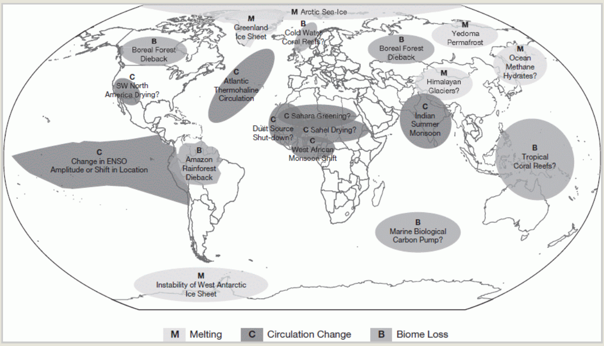

Figure 2.1 Map of potential policy-relevant tipping elements in the Earth's climate system.Questionmarks indicate systems whose status as tipping elements is particularly uncertain (Lenton 2012).

The *West Antarctic ice sheet* (WAIS) is currently assessed to be further from a tipping point than the GIS, but this is more uncertain (Kriegler *et al*. 2009; Lenton *et al*. 2008). Recent work (Schoof 2007) has shown that multiple stable states can exist for the grounding line of the WAIS, and that it has collapsed repeatedly in the past (Naish *et al*. 2009; Pollard and DeConto 2009). It has the potential for more rapid change and hence greater impacts than the GIS. Current models (Pollard and DeConto 2009) put the threshold for WAIS collapse when the surrounding ocean warms by around 5°C, and expert elicitation concurs that if global warming exceeds 4°C, it is more likely than not that the WAIS will collapse (Kriegler *et al*. 2009). The WAIS has the potential to cause sea-level rise of the order of 1 m per century and 3–4 m in total.

The *Yedoma permafrost* (perennially frozen soil), in north-eastern Siberia (150–168°E and 63–70°N), has an extremely high carbon content (2–5 per cent) and may contain up to 500 PgC (billion tonnes of carbon) (Zimov *et al*. 2006). It could tip into irreversible, self-sustaining collapse, due to an internally generated source of heat released by biochemical decomposition of the carbon, triggering further melting in a runaway positive feedback (Khvorostyanov *et al*. 2008a; Khvorostyanov *et al*. 2008b). This would produce emissions of 2–3 PgC yr^{-1} (equivalent to about a third of current fossil fuel burning). Tipping this system requires an estimated >9°C of regional warming (Khvorostyanov *et al*. 2008a), and may also be rate sensitive (Wieczorek *et al*. 2011). Although this seems far off, during the sea-ice retreat of 2007, Arctic land temperatures jumped (Lawrence *et al*. 2008) around 3°C.

Ocean methane hydrates may store up to 2000 PgC beneath the seafloor (Archer *et al*. 2009), and as the deep ocean warms, this reservoir of frozen methane could be destabilized, perhaps triggering submarine landslides **(p.28)** (Kayen and Lee 1991). However, an abrupt massive release of methane into the atmosphere is very unlikely (Archer 2007).

The *Himalayan glaciers* could lose much of their mass this century (Ramanathan and Feng 2008), and this will likely involve self-amplifying processes whereby dust accumulation and the exposure of bare ground lower the surface albedo and accelerate melt (Oerlemans *et al*. 2009; Pepin and Lundquist 2008). However, it is unclear whether there is a large-scale tipping point for this particular montane ice melt.

Biome loss

The *Amazon rainforest* experienced widespread droughts in 2005 and 2010, which turned the region from a sink to a source of carbon (0.6–0.8 PgC yr^{-1}) (Phillips *et al*. 2009). If anthropogenic-forced (Vecchi *et al*. 2006) lengthening of the dry season continues, and droughts increase in frequency or severity (Cox *et al*. 2008), the rainforest could reach a tipping point resulting in dieback of up to 80 per cent of trees (Cook and Vizy 2008; Cox *et al*. 2004; Salazar *et al*. 2007; Scholze *et al*. 2006), and its replacement by seasonal forest (Malhi *et al*. 2009) or 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 (Kriegler *et al*. 2009), and it could be committed to at a lower global temperature, long before it begins to be observed (Jones *et al*. 2009). Toby Gardner (4.3) considers the social and economic implications of these forecasts for the region.

The *boreal forest* in Western Canada is currently suffering from an invasion of mountain pine beetle that has caused widespread tree mortality (Kurz *et al*. 2008a) and has turned the nation's forests from a carbon sink to a carbon source (Kurz *et al*. 2008b). More widespread future dieback has been predicted at >3°C global warming (Kriegler *et al*. 2009; Lucht *et al*. 2006) (7°C regional warming), through a mixture of heat stress, increased vulnerability to disease, decreased reproduction rates and more frequent fires, all increasing mortality. The forest could be replaced by open woodlands or grasslands, in turn amplifying summer warming, drying and fire frequency.

Tropical *coral reefs* have recently experienced widespread and detrimental bleaching events as the ocean warms, and may be nearing a 'point of no return' (Veron *et al*. 2009). Ocean acidification (due to rising atmospheric CO_2) may also contribute to threshold-like changes (Riebesell *et al*. 2009) **(p.29)** particularly for cold-water corals that grow down to 3000 m depth. Up to 70 per cent of them could be in corrosive waters by the end of this century (Guinotte *et al*. 2006). However, it is unclear whether there is a large-scale tipping point in the offing.

Circulation change

The *Atlantic thermohaline circulation* (THC) could be shut down if sufficient freshwater enters the North Atlantic to halt density-driven deep water formation there (Hofmann and Rahmstorf 2009; Peng 1995; Stommel 1961). This probably needs >4°C warming this century (Kriegler *et al*. 2009), although existing models are systematically biased towards a stable THC (Drijfhout *et al*. 2011). Still, as the THC weakens (IPCC 2007) it may pass a nearer tipping point in which deep water stops forming in the Labrador Sea region (to the west of Greenland) and switches to only occurring in the Greenland-Iceland-Norwegian Seas (to the east of Greenland) (Born and Levermann 2010; Levermann and Born 2007). This would increase sea level down the north-eastern seaboard of the USA by around 25 cm (in addition to a rise in global mean sea level) (Yin *et al*. 2009).

The *Sahel and the West African Monsoon* (WAM) have experienced rapid but reversible changes in the past, including devastating drought from the late 1960s through to the 1980s. Forecast future weakening of the THC contributing to 'Atlantic Niño' conditions, including strong warming in the Gulf of Guinea (Cook and Vizy 2006), could disrupt the seasonal onset of the WAM (Chang *et al*. 2008) and its later 'jump' northwards (Hagos and Cook 2007) into the Sahel. Whilst this might be expected to dry the Sahel, 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 (Cook and Vizy 2006; Patricola and Cook 2008), greening the region in a rare example of a positive tipping point.

The *Indian Summer Monsoon* (ISM) is already being disrupted (Meehl *et al*. 2008; Ramanathan *et al*. 2005) and rice harvests impaired (Auffhammer *et al*. 2006) by an atmospheric brown cloud (ABC) haze that sits over the sub-continent and, to a lesser degree, the Indian Ocean. The ABC haze comprises a mixture of soot, which absorbs sunlight, and some reflecting sulphate. It causes heating of the atmosphere rather than the land surface, weakening the seasonal establishment of a land–ocean temperature gradient which triggers monsoon onset (Ramanathan *et al*. 2005). Conversely, greenhouse gas forcing is acting to strengthen the monsoon as it warms the **(p.30)** northern land masses faster than the ocean to the south. In some future projections, ABC forcing could double the drought frequency within a decade (Ramanathan *et al*. 2005) with large impacts, although it should be highly reversible.

The *El Niño–Southern Oscillation* (ENSO) has recently produced severe El Niño events (e.g. in 1983 and 1998), and their pattern has arguably changed towards 'Modiki' events where the warm pool shifts from the west to the middle (rather than the east) of the equatorial Pacific (Ashok and Yamagata 2009; Yeh *et al*. 2009). Models disagree over the sign of future changes in El Niño amplitude (Collins *et al*. 2010) but generally give no change in frequency. Some models simulate increased El Niño amplitude in future (Collins *et al*. 2010; Guilyardi 2006), but ENSO is unlikely to either vanish or become overly strong this century (Kriegler *et al*. 2009; Latif and Keenlyside 2009). Whether there is any underlying tipping point is highly uncertain.

Southwest North America (land within 125–95°W, 25–40°N) is probably already in transition to a drier state 'unlike any … we have seen in the instrumental record' (Seager *et al*. 2007), which may link to increased flooding in the Great Plains (Cook *et al*. 2008). However, a tipping point is again unclear.

Other stressors

Of course human activities could trigger large-scale tipping points that are unrelated to climate change. Humans are stressing the planet in a variety of ways, including profound changes in land-use, an order-of-magnitude increase in soil erosion rates (and associated sedimentation in marine margins) and widespread reductions in biodiversity. As humans progressively eliminate the links in complex food webs, and introduce new links in the form of invasive species, there will likely come points at which the underlying network structures and the functioning of the corresponding ecosystems must be fundamentally altered. Meanwhile the widespread erosion of the soils is depleting stores of essential nutrients and the storage capacity for water, upon which ecosystems (including agricultural ones) depend. The transfer of fertilizer nutrient inputs and eroded soil to the ocean, either washed through freshwaters, or carried in dust and gases through the atmosphere, then tends to fuel the depletion of oxygen in coastal waters, and ultimately the open ocean. Toxic algal blooms can be triggered in coastal waters. In the open ocean, oxygen minimum **(p.31)** zones (or 'dead zones') at depth are already spreading (Stramma *et al*. 2008) and causing essential nutrients to be released from the sediments, in a positive feedback loop that is thought to have driven much of the ocean anoxic in intervals of Earth's past (Handoh and Lenton 2003).

Risk assessment

The prospect of having to deal with high-impact but uncertain events, including a strong element of unpredictability, is not new. Think of earthquakes or hurricanes making landfall. Systems exist for dealing with such events, and they hinge around a risk management approach. Although these are relatively short-timescale 'events', some of the risk management principles may be usefully mapped over to climate tipping points. Risk, in the formal sense, is the product of the likelihood (or probability) of something happening and its (negative) impact. So a meaningful risk assessment of tipping elements would demand careful assessment of the likelihood of passing various tipping points (under different forcing scenarios), as well as the associated impacts.

How close are tipping points?

It is natural to try to locate tipping points in terms of global mean temperature change ('global warming'), although the connection is always indirect, often difficult to make, and sometimes not meaningful. Recent efforts suggest that 1°C global warming (above the 1980–1999 mean) could be dangerous as there are 'moderately significant' (Smith *et al*. 2009) risks of large-scale discontinuities (i.e. tipping points). Also, Arctic sea-ice and possibly the Greenland ice sheet would be threatened (Hansen *et al*. 2007; Lenton *et al*. 2008). Warming of 3°C is clearly dangerous as risks of large-scale discontinuities are 'substantial or severe' (Smith *et al*. 2009), and several tipping elements could be threatened (Lenton *et al*. 2008). Under a 2–4°C committed warming, expert elicitation (Kriegler *et al*. 2009) gives a >16 per cent probability of crossing at least one of five tipping points, which rises to a >56 per cent probability (i.e. more likely than not) for a >4°C committed warming. Considering a longer list of nine potential tipping elements, Figure 2.2 summarizes recent information on the likelihood of tipping them, under the IPCC range of projected global warming this century. **(p.32)**

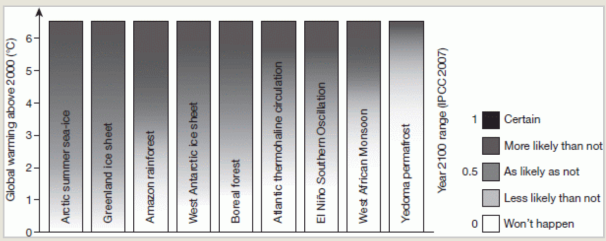

Figure 2.2 The likelihood of tipping different elements under different degrees of global warming (Lenton and Schellnhuber 2007), updated, based on expert elicitation results (Kriegler *et al*. 2009) and recent literature.

Current assessments suggest that Arctic tipping points involving ice melting are probably most vulnerable, with the least uncertainty surrounding this (Lenton *et al*. 2008). However, the greater uncertainty surrounding other tipping points allows for the possibility that some of them may be close as well. More detailed information can be found in the expert elicitation results (Kriegler *et al*. 2009).

Which tipping points carry the greatest impacts?

Passing a climate tipping point is generally expected to have large negative impacts, but these have only begun to be quantified for some elements and scenarios (Lenton *et al*. 2009a), notably a collapse of the THC (Arnell *et al*. 2005; Higgins and Vellinga 2004; Link and Tol 2004), where questionable (Shearer 2005) extrapolations have been made to national security concerns (Schwartz and Randall 2003). To translate climate tipping points into societal impacts typically involves several intervening steps and variables. Underestimation problems arise because studies tend to only consider a subset of consequences or impacted sectors (e.g. insurance (Lenton *et al*. 2009a)). Still, estimated impacts are already large for several tipping points (Lenton *et al*. 2009a). For a THC collapse this has been contested (Link and Tol 2004), although one is tempted to quip that only an economist could come to the conclusion that rearranging the large-scale ocean circulation would be beneficial to societies. Such disagreement (Arnell *et al*. 2005; Link and Tol 2004) is to be expected, as impacts depend on human responses **(p.33)** and are thus more epistemologically contested than assigning likelihoods to events (Stirling 2003).

With these caveats in mind, a 'straw-man' tipping point risk matrix is presented (Figure 2.3). Here tipping elements from the original shortlist (Lenton *et al*. 2008) where a threshold can be meaningfully linked to global temperature change are considered (thus excluding the Indian Summer Monsoon). Relative likelihoods and impacts are assessed on a five-point scale: low, low-medium, medium, medium-high, and high. Information on likelihood is taken from review of the literature (Lenton and Schellnhuber 2007; Lenton *et al*. 2008; Lenton 2012) and expert elicitation (Kriegler *et al*. 2009). Impacts are considered in relative terms, based on limited research (Lenton *et al*. 2009a) and my subjective judgement. The bold ring indicates the one system where impacts have been considered in several studies (Arnell *et al*. 2005; Higgins and Vellinga 2004; Lenton *et al*. 2009a; Link and Tol 2004), which thus forms a reference point. Impacts depend on timescale and here the full 'ethical time horizon' of 1000 years is considered (Lenton *et al*. 2008)

(p.34) assuming minimal discounting of impacts on future generations. (Note that if placed on an absolute scale compared to other climate eventualities most tipping point impacts would be high.)

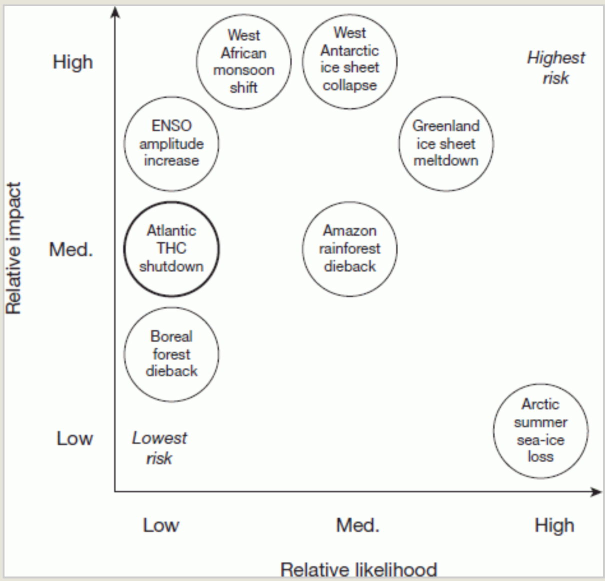

Figure 2.3 A 'straw-man' risk matrix for climate tipping points (Lenton 2011).

This risk matrix illustrates some familiar dilemmas for the would-be risk manager: 'relatively high impact–low probability' events, such as West African monsoon shift, come out with a similar risk to 'relatively lower impact–high probability' events, such as Arctic summer sea-ice loss. However, what stand out are the 'high impact–high-probability' scenarios as a priority for risk management effort: in this case Greenland ice sheet meltdown and West Antarctic ice sheet collapse. I emphasize that this straw-man assessment could be spectacularly wrong, especially on the impact axis. The point is to inspire a more scientifically credible and socially legitimate assessment of the risks, which in turn demands the engagement of a wider team of experts and relevant stakeholders (Stirling 2003).

The effort to translate climate tipping points into impacts inevitably leads down to regional, local and individual scales where the impacts will be felt. Whilst the Earth system scientist tries to gaze omnisciently at the planet from the top down, an alternative approach would be to define tipping points in impacts from the bottom up. The bottom-up approach would doubtless lead to the identification of some different threats, not least because some nations may experience tipping points as a result of entirely smooth changes in climate. For example, even a smooth movement in latitude of the jet streams, relative to island nations that are fixed in location underneath, can cause tipping point changes. The 2007 summer flooding in the UK is a seasonal example of the effects of a southward-straying polar jet. For Australia, the future depends crucially on whether the subtropical jet, which has been weakening, drifts away from the continent.

Having taken a risk-assessment approach, where the tipping points are treated independently, it is also worth considering a worst case scenario, which includes potential interactions between them. The aim of such horizon scanning is to be braced for all possible eventualities.

What is the worst case scenario?

By 2100, the worst case would be to be locked on to a trajectory to a hotter, higher sea-level, low-ice state for the planet, with qualitatively different patterns of atmospheric and oceanic circulation, different modes of internal **(p.35)** variability, diminished carbon stores on land, and major changes in biomes – in short, a structural change in the Earth system. In this worst case scenario, unmitigated radiative forcing and high climate sensitivity trigger 'domino dynamics', in which tipping one element of the Earth system significantly increases the probability of tipping another, and so on. Worryingly, from the limited information (Kriegler *et al*. 2009) that exists on the causal relations between different individual tipping events, the majority of connections do reinforce one another. Furthermore, the palaeo-record shows us that the Earth system 'prefers' particular states from time to time and tends to switch between them. On several occasions in the past, the planet was radically reorganized without there being any sign of a particularly large forcing perturbation (e.g. at the end of the last ice age).

This scenario might go something like this. The loss of Arctic summer sea-ice accelerates warming on the neighbouring land surfaces. The Greenland ice sheet is already in a state of irreversible shrinkage, and sea-ice loss accelerates its contribution to sea-level rise. The West Antarctic ice sheet starts to collapse and the rate of sea-level rise exceeds 1 metre per century (upper limit 2 metres by 2100 (Pfeffer *et al*. 2008)). The Atlantic overturning circulation weakens and deep water formation shifts in location, leading to regionally enhanced sea-level rise along the north-east cost of North America (Yin *et al*. 2009). Weakening of the overturning contributes to strong warming in the tropical Atlantic and a collapse of the West African monsoon (Chang *et al*. 2008). Meanwhile the monsoon in Southeast Asia shows enhanced inter-annual variability and Himalayan glaciers shrink, first increasing and later reducing dry season river flow. El Niño events become stronger and droughts afflicting the Amazon cause rainforest dieback mid-century. Some regions of unfreezing tundra lose their carbon abruptly (Khvorostyanov *et al*. 2008a), and large areas of boreal forest dieback (Lucht *et al*. 2006), releasing yet more carbon. Arctic sea-ice is lost year-round at the end of the century (Eisenman and Wettlaufer 2009), contributing to further reorganization of atmospheric and ocean circulation patterns.

This is an apocalyptic storyline, which should not be viewed as a prediction or projection. In its totality, the scenario is highly unlikely to transpire. However, the impacts are so great that from a risk-management point of view, it deserves consideration. Furthermore, parts of the scenario may become more likely than not (Kriegler *et al*. 2009) if we are heading into a >4°C warmer world.

(p.36) What early warning signs should we be looking for?

Faced with the risk of unpleasant climate surprises, perhaps the most useful information that science could provide to help societies cope is some early warning of an approaching tipping point. Early warning information can take several forms, ranging from the knowledge that a threshold change could occur, through qualitative assessment that it is becoming more likely, to a forecast of its timing. For several rapid onset natural hazards, e.g. hurricanes (Willoughby *et al*. 2007) and tsunamis (Titov *et al*. 2005), quite sophisticated early warning systems are already in place (Sorensen 2000), whilst for some slower onset hazards, e.g. drought (Verdin *et al*. 2005) and malaria outbreaks (Thomson *et al*. 2006), seasonal forecasting skill is beginning to be used in early warning. The United Nations (2006) has called for the development of a globally comprehensive early warning system, but this has yet to consider early warning of climate tipping points.

There are encouraging signs that we can directly extract some information on the present stability (or otherwise) of different tipping elements. Recent progress has been made in identifying and testing generic early warning indicators of an approaching tipping point (Dakos *et al*. 2008; Lenton *et al*. 2008; Lenton *et al*. 2009b; Livina and Lenton 2007; Scheffer *et al*. 2009). In particular, slowing down in response to perturbation is a nearly universal property of systems approaching various types of tipping point (Dakos *et al*. 2008; Scheffer *et al*. 2009; Wissel 1984). To visualize this, picture the present state of a system as a ball in a curved potential well (attractor) that is being nudged around by some stochastic (random) noise process, e.g. weather (Figure 2.4). The ball continually tends to roll back towards the bottom of the well – its lowest potential energy state – and the rate at which it rolls back is determined by the curvature of the potential well. As the system is forced towards a bifurcation point, the potential well becomes flatter. Hence the ball will roll back ever more sluggishly. At the bifurcation point, the potential becomes flat and the ball is destined to roll off into some other state (alternative potential well).

Slowing down can be detected as increasing temporal or spatial correlation in data, increasing memory, or a shift to greater fluctuations at lower frequencies. Such signals have been successfully detected in past climate records approaching different transitions (Dakos *et al*. 2008; Lenton *et al*. 2012a; Lenton *et al*. 2012b; Livina and Lenton 2007), and in model experiments (Dakos *et al*. 2008; Held and Kleinen 2004; Kleinen *et al*. 2003; Lenton *et al*. 2009b; Lenton *et al*. 2012b; Livina and Lenton 2007). This offers the prospect of probabilistic forecasting of some conceivable future climate **(p.37)**

tipping points (Lenton *et al*. 2008), especially if such statistical early warning indicators can be combined with dynamical models. However, critics have questioned the statistical robustness of proposed early warning signals (Ditlevsen and Johnsen 2010), and have noted that some types of abrupt transition carry no early warning signals (Ditlevsen and Johnsen 2010; Hastings and Wysham 2010).
Other early warning indicators that have been explored for ecological tipping points include increasing variance (Biggs *et al*. 2009), skewed responses (Biggs *et al*. 2009; Guttal and Jayaprakash 2008), and their spatial equivalents (Guttal and Jayaprakash 2009). Successful tests on ecological models (Dakos *et al*. 2010) suggest it would be worth looking for increasing **(p.38)** spatial correlation as an early warning indicator in climate data and models. Also, increasing variability is beginning to be applied to anticipating climate tipping points (Ditlevsen and Johnsen 2010). 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 (Bakke *et al*. 2009). 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 (Livina *et al*. 2010).

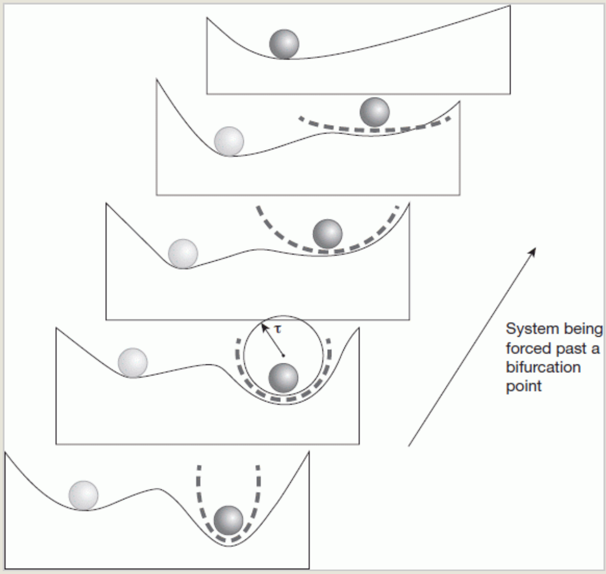

Figure 2.4 Schematic representation of a system being forced past a bifurcation point. The system's response time to small perturbations is related to the growing radius of the potential well (Lenton *et al*. 2008).

Looking ahead, there is a need for much better targeted monitoring of tipping elements and their leading indicators of vulnerability. In many cases, model-based research is needed to establish which variables best indicate underlying vulnerability (and can be readily monitored). Then direct or remote-sensing-based monitoring can be designed and imple-mented (for example, much recent effort has been invested in directly monitoring (Cunningham *et al*. 2007) the overturning strength of the Atlantic at 26.5°N).

When can we get reliable predictions?

Whilst the prospects for early warning are encouraging, the very nature of Earth system dynamics is such that we can never have complete predictability of tipping points: a mixture of deterministic and stochastic processes will always be at work. We can work to better constrain the deterministic components, and to get a measure of the nature, level and influence of the 'noise'. But there will always be the potential for a random fluctuation to tip a vulnerable system at a time that cannot be precisely predicted. This is a kind of 'irreducible uncertainty'. It means that any tipping point early warning system has the potential for missed alarms.

Still, by 2030, if we continue to clean up our aerosol pollution, then we may get a much better measure of the sensitivity of global temperature to radiative forcing. The reason is that the direct and indirect effects of aerosols (especially on cloud properties) are currently having a cooling effect, but the size of that effect is by far the most poorly constrained term in the equation determining global temperature. By removing the aerosols we will learn how much cooling effect they have been imparting. This will greatly improve our upper limit on how warm it could get by the end of the century, and hence which tipping elements are vulnerable.

(p.39) How should we respond?

Once an early warning of an approaching climate tipping point has been obtained and effectively communicated, risk can be reduced by trying to minimize the likelihood of passing a tipping point, or by trying to minimize the impacts of passing it. Corresponding risk-reduction strategies need to be considered and evaluated (Keller *et al*. 2008). Conceivably, for some climate tipping points, warning could be early enough to allow aversive action by mitigation of short-lived radiative forcing agents (Jackson 2009), or by geo-engineering to reduce incoming sunlight (Lenton and Vaughan 2009). However, the multiple sources of inertia in the climate system, and in human response systems, make this proposition questionable. An analogous problem of avoiding an approaching tipping point in an ecological system – a fishery (Biggs *et al*. 2009) – shows that once there is a reliable early warning of an approaching tipping point, it is too late for slow intervention methods to avoid it. Even where a tipping point is unavoidable, mitigation action may still help. For example, the rate of Greenland ice sheet melt and corresponding sea-level rise, even when committed to irreversible meltdown, depends on the extent to which this threshold has been exceeded (Huybrechts and De Wolde 1999). Still, adaptation to minimize impacts is likely to be the dominant response when faced with most tipping point early warnings. Appropriate adaptation action will clearly depend on the particular tipping point, but in the worst case it could involve intentional resettlement of populations before their home region becomes uninhabitable. As a general rule, early warning information is only useful if the warning recipients are empowered to act effectively on the information (Patt and Gwata 2002).

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