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1. Introduction

Characterising the social impacts and economic costs of passing climate tipping points under different scenarios is a vast and challenging topic, but also an extremely important one for policymakers. Central questions are: What are the biophysical impacts of passing particular tipping points? How do those biophysical impacts translate into social impacts and economic costs? Which tipping points could be passed under particular climate change scenarios? And to what degree can the impacts of tipping points be ameliorated by adaptation? Here we tackle these questions in turn, reviewing what is known (and unknown), presenting some new analyses, and highlighting priorities for further research. We consider a relatively long list of potential climate tipping points (Table 1), based on previous and ongoing research (Lenton, 2012, 2013; Lenton and Ciscar, 2013; Lenton et al., 2009; Lenton et al., 2008; McNeall et al., 2011).

2. What are the biophysical impacts of individual tipping points?

We start by briefly mapping out the physical consequences of passing different potential climate tipping points, for the nine tipping elements identified previously (Lenton et al., 2008), and for some additional candidates that have been identified since (Table 1). For each tipping event, we consider potential impacts on temperature, precipitation, sea level, atmospheric and ocean circulation. We also consider potential causal interactions between tipping events (Kriegler et al., 2009). Furthermore, we consider how different tipping points 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 social and economic impacts of passing tipping points. Table 2 summarises the biophysical impacts of passing the nine tipping points originally identified (Lenton et al., 2008). The likelihood of particular tipping points under different global warming scenarios, and the rate at which their impacts would unfold, is discussed in Section 4.

Collapse of the Atlantic Meridional Overturning Circulation (AMOC)

The Atlantic meridional overturning circulation (AMOC) – also referred to as the Atlantic thermohaline circulation (THC) – can pass a tipping point if sufficient freshwater enters the North Atlantic to halt density-driven deep water (NADW) formation there (Hofmann and Rahmstorf, 2009; Rahmstorf, 1995; Stommel, 1961). Several studies have looked at the physical impacts of a deliberately forced collapse of the AMOC in climate models of varying complexity (Jackson et al., 2015; Kuhlbrodt et al., 2009; Stouffer et al., 2006; Vellinga and Wood, 2002; Vellinga and Wood, 2008). Typically these studies apply an idealised freshwater (or equivalent salt) perturbation necessary to shut down NADW formation, to either a preindustrial or present climate state, although one study applies it to a future climate state (Vellinga and Wood, 2008), and one has a more realistic transient forcing scenario (Kuhlbrodt et al., 2009). The following describes the physical impacts of AMOC collapse, which would in reality be overlaid on an overall climate change.

Collapse of the AMOC represents a fundamental reorganisation of ocean circulation, causing a redistribution of heat around the planet and a corresponding coupled response from the atmosphere. Robust physical impacts of this are to cool the North Atlantic region and the Northern Hemisphere in general and to warm the Southern Hemisphere. The reorganisation of ocean circulation slows the uptake of heat by the ocean (Kostov et al., 2014), and it tends to increase sea-ice in the North Atlantic region (Jackson et al., 2015). It causes dynamic changes in sea level with increases of >0.5m along some coastlines of the North Atlantic region (Levermann et al., 2005) (and decreases elsewhere in the world). The Inter-Tropical Convergence Zone (ITCZ) of the atmosphere shifts southward, especially in the Atlantic sector, causing drying of the Sahel and parts of Central America. The drying over the Sahel in some simulations amounts to a collapse of the West African Monsoon (WAM) with rainfall locked to the coast and not seasonally jumping northwards into the Sahel (Chang et al., 2008). Some models show a marked drying over Amazonia amounting to weakening of the South American monsoon (Jackson et al., 2015; Parsons et al., 2014). Drying of the South Asian monsoon region is also seen in model simulations (Jackson et al., 2015) and in paleoclimate data (Deplazes et al., 2013). The atmospheric pressure response resembles a positive North Atlantic Oscillation (NAO) in winter – i.e. an increase in the pressure difference between the Azores High and the Icelandic Low – which causes the North Atlantic storm track to strengthen and penetrate further over land. This brings the potential for extreme winter snowfall events over Europe in much harsher winters (Jackson et al., 2015; Jacob et al., 2005). In summer the atmospheric pressure response resembles a negative NAO pattern, causing a decrease in precipitation over much of Europe but an increase in the Mediterranean (Jackson et al., 2015). The longer-term Atlantic Multi-decadal Oscillation (AMO) mode of climate variability would be expected to disappear as it is linked to fluctuations in AMOC strength, whilst the El Nino Southern Oscillation (ENSO) is expected to strengthen. Terrestrial Net Primary Productivity (NPP) is predicted to decrease markedly over Europe (Jackson et al., 2015) and the Northern Hemisphere in general with little net change in the Southern Hemisphere leading to a global reduction in NPP by as much as 18% (Jackson et al., 2014). AMOC collapse also weakens the ocean carbon sink (Perez et al., 2013; Zickfeld et al., 2008).

In AMOC weakening scenarios (without total collapse) some models forecast a sub-polar gyre switch in the North Atlantic in which deep convection shuts off in the Labrador Sea region (to the west of Greenland) and convection 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 have dynamic effects on sea level, increasing it down the eastern seaboard of the USA by around 25 cm in the regions of Boston, New York and Washington DC (Yin et al., 2009).

Meltdown/collapse of major ice sheets (GIS, WAIS, EAIS)

The Greenland Ice Sheet (GIS), West Antarctic Ice Sheet (WAIS), and parts of the East Antarctic Ice Sheet (EAIS) can all pass tipping points, beyond a particular level of atmospheric and/or ocean warming, leading to irreversible loss of part or all of the ice sheets. The tipping point for a land-grounded ice sheet – e.g. GIS – is associated with the surface mass balance going negative (Huybrechts and De Wolde, 1999), whereas for a marine-grounded ice sheet – e.g. WAIS, parts of the EAIS – it is linked to retreat of the grounding line (Mercer, 1978; Schoof, 2007; Vaughan, 2008; Weertman, 1974), potentially triggered by the loss of protective ice shelves or ice ‘plugs’ (Mengel and Levermann, 2014), or due to the loss of neighbouring parts of the ice sheet (Feldmann and Levermann, 2015). The amount by which a tipping point is passed is expected to affect the rate of melt and hence sea-level rise (Huybrechts and De Wolde, 1999). Loss of major ice sheets has been simulated using ice sheet models often driven ‘offline’ by a chosen climate model forcing scenario, and sometimes in fully coupled simulations. Separate simulations have shown how the loss of particular ice sheets leads to spatially variable patterns of sea-level rise thanks to gravitational adjustment; with the smallest rise nearest the ice sheet that is being lost and the greatest rise on the opposite side of the planet (Mitrovica et al., 2009; Mitrovica et al., 2001).

Irreversible melt of the entire Greenland ice sheet would lead ultimately to about 7 m global sea level rise. In some models, there is an earlier tipping point beyond which the ice sheet retreats on to land, leading to about 1 m of global sea-level rise (Ridley et al., 2010). Greenland can contribute a maximum of 50 cm to sea level rise this century (Pfeffer et al., 2008), although a state-of-the-art estimate is only 4.5 cm (Price et al., 2011). The sea level rise is greatest at the opposite pole and would tend to destabilise marine-grounded parts of the West and East Antarctic ice sheets (Kriegler et al., 2009). Melt water from Greenland would contribute to weakening the AMOC (Bamber et al., 2012; Driesschaert et al., 2007; Jungclaus et al., 2006). Ultimately, losing the ice sheet would cause local warming (due to lowered albedo), affect patterns of atmospheric circulation in the Northern Hemisphere, and stop ocean deep convection in the Irminger Sea, which depends on the ‘tip jet’ of cold air pouring off the ice sheet (Pickart et al., 2003).

Collapse of the West Antarctic ice sheet ultimately would lead to around 3 m of global sea level rise (Bamber et al., 2009). Parts of the East Antarctic ice sheet grounded below sea level are also vulnerable to irreversible loss, the largest being the Wilkes basin which contains 3-4 m of global sea level rise (Mengel and Levermann, 2014). In extreme scenarios, due to interactions between parts of the ice sheet (Feldmann and Levermann, 2015), there is the potential for eventual total loss of the EAIS leading to over 50 m sea level rise (Winkelmann et al., 2015). The maximum contribution from Antarctica to the rate of sea level rise was previously estimated at around 60 cm this century (Pfeffer et al., 2008), but this is questionable because outlet glaciers are less constrained by topography than assumed (Levermann et al., 2012). Indeed the latest simulations suggest sea level rise exceeding 3 m per century is possible this millennium in extreme scenarios (Winkelmann et al., 2015). The sea level rise from loss of ice on Antarctica is greatest at the opposite pole and could flood extensive regions of low-lying permafrost in the Arctic, releasing methane and carbon dioxide. It would also tend to destabilise marine-grounded parts of the Greenland ice sheet (Kriegler et al., 2009). Antarctic ice sheet collapse would produce armadas of icebergs entering the Southern Ocean. Ultimately the loss of south polar ice would disrupt the polar vortex in the atmosphere and reorganise atmosphere and ocean circulation.

ENSO

Expert elicitation has considered an abrupt shift to a more El Niño-like mean state as a potential climate tipping point (Kriegler et al., 2009). However, the latest work suggests the scenario should be redefined somewhat. In particular, models forecast an increase in the amplitude of ENSO variability (Guilyardi, 2006) with more frequent extreme El Niño events (Cai et al., 2014) and extreme La Niña events (Cai et al., 2015a). The physical impacts of increased ENSO amplitude can be thought of as amplifying the known pattern of impacts of El Niño and La Niña events on temperature and precipitation (see e.g. http://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/gpc-outlooks/el-nino-la-nina/ENSO-impacts). Extreme El Niño events produce flooding in the eastern equatorial region of Ecuador and northern Peru and severe droughts in regions to the south and north (Cai et al., 2014). Extreme La Niña events trigger drought in the eastern equatorial Pacific and southwestern United

States and floods in the western Pacific and central America, as well as an increase in land falling west Pacific cyclones and Atlantic hurricanes (Cai et al., 2015a). An increase in ENSO amplitude would be expected to affect the longer-term Pacific Decadal Oscillation (PDO), the Atlantic Multi-decadal Oscillation (AMO) and the South Asian Monsoon system. Inter-annual variability in atmospheric CO_2 would increase with the El Niño phase tending to encourage Amazon drying, fires and dieback. Change in the Walker circulation and associated moisture transport would tend to strengthen the AMOC.

Monsoon disruption (South Asia, West Africa)

Monsoons are inherently self-amplifying, non-linear phenomena exhibiting thresholds (Levermann et al., 2009). Hence the strength and location of their seasonal recurrence can be disrupted by changes in the input and distribution of heat around the planet. Local accumulation of atmospheric aerosol pollution leading to solar radiation reflection (sulphate aerosols) and atmospheric absorption (black carbon aerosols) tends to weaken monsoons. Global warming generally warms the land faster than the ocean tending to strengthen monsoons (Schewe et al., 2011; Zickfeld et al., 2005). At a global scale, past aerosol-driven cooling of the Northern Hemisphere tended to shift the ITCZ southward promoting drought in e.g. the Sahel (Rotstatyn and Lohmann, 2002), whereas forecast faster warming of the Northern Hemisphere will tend to drag the ITCZ northwards. Ocean-driven changes in heat distribution in the Atlantic can also trigger abrupt monsoon shifts (Burns et al., 2003; Chang et al., 2008; Goswami et al., 2006; Gupta et al., 2003; Shanahan et al., 2009).

The South Asian (also known as Indian summer) monsoon has been weakened by the 'atmospheric brown cloud' of aerosol pollution (Lau and Kim, 2010; Meehl et al., 2008; Ramanathan and Carmichael, 2008; Zickfeld et al., 2005) and is forecast to weaken further in the near future (Held et al., 2005; Ramanathan et al., 2005). The direct impacts would be to reduce monsoonal rainfall and increase summer temperatures, encouraging drought and heatwave episodes in India.

The West African Monsoon is forecast to pass a tipping point in some models in which the rains fail to make their seasonal jump into the continental interior, drying the Sahel and increasing rainfall in coastal regions (Cook and Vizy, 2006; Hagos and Cook, 2007). This could be triggered by a weakening of the AMOC below ~8 Sv triggering abrupt warming in the Gulf of Guinea (Chang et al., 2008).

Forest dieback (Amazon, boreal)

Dieback of much of the Amazon rainforest has been forecast in some models due to drying of the regional climate (Cook and Vizy, 2008; Cox et al., 2000; Cox et al., 2008; White et al., 1999), whereas other climate models do not forecast regional drying or dieback (Salazar et al., 2007; Scholze et al., 2006). Amazon dieback could replace rainforest with grassland, savannah or seasonal forests (Malhi et al., 2009). Recent experimental studies suggest interaction between drought and fire would accelerate forest loss and promote a transition to grassland (Brando et al., 2014). The impacts of Amazon dieback would include amplification of regional warming and precipitation decline (Betts et al., 2004), loss of up to ~100 GtC to the atmosphere at a rate of up to ~2 GtC/yr (Cox et al., 2000), increased fire frequency (Brando et al., 2014; Cochrane and Barber, 2009), and massive loss of biodiversity and other ecosystem services. Remote effects including weakening of tropical atmospheric circulation (Kleidon and Heimann, 2000; Zeng et al., 1996).

Widespread dieback of boreal forests has also been predicted in some future projections, replacing the forest with open woodlands or grasslands (Lucht et al., 2006). This would in turn amplify summer warming and drying and increase fire frequency, producing a potentially strong positive feedback. Given the ~90 GtC stored in boreal forest vegetation and ~470 GtC in soils, a loss on the order of 100 GtC is conceivable, at a rate of up to ~2 GtC/yr (Lucht et al., 2006). Potential remote effects on the atmosphere include a southward shift of the ITCZ contributing to reduced precipitation in monsoon regions, especially South Asia (Devaraju et al., 2015). Again, biodiversity and other valuable ecosystem services would be lost.

Arctic sea-ice loss (summer, winter)

The loss of Arctic sea-ice is amplified by the ice-albedo positive feedback and potentially by cloud feedbacks (Arnold et al., 2014). The loss of Arctic summer sea-ice is already occurring rapidly although there is ongoing debate about how reversible this is (Abbot et al., 2011; Eisenman and Wettlaufer, 2009; Notz, 2009; Tietsche et al., 2011) whereas the loss of year-round (winter) ice more likely involves an irreversible tipping point (Eisenman and Wettlaufer, 2009). Loss of Arctic sea-ice is already amplifying polar warming (Screen and Simmonds, 2010), triggering a shift from snowfall to rainfall (Screen and Simmonds, 2011), and causing large-scale changes in atmospheric circulation (Overland and Wang, 2010). The centre of action of the North Atlantic Oscillation has moved into the Barents Sea region (Zhang et al., 2008), and loss of sea-ice cover in the Barents and Kara Sea has been linked to recent severe cold winters in Europe (Petoukhov and Semenov, 2010). However, the effect of Arctic sea-ice loss on mid-latitude weather extremes is currently a subject of intense research and debate (Cohen et al., 2014; Screen et al., 2015). Amplified warming over Arctic land surfaces is contributing to permafrost thawing (Lawrence et al., 2008) and tundra wildfires (Hu et al., 2010), and further effects on both the marine and terrestrial carbon cycles are expected in future (Parmentier et al., 2013). As one of the respondents to Nordhaus' (1994) survey noted: "It is hard to image what the world would be like with an ice-free Arctic, with a weakening of the circumpolar vortex and a movement of storms to the north, mild temperatures in the Arctic regions, agricultural possibilities in high northern latitudes, as well as substantial mid-latitude desiccation..."

Recently atmospheric general circulation model experiments aimed at isolating the effect of Arctic sea-ice loss on extreme events have begun to be conducted (Screen et al., 2015), although at relatively low resolution. As part of HELIX we are undertaking new work prescribing Arctic sea-ice loss as a lower boundary condition in a high resolution atmospheric general circulation model (AGCM) run by SMHI to allow a detailed exploration of the impacts on weather extremes.

Permafrost collapse (Yedoma)

Most permafrost is expected to thaw in proportion to global warming (i.e. does not possess a tipping point), however a large area of frozen loess (windblown organic material) in northeastern Siberia (150–168°E and 63–70°N), known as Yedoma, has an extremely high carbon content (2–5%) (Zimov et al., 2006) and could pass a tipping point triggering self-sustaining, irreversible collapse. This involves the heat released by biochemical decomposition of the carbon triggering further melting in a runaway positive feedback (Khvorostyanov et al., 2008a; Khvorostyanov et al., 2008b). Once underway, this process could release ~2.0–2.8 GtC/yr (mostly as CO_2 but with some methane) over about a century, removing ~75% of the initial carbon stock, which is estimated at up to 500 PgC.

3. Translating physical impacts into social impacts and economic costs

Translating the physical impacts of crossing climate tipping points into social impacts and economic costs is a hugely challenging exercise. A central difficulty is that the transmission mechanisms between biophysical impacts and social and economic impacts are relatively poorly understood. Indeed, the whole field of climate impacts research is at a relatively early stage.

Key considerations with regard to social and economic impacts

There are some key general considerations regarding the translation of biophysical impacts of tipping points into a quantification of their social and economic impacts.

The most fundamental consideration is the substitutability or otherwise of 'natural capital' lost due to passing tipping points (Hoel and Sterner, 2007; Neumayer, 1999; Sterner and Persson, 2008). Here 'substitutability' refers to whether the things lost or damaged due to a tipping scenario can be replaced with an alternative form of capital, e.g. something that can be purchased in the economy. The majority of integrated assessment model studies of climate damages assume perfect substitutability, which is clearly flawed (Neumayer, 1999). Those few studies that account for the imperfect substitutability of services provided by the climate and the biosphere show that this has a profound effect on policy recommendations (Hoel and Sterner, 2007; Sterner and Persson, 2008). In particular, as the economy tends to grow, then imperfectly substitutable climate and ecosystem services gain in relative value over time because they become scarcer commodities (this is called a 'relative pricing effect') (Hoel and Sterner, 2007; Sterner and Persson, 2008). The prospect of tipping point losses in these services then produces a much stronger incentive to mitigate now (Cai et al., 2015b).

Accepting that not everything can be monetised nor should it be, the rate of accumulation of biophysical impacts from passing a tipping point – i.e. the 'transition time' of the corresponding tipping element (Figure 1) – will affect its social and economic impacts. In general, faster transitions lead to greater impacts. This is partly because adaptation generally gets harder if changes are more rapid, and partly because impacts that occur further in the future tend to be discounted on the assumption that economic growth will continue and therefore the same damages will have a smaller effect on future societies. This discounting effect is counterbalanced by the aforementioned 'relative pricing effect' due to imperfect substitutability (Hoel and Sterner, 2007; Sterner and Persson, 2008). Existing integrated assessment model studies that consider tipping points tend to treat them as having instantaneous (and irreversible) impacts, i.e. a discontinuity in the damage function, which is physically unrealistic. 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 ice sheet collapse. In recent work we have included explicit transition times for different tipping elements in an integrated assessment model (Figure 1) (Cai et al., in review; Lontzek et al., 2015). In general, the longer the transition time the weaker the incentive to mitigate now to avoid a tipping point, because the future damages tend to be discounted (Cai et al., in review; Lontzek et al., 2015).

Moving specifically to how to treat the economic impacts of climate change, most studies just consider short-term impacts on output (e.g. GDP). However, any assessment of climate change impacts should ideally 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 3 represents how impacts on key sectors would affect the four economic variables. This information could potentially be combined with an analysis of the sectoral impacts induced by different tipping points.

Available tools and their limitations

Current tools to evaluate climate impacts range from empirical correlations to process-based sectoral models, and they are mostly restricted to considering impacts on GDP. Empirical correlations are typically between some aggregate environmental variable – typically mean annual temperature (or precipitation) – and some aggregate impact variable – e.g. national GDP. There is a flourishing of work on such empirical correlations, recently reviewed by (Dell et al., 2014), which typically form the basis of the damage functions used in simple, global integrated assessment models such as DICE, PAGE, and FUND. Process-based impacts models translate biophysical input variables into output variables pertaining to social and economic impacts. Impacts models are typically sectoral, with key sectors being agriculture, health, tourism, coastal zones and river floods (Table 3). Whilst they may take more complex time-dependent inputs and produce more complex time dependent outputs, only some impacts models consider the effects of extreme events, which we know can have a disproportionate effect on damages.

Clearly one way into the problem of quantifying the social and economic impacts of climate tipping points would be to run the biophysical impacts of a tipping point scenario through existing empirical damage functions and/or impacts models. However, these existing impacts tools have some serious limitations, in that (i) they do not consider a wide enough range of biophysical variables that could impact society and the economy (Table 2); (ii) they only tend to consider the effects of mean states of biophysical variables rather than extremes; (iii) they only tend to consider short-term economic impacts on output, rather than broader economic impacts on e.g. growth, or broader social impacts that cannot be monetised. More fundamentally, societies and the global economy are, like the climate, complex systems that may respond highly non-linearly to shocks. This means that simply summing up sectoral damages on output without considering interactions through the global socio-economic system may be deeply flawed.

Existing studies of tipping point impacts

Existing efforts to quantify tipping point impacts using some kind of impact model or empirical damage function are limited. Existing studies are largely restricted to considering either AMOC collapse or accelerated sea-level rise. Here we briefly review and critique existing studies.

Collapse of the Atlantic Meridional Overturning Circulation (AMOC)

Several studies have considered the social and economic impacts of a collapse of the AMOC (Arnell et al., 2005; Kuhlbrodt et al., 2009; Link and Tol, 2011; Link and Tol, 2004; Schwartz and Randall, 2003). AMOC collapse is widely viewed as a potential economic catastrophe (Nordhaus, 1994), although at least one study has argued it could have a net economic benefit (Link and Tol, 2004). Nordhaus uses AMOC collapse as an example of a climate catastrophe, which he defines in his DICE model as leading to a permanent loss of 25% of global GDP –

comparable to the cumulative loss over several years after the 1929 Great Depression. This was later increased to 30% global GDP loss, ostensibly to account for new evidence about the effects of a collapse or slowdown of the AMOC (Nordhaus and Boyer, 2000). Subsequent work with DICE has considered AMOC collapse to cause a loss in the range of 1-25% of global GDP (Mastrandrea and Schneider, 2004) or 10-20% of global GDP (Cai et al., in review). All of these choices are essentially arbitrary – they do not involve any attempt at a bottom-up quantification of the impacts of AMOC collapse.

Some attempts have been made to assess the economic impacts of AMOC collapse on a country-by-country basis, using the FUND 2.8n model (Link and Tol, 2011; Link and Tol, 2004). However, only the effects of annual mean temperature changes were considered. The modelled scenario was a weakening of the AMOC starting in 2070 with shutdown completing in 2100 (i.e. a 30 year transition time), superimposed on an underlying business-as-usual climate change scenario (Link and Tol, 2011). This is a rapid shutdown when compared to many models, though not when compared to paleo-data. In the scenario 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 of these temperature changes is negative but limited to at most 0.3% of global GDP, which adds to around 1% reduction in GDP due to climate change alone in this model (which has generally low damages). There are larger negative effects in some countries and sectors, counterbalanced by benefits elsewhere. However, effects that were not considered, on seasonal temperatures, associated extreme events, and on many other climate variables (Table 2), could have much larger impacts than the effects of mean annual temperature changes.

Accelerated sea-level rise nominally linked to WAIS collapse

FUND 2.8n has also been used to assess the economic impacts of sea level rise due to a collapse of the West Antarctic ice sheet, on a country-by-country basis (Nicholls et al., 2008). The WAIS collapse scenarios involved a globally-uniform 5 metre rise in sea level, starting in 2030 and taking from 100 to 1000 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. However, the fastest WAIS collapse yet simulated by models takes around 1000 years (Pollard and DeConto, 2009), and 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). Furthermore, the sea-level contribution from WAIS collapse would be globally uneven and exceed the mean along e.g. the eastern seaboard of the US (Mitrovica et al., 2009). Only the impacts of sea level rise on coastal zones were 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 reduce 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. However, other impacts of WAIS loss are not considered (Table 2). Notably the model predicts that large (but thinly populated) areas of agricultural land, boreal forest, and tundra are abandoned to rising seas – but the attendant effects on the carbon cycle are ignored.

Other work on the implications of climate tipping points for the insurance sector (Lenton et al., 2009), has used the DIVA model (http://www.diva-model.net/) to consider a tipping point scenario of ice sheet meltdown leading to 0.5 m global sea level rise by 2050, relative to a baseline scenario of 0.15 m global sea level rise. Global population exposed to a 1-in-100 year flood event was increased by 34 million people in the tipping scenario (relative to no tipping), with greatest increases in exposure in Africa and North America. Exposed assets across 136 port megacities increased by US$25 trillion in the tipping scenario (relative to US$3 trillion today) with the greatest exposure in China (~US$8.5 trillion) and the USA (~US$7 trillion), followed by India (~US$3 trillion) and Japan (~US$3 trillion). A further tipping scenario of a sub-polar gyre switch linked to slowdown in the AMOC considered an additional 0.15 m regional sea level rise along the northeast US coastline (i.e. 0.65 m regional sea level rise in total in 2050) affecting five port megacities (Baltimore, Boston, New York, Philadelphia, Providence). The increase in exposure in the tipping scenario was US$6 trillion (relative to US$1.35 trillion today) with the extra 0.15 m regional sea level rise responsible for a US$300 billion increase in exposure.

Aggregate catastrophic damages in simple integrated assessment models (IAMs)

The simple integrated assessment models DICE, PAGE and FUND which have been used in the US Federal Assessments (2010; 2013) of the social cost of carbon, all include a component of catastrophic (i.e. tipping point) damages. Whilst these potential damages can be set quite high, e.g. the aforementioned instantaneous 30% reduction in global GDP in DICE, their assigned probabilities are typically set very low. Hence the expected GDP loss and the resulting willingness to pay to avoid the catastrophe tend to be quite small. For example, in an earlier version of DICE the willingness to pay to avoid catastrophe is 1% of global GDP in a 2.5°C global warming scenario rising to 7% of GDP in a 6°C warming scenario. In a version of the PAGE model, the mode of the GDP loss in a 6°C global warming scenario is only 1%, rising to 4% of GDP in a 7°C warming scenario, and 9% of GDP under 8°C of warming. In the version of FUND used in US federal (2010) assessment, the catastrophic component of damages is small (based on the studies discussed above) and even the total climate damages are only about 7% of GDP at 8°C of global warming. Many recent authors, notably Weitzman (Weitzman, 2009, 2012) have argued that these low assessments of catastrophic damages are fundamentally flawed, as they assume economic growth continues to levels of warming that we know would make the world largely unliveable for humans and other complex life forms.

Extrapolating tipping point impacts from experience

Another way to start to assess the impacts of some tipping points is to extrapolate from past experience of related extreme events. For example, a landmark study of the economic impacts of the 1930s American dustbowl has shown that it had long-term effects on population and economic growth that lasted for several decades (Hornbeck, 2012). Here we discuss tipping points where past experience could be useful toward quantifying the impacts that could emerge.

Increase in ENSO amplitude

The impacts of an increase in ENSO amplitude, including a doubling in frequency of extreme El Niño and La Niña events (Cai et al., 2014; Cai et al., 2015a) could be extrapolated from the known impacts of current ENSO variability on e.g. agriculture (Meza et al., 2008) and health (Patz et al., 2005). There are known correlations between ENSO variability and food security in a variety of regions, including Australia, Southeast Asia, the Western Hemisphere, and Sub-Saharan Africa (Hansen et al., 2011; Meza et al., 2008). Just within the U.S., early warning of an oncoming El Niño has an estimated annual value to U.S. agriculture of over $300 million (Chen et al., 2001; Solow et al., 1998). Outbreaks of several infectious diseases have been correlated with ENSO variability, notably malaria, cholera, dengue, and rift valley fever (Patz et al., 2005). For malaria the effects span the Indian subcontinent, South America, and southern Africa (Thomson et al., 2006). ENSO has also been correlated with civil conflict (Hsiang et al., 2011). Recently significant correlations have been derived between ENSO variability, cereal yield, cereal production and agricultural income across the tropics (Hsiang and Meng, 2015). These correlations indicate that a 1°C increase in ENSO index (noting that an extreme El Niño such as 1997/98 exceeded a 2°C increase in ENSO index) lowers tropical cereal yield -2%, cereal production -3.5%, and agricultural income -1.8% (Hsiang and Meng, 2015). There is also a 1.6% increase in agricultural value in temperate regions, perhaps due to general equilibrium price changes driven by food shortage in the tropics (Hsiang and Meng, 2015).

Monsoon disruption (South Asia and West Africa)

Although the contribution of agriculture to India's GDP has declined, nearly 70% of the working population still depends on agricultural activities for their livelihood. Negative impacts on Indian agricultural output due to weakening of the monsoonal rains have already been observed (Auffhammer et al., 2006), for example, the 2002-2003 drought reduced food grain production by 18% and lowered GDP growth by about 2.5% in that year. A tipping point scenario is that drought frequency in India has been forecast to double from around 2 to 4 per decade in the first half of this century (Ramanathan et al., 2005). Overlaid on this will be projected population growth and increasing food demand, together with the effects of increasing ENSO amplitude on the monsoon, and the effect of Himalayan glacier loss on dry season rainfall. Considering these factors together existing estimates range up to a 10% reduction in national GDP for India (Lenton et al., 2009).

The impact of potential future disruption of the West African monsoon can also draw on the recent historical experience of Sahel drought, on which must be overlaid projected population growth.

Quantifying impacts of abrupt ecosystem loss

Assessing the impacts of tipping point losses of major ecosystems can benefit greatly from efforts that are already underway worldwide to assess the monetary value of ecosystem services and how they are changing (Costanza et al., 2014). Furthermore, the cost of releases of CO_2 to the atmosphere can be quantified based on current assessments of the social cost of carbon emissions, and this approach might also be extended to methane emissions.

Amazon rainforest dieback

Considering dieback that is committed to long before it becomes apparent (Jones et al., 2009) and that around 85% of carbon stored in biomass is lost, the committed emissions of carbon from Amazon dieback could exceed 80 GtC (Lenton et al., 2009). Using the current US Federal social cost of carbon emissions of $121/tC (which many think is too low) this would amount to a loss of around $10 trillion were it to all occur today. Of course the loss will be spread out over time, potentially at a mean rate of 1.6 GtC/yr (for a 50 year transition time), which translates to damages of order $200 billion/yr. These figures do not consider losses of other valuable ecosystem services (Costanza et al., 2014). Taking the area of the Amazon as 550 Mha and the estimated 2011 value of tropical forest ecosystem services of $5382/ha/yr (Costanza et al., 2014) gives a current value to Amazon ecosystem services of $3 trillion/yr. If dieback were to remove 85% of the forest this amounts to an eventual loss of $2.5 trillion/yr (at present values). For reference, this is 2% of the estimated total global value of ecosystem services in 2011 of $125 trillion/yr, and equivalent to ~3.3% of current gross world production of ~$75 trillion/yr. Note however that these services are clearly not perfectly substitutable in the marketplace, further increasing their true value.

Boreal forest dieback

A similar exercise can be conducted for a scenario of boreal forest dieback where the unit value of ecosystem services is estimated at $3137/ha/yr (Costanza et al., 2014). Expert elicitation considered a dieback scenario involving at least a halving of boreal forest area (Kriegler et al., 2009), which would amount to losing at least 700 Mha, giving an eventual loss of $2.2 trillion/yr (at present values), which is comparable to the figure for Amazon dieback. The cost of carbon losses within this total could also be comparable to those from Amazon dieback, of order $200 billion/yr.

Yedoma permafrost loss

No estimate is available yet for the global value of tundra ecosystem services (Costanza et al., 2014). However, the carbon release scenario of 2.0-2.8 GtC/yr at a social cost of carbon emissions of $121/tC amounts to $242-339 billion/yr of damages. The total loss over a century amounts to ~$25-35 trillion were it to all occur today. There are also other economic consequences of permafrost thaw, notably the loss of 'ice roads' reducing the inland transport accessibility of Arctic states (Stephenson et al., 2011).

Arctic sea-ice loss

One tipping element not covered above is the loss of Arctic sea-ice, in summer or ultimately year-round. Some recent studies have begun to look at how Arctic sea-ice loss could increase shipping access to and through the Arctic (Smith and Stephenson, 2013; Stephenson et al., 2011) with presumed global economic benefits. This increased shipping access in turn is likely to increase the input of invasive species to Arctic waters (through the release of ship ballast water) with unquantified ecological consequences (Miller and Ruiz, 2014). Sea-ice loss has also triggered widespread commercial interest in the extraction of fossil fuels and other mineral resources from the Arctic, which would be detrimental to the climate but would have short-term economic benefits. Quantifying the economic impacts of extreme mid-latitude weather events that may be due to Arctic sea-ice loss is premature, because the causal role of sea-ice loss in climate extremes is still being debated. Some studies suggest that sea-ice loss has reduced temperature variance in mid- to high-latitudes of the Northern Hemisphere and this is expected to continue in future (Screen, 2014), whilst wet extremes are generally projected to increase (Screen et al., 2015). As the nature and strength of any causal connection becomes more firmly established, it should be possible to use known insurance losses for past extreme events to begin to quantifying the effects of projected future changes in extremes.

4. Which tipping points could be crossed in 2°C, 4°C, 6°C scenarios?

To characterise the combined social and economic impacts of tipping points under different global climate change scenarios we need to know which tipping points are likely to be crossed under the different scenarios. For five tipping points probability estimates are available from expert elicitation (Kriegler et al., 2009), whereas for other tipping points we must rely on existing literature.

Use of expert elicitation results

Here we undertake a preliminary analysis of tipping point probabilities based on an existing expert elicitation (Kriegler et al., 2009), which provides imprecise probability assessments of the likelihood of passing five different tipping points under three different temperature scenarios. The five tipping points are those triggering collapse of the AMOC, meltdown of the Greenland ice sheet, collapse of the West Antarctic ice sheet, dieback of the Amazon rainforest, and a shift in ENSO variability. From the expert results of probabilities by 2200 it is possible to derive a 'hazard rate' (Table 4) (Cai et al., in review) for each of the five tipping points which is a likelihood of tipping per year per degree of warming above a baseline (/yr/K), where we take the baseline to be 1°C warming above pre-industrial. The resulting hazard rates are found to be internally consistent – that is the hazard rates inferred from different temperature trajectories are found to be in agreement (Lontzek et al., 2015).

To convert the hazard rates into tipping point probabilities at particular times they have to be combined with temperature scenarios. In essence this generalises the expert elicitation results to any temperature scenario. Here we constructed idealised scenarios of 2°C, 4°C and 6°C warming above pre-industrial, based on previous results from the HELIX project with regard to the likely timing of these specific warming levels. The idealised scenarios are: 2°C warming followed by stabilisation, 4°C warming (slowly) followed by stabilisation, 4°C warming (slowly) with ongoing warming thereafter, 6°C warming (after 4°C warming quickly) followed by stabilisation, and 6°C warming with ongoing warming thereafter. We calculate the probability of each tipping event in each scenario, on time horizons of 2050, 2100, 2150, and 2200. We also calculate the combined probability of any of the five tipping points occurring in each scenario on these time horizons, and the time when tipping becomes inevitable for each element under each scenario. The results are summarised in Tables 4-7.

In the expert elicitation there was also some information on the likelihood of boreal forest dieback provided by a limited number of experts (Kriegler et al., 2009), which suggests it has a comparable hazard rate to Amazon dieback, which would lead to comparable probabilities under the scenarios (Tables 4-7). This is consistent with model studies that show widespread boreal forest dieback when regional temperatures reach around 7°C above present, corresponding to around 3°C global warming (Lucht et al., 2006).

The expert elicitation is a few years old now and subsequent research would suggest some revisions. Notably the expected change in ENSO is now somewhat different to that considered in the elicitation, which would be expected to change the results. Also, new ice sheet modelling research suggests that the WAIS is vulnerable to peak global warming in excess of 2°C (Golledge et al., 2015; Winkelmann et al., 2015), which is more pessimistic than the expert elicitation.

Likelihood assessment for other tipping points

Other key tipping points where likelihood has not been considered in an expert elicitation are; South Asian monsoon disruption, West African monsoon collapse, Arctic summer sea-ice loss, Arctic winter sea-ice loss, collapse of parts of the East Antarctic ice sheet, and Yedoma runaway breakdown. Based on existing studies we can say the following.

South Asian monsoon disruption is driven in the short-term by aerosol forcing not global warming hence it cannot be directly related to global temperature scenarios. In the longer term global warming is expected to lead to strengthening of the South Asian monsoon.

West African monsoon collapse is sensitive to redistribution of heat by the ocean, linked to weakening of the AMOC, so any link to global temperature is indirect. Nevertheless greater global warming is generally related to greater AMOC weakening and therefore greater risk of WAM disruption. If the modelled threshold of the AMOC weakening by ~65% to below ~8 Sv (Chang et al., 2008) is correct, then probabilistic projection (Schleussner et al., 2014) suggests this could occur under RCP8.5 i.e. 4°C warming that is ongoing, or under a 6°C warming scenario, but is unlikely under the other scenarios.

Arctic summer sea-ice loss was originally assessed to occur at 0.5-2.0°C above year 2000 (~1.2-2.7°C above pre-industrial) (Lenton et al., 2008), which is consistent with more recent studies. Extrapolations based on observations suggest the Arctic could be largely ice-free in summer by circa 2040 when global temperatures are expected to be approaching around 2°C above pre-industrial. Climate models generally under-predict the observed loss of Arctic sea-ice. Bearing this in mind, the CMIP5 ensemble still predicts near summer ice free conditions under RCP4.5 (corresponding to ~3°C warming above pre-industrial) and total summer ice loss in RCP8.5. Thus we can expect summer Arctic sea-ice loss under any 4°C and 6°C global warming scenarios, and it may occur under 2°C warming. The loss of Arctic winter sea-ice occurs in 7 of 9 models under the RCP8.5 extended forcing, typically occurring in the 22nd century when global warming is in the range 4-8°C (Hezel et al., 2014). Hence we can consider this a potential tipping point under a 6°C warming scenario.

In East Antarctica recent work suggest that the 3-4 m global sea level rise equivalent of ice in the Wilkes Basin could be threatened by peak warming of around 3°C (corresponding to future emissions of 1000 GtC) (Winkelmann et al., 2015). Furthermore, only a 2°C scenario can prevent long-term sea-level rise of order 10 m. In a different recent model study the Wilkes Basin is threatened by RCP8.5 forcing (Golledge et al., 2015).

To pass the tipping point for Yedoma permafrost breakdown requires an estimated >9°C of regional warming (Khvorostyanov et al., 2008a), but this is a region already experiencing strongly amplified warming, partly linked to shrinkage of the Arctic sea-ice. Hence Yedoma could be threatened under a 4°C global warming scenario and would be threatened under 6°C global warming scenarios.

Summary by scenario

A summary of the likelihood of different tipping points under 2°C, 4°C, 6°C warming scenarios on a time horizon out to the year 2200 is given in Table 8. Here we adopt the IPCC likelihood scale where in probability terms, virtually certain = 0.99-1, very likely = 0.9-1, likely = 0.66-1, about as likely as not = 0.33-0.66, unlikely = 0-0.33, very unlikely = 0-0.1, exceptionally unlikely = 0-0.01. The summary highlights that under a 2°C warming scenario most individual tipping points remain unlikely, but the joint probability of at least one tipping point occurring is about as likely as not this century and becomes likely by 2200. Under a 4°C (stabilised) warming scenario several tipping points become likely and the joint probability of at least one tipping point occurring becomes likely this century and virtually certain by 2200. Under a 6°C (stabilised) warming scenario all tipping points become at least as likely as not by 2200, and their combined likelihood correspondingly increases.

5. Potential for adaptation to reduce impacts

There has been very little work on the potential for adaptation to reduce the impacts of passing climate tipping points, with the exception of scenarios for high magnitudes and rates of sea-level rise. Here we offer some general consideration of the issues that need to considered, then turn to the specific example of sea level rise, before considering other types of tipping point impact.

General considerations

In general, tipping point impacts are expected to be larger, to unfold faster, and to be harder to reverse, than other climate change impacts. For all these reasons they will pose a greater adaptation challenge. At the same time their perceived magnitude and irreversibility may provoke more pre-emptive (and therefore effective) adaptation action. Regarding timescales, the later we cross any tipping point, the more time this gives us to adapt, provided we act pre-emptively. Also, the slower that tipping point impacts unfold, even if they are irreversible, the greater the potential to adapt. Conversely, faster accumulation of impacts challenges adaptation capacity, and if the costs of response increase more quickly than available resources, then society will have fewer and fewer options as time passes (Huntington et al., 2012). Ultimately some things simply cannot be adapted to – there are limits to adaptation – and for any given adaptation strategy it is usually possible to identify an "adaptation tipping point" (Kwadijk et al., 2010). The idea here is to consider a particular adaptation strategy and ask "how much change can it cope with?" thus identifying where a particular strategy fails (Kwadijk et al., 2010). The resulting interaction between climate tipping points leading to the crossing of adaptation tipping points is largely unexplored.

Some economic work on adaptation strategies uses an optimising cost-benefit analysis framework, which assumes perfectly rational decision making by a 'social planner', and instantaneous implementation of adaptation options. In such a perfect rationality framework, whenever adaptation is cheaper than the damages avoided it will be the chosen option and be decisively implemented. Reality of course is not like this, leading inevitably to imperfect adaptation. There are lags in real systems. Institutions don't respond perfectly, raising capital can be hard for up-front expensive adaptation actions, even if they pay back in a long-run cost-benefit analysis. More generally, the financial and institutional capacity to adapt ('adaptive capacity') may simply not be there in some regions and social contexts. Tipping point impacts generally challenge adaptive capacity more than baseline climate change.

Accelerated sea level rise

The one aspect of tipping point impacts for which adaptation options have been explicitly considered are fairly large magnitudes and accelerated rates of sea level rise stemming from the collapse of major ice sheets. The FUND model has been used to consider scenarios involving a globally-uniform 5 metre rise in sea level, taking at a minimum 100 years, i.e. a rate of up to 5 m/century (Nicholls et al., 2008). Subsequent work by the same group considered the impacts of a more modest and widely accepted upper limit of 2 m sea level rise on the 21st century time scale (Nicholls et al., 2011). The FUND model assumes perfect (i.e. optimal) adaptation action based on cost-benefit analysis – in other words, wherever the cost of building coastal protection is less than the expected losses, there is instantaneous action to build that protection. Hence even in a 5 m/century sea level rise scenario, high levels of coastal protection are predicted around low-lying population centres, which massively reduce the number of people exposed to flooding to around 2-3% of the 400 million that live within 5 m of sea level. However, in reality, 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 than coastal protection (Lonsdale et al., 2008; Olsthoorn et al., 2008). Thus imperfect adaptation could greatly increase the economic damages from tipping point sea level rise scenarios.

Consideration of high levels of sea level rise originally led to the concept of “adaptation tipping points” (Kwadijk et al., 2010). For the example of sea level rise in the Netherlands it was identified that the current protection of Rotterdam Harbour can only cope with up to 0.5 m sea-level rise, which could be reached in 2050 in a climate tipping point scenario, and drinking water supply can only cope with a 0.35 m sea-level rise, which could be reached as early as 2030. Clearly new adaptation strategies can be deployed, such as the building up of additional sea defences discussed above. However, these strategies also have limits, for example, in the Thames estuary it would become difficult to protect London at a sea-level rise of 5 m (Reeder and Ranger, 2011). Although 5 m of sea-level rise just from WAIS collapse is unrealistic, it could be exceeded just from GIS meltdown, and could readily be exceeded from collapse of parts of East Antarctica. Under extreme scenarios the combined sea level rise from East and West Antarctica could approach 3 m/century in the coming centuries and the total sea level rise could exceed 10 m on the millennial timescale and ultimately reach 50 m (Winkelmann et al., 2015). Thus either GIS meltdown and/or ice loss from Antarctica would ultimately cause adaptation tipping points to be passed requiring managed retreat from major coastal megacities.

There is an interesting potential trade-off between investment in mitigation and adaptation options in response to tipping point threats. In a simple economic model of a WAIS collapse scenario, as soon as the WAIS is tipped (and this is assumed irreversible), emissions reduction investments falls to free up resource to prepare for adapting to the inevitable (Guillerminet and Tol, 2008).

Adaptation to other climate tipping point impacts

A key dimension of crossing some climate tipping points, notably AMOC collapse, is that they will change the spatial pattern of climate change and the resulting impacts. This includes the possibility that in some regions there is even a reversal of the sign of change from warming to cooling, and (on a broader geographic scale) between wetting and drying trends. Thus, existing adaptation strategies predicated on a particular sign of environmental change may become unfit for purpose and possibly even maladaptive. The same issue could arise on a regional scale with disruption of monsoon systems. For example, the short-term forecast for the South Asian monsoon is a weakening of rainfall, but with long-term warming the monsoon is expected to strengthen. In contrast, an increase in ENSO amplitude represents an example of amplifying an existing pattern of change, where the challenge becomes building adaptive capacity for the resulting intensification of extreme events.

Regarding the potential loss of major ecosystems, there is some scope for adaptation to function like mitigation and reduce the likelihood of a tipping point transition, for example through managing human intervention in fire regimes in forest ecosystems. The threat of dieback for the Amazon rainforest comes from a combination of climate change and deliberate deforestation interacting through fire (Golding and Betts, 2008). Hence policies to reduce deforestation could be viewed as one form of adaptation to help avoid this tipping point. In the boreal forest of Alaska, fire frequency is increasing and there is some active management of fires in more populated areas which if expanded could help counteract the transition away from black spruce forest (Huntington et al., 2012). However, the resource to increase wildfire management is limited and this financial limit is likely to mean the transition to a different vegetation type continues (Huntington et al., 2012).

Relationship to early warning potential

The previous deliverable from this HELIX work package demonstrated the potential for early warning of at least some climate tipping points. Such early warning, if realised in practice, is envisaged partly as a spur to mitigation action but primarily as an aid to adaptation to reduce the impacts of tipping points, even if they cannot be avoided. Here the idea is that pre-emptive adaptation action would be taken, at least in some cases, to reduce the impacts of a forthcoming tipping point. Of course another possibility is that successful early warning of the distance of an approaching tipping point might be used as a trigger to delay action. Equally there are some tipping points for which we might not want to wait to get an early warning signal, perhaps because it would be too late to act effectively, or perhaps because pre-emptive adaptation is a no regrets option anyway.

Clearly the capacity for early warning of a tipping point (or lack of it) has the potential to influence the choice and timing of adaptation options. To sharpen up these considerations we need to think about the timescale over which particular systems could be tipped, the timescale of early warning that might be provided, the timescale of transition over which their impacts unfold, and the timescale of implementing adaptation actions. Across the set of tipping points, much of this information is missing. However, we can consider the balance of timescales for at least one well studied tipping event – AMOC collapse. We have shown that a statistically robust early warning signal of approaching AMOC collapse could be present up to 200 years in advance (Boulton et al., 2014). AMOC collapse is currently deemed unlikely on the timescale of the next 200 years, except under the highest warming scenarios (Table 8). Therefore there is in principle plenty of time for pre-emptive adaptation. In contrast, paleo-data cautions that an AMOC transition once underway could happen in as little as 10 years. If so, waiting to adapt until tipping is underway could close out several adaptation options. The rational course of action in this case, when faced with an early warning signal, would be pre-emptive adaptation, assuming the benefits of that adaptation would outweigh the costs.

Summary

We have characterised the biophysical impacts of passing different climate tipping points, considered how to translate them into social impacts and economic costs, assessed which tipping points could be passed under 2°C, 4°C and 6°C warming scenarios, and considered to what degree can the impacts of tipping points be ameliorated by adaptation. One key take home message is that under 4°C and 6°C warming scenarios tipping points become likely if not certain, their impacts are expected to be large, and not all of them can be adapted to. Even under a 2°C warming scenario, some tipping points with significant impacts need to be considered together with our capacity to adapt to them. Clearly there is a massive need for further research as the scientific community has barely begun to quantify the impacts of passing climate tipping points, and it needs in part to develop a new set of tools to undertake this important exercise.

Tables

Table 1 – Tipping elements and their potential tipping point considered herein

Label	Tipping element	Tipping point scenario(s)	Brief description
Tipping points in the original list (Lenton et al., 2008) and expert elicitation (Kriegler et al., 2009)			
AMOC	Atlantic Meridional Overturning Circulation	Collapse of the AMOC	Shutdown of Labrador Sea convection and >80% reduction in deep water overflow across the Greenland-Scotland ridge
GIS	Greenland Ice Sheet	Meltdown of the GIS	Excess of melting and discharge over accumulation and altitude-melt feedback lead eventually to a nearly ice-free state
WAIS	West Antarctic Ice Sheet	Disintegration of the WAIS	Grounding line retreat and altitude-melt feedback leads to ice sheet loss
ENSO	El Niño Southern Oscillation	ENSO amplification	Increase in the amplitude of ENSO variability including more frequent extreme El Niño and extreme La Niña events
AMAZ	Amazon rainforest	Dieback of the Amazon rainforest	Regional drying and vegetation-water cycle and vegetation-fire feedbacks lead to widespread dieback (at least 50% loss of rainforest)
BOFO	Boreal forest	Dieback of boreal forests	Regional summer warming, insect pests and fires lead to widespread dieback (at least 50% loss of boreal forest)
Tipping points in the original list (Lenton et al., 2008) but not the expert elicitation			
SAM	South Asian Monsoon	Disruption of the SAM	Aerosol pollution leads to reduction in rainfall and doubling of drought frequency
WAM	West African Monsoon	Collapse of the WAM	Warming in the Gulf of Guinea leads to locking of monsoon rainfall to the West African coast, starving the Sahel of rainfall
ASI	Arctic sea-ice	Rapid summer sea-ice loss	Rapid (but reversible) loss of Arctic summer sea-ice
Tipping points considered here in additional to the original list			
ASI	Arctic sea-ice	Abrupt winter sea-ice loss	Irreversible loss of year-round Arctic sea-ice
EAIS	East Antarctic ice sheet	Partial disintegration	Removal of ice plug and grounding line retreat leads to drainage of ice from Wilkes Basin
Yedoma	Yedoma permafrost	Runaway breakdown	Self-sustaining breakdown of Yedoma due to biochemical heat release

Table 2 – Potential physical impacts of passing different climate tipping points, updated from (Lenton and Ciscar, 2013).

Tipping event	Temperature	Sea level	Precipitation	Atmospheric circulation	Ocean circulation	Biogeochem-ical cycles	Modes of variability	Extreme events
AMOC collapse	↓N. Atlantic ↑S. Hem.	Regional shifts ↑0.5m 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?
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	?	Iceberg armadas storm surges
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
Amazon rainforest dieback	↑regional	-	↓regional	Walker circulation?	-	↑CO_2	Feedback to ENSO?	Droughts, fires, loss biodiversity
Boreal forest dieback	↓winter ↑summer	-	↓regional?	Regional effects?	-	↑CO_2	-	Fires, insect pests, biome loss
South Asian monsoon (SAM) disruption	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
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

NAO = North Atlantic Oscillation, AMO = Atlantic Multi-decadal Oscillation, PDO = Pacific Decadal Oscillation, SO = Southern Oscillation

Table 3 – Mapping from sectoral impacts to economic variables (Lenton and Ciscar, 2013)

		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

Table 4 – Hazard rates and tipping probabilities for five tipping events under different scenarios

Tipping Element	Hazard rate, h (/yr/K)	Probability of tipping at specific warming levels			Probability of tipping in 2100 for particular warming scenarios				
		2°C in 2040	4°C in 2070	6°C in 2080	2°C then stabilise	4°C then stabilise	4°C then rise	6°C then stabilise	6°C then rise
AMOC	0.00063	0.008	0.052	0.102	0.046	0.109	0.124	0.165	0.174
GIS	0.00188	0.024	0.155	0.306	0.136	0.324	0.370	0.494	0.520
WAIS	0.00104	0.013	0.086	0.169	0.075	0.179	0.205	0.273	0.288
ENSO	0.00053	0.007	0.044	0.086	0.038	0.091	0.104	0.139	0.147
AMAZ	0.00163	0.020	0.135	0.265	0.118	0.281	0.321	0.428	0.451
any of 5		0.070	0.394	0.652	0.354	0.677	0.734	0.849	0.868

Table 5 – Probabilities of five tipping events under different stabilisation scenarios

Tipping Element	Probability of tipping at particular times under different stabilisation scenarios											
	2°C then stabilise				4°C then stabilise				6°C then stabilise			
	2050	2100	2150	2200	2050	2100	2150	2200	2050	2100	2150	2200
AMOC	0.014	0.046	0.077	0.109	0.021	0.109	0.203	0.298	0.030	0.165	0.323	0.480
GIS	0.042	0.136	0.230	0.324	0.063	0.324	0.606	0.888	0.088	0.494	0.964	1
WAIS	0.023	0.075	0.127	0.179	0.035	0.179	0.335	0.491	0.049	0.273	0.533	0.793
ENSO	0.012	0.038	0.065	0.091	0.018	0.091	0.171	0.250	0.025	0.139	0.272	0.404
AMAZ	0.037	0.118	0.200	0.281	0.055	0.281	0.526	0.770	0.077	0.428	0.835	1
any of 5	0.122	0.354	0.536	0.677	0.178	0.677	0.918	0.993	0.242	0.849	0.999	1

Table 6 – Probabilities of five tipping events under different ongoing warming scenarios

Tipping Element	Probability of tipping at particular times under different ongoing warming scenarios							
	4°C then linear rise				6°C then linear rise			
	2050	2100	2150	2200	2050	2100	2150	2200
AMOC	0.021	0.124	0.313	0.588	0.030	0.174	0.440	0.826
GIS	0.063	0.370	0.934	1	0.088	0.520	1	1
WAIS	0.035	0.205	0.517	0.971	0.049	0.288	0.726	1
ENSO	0.018	0.104	0.263	0.495	0.025	0.147	0.370	0.695
AMAZ	0.055	0.321	0.810	1	0.077	0.451	1	1
any of 5	0.178	0.734	0.997	1	0.242	0.868	1	1

Table 7 – The time when each tipping event becomes inevitable (p=1) for each of the scenarios

Tipping Element	2°C then stabilise	4°C then stabilise	4°C then linear rise	6°C then stabilise	6°C then linear rise
AMOC	3615	2572	2256	2365	2218
GIS	2559	2220	2155	2154	2133
WAIS	2989	2363	2203	2240	2173
ENSO	3914	2671	2278	2425	2237
AMAZ	2641	2247	2165	2170	2141

Table 8 – Summary of tipping point likelihoods under different scenarios

Tipping element	2°C stabilisation scenario		4°C stabilisation scenario		6°C stabilisation scenario	
	Likelihoods quantified from expert elicitation derived hazard rates*					
Year	2100	2200	2100	2200	2100	2200
AMOC	Very unlikely	Unlikely	Unlikely	Unlikely	Unlikely	About as likely as not
GIS	Unlikely	Unlikely	Unlikely	Likely	About as likely as not	Virtually certain
WAIS	Very unlikely	Unlikely	Unlikely	About as likely as not	Unlikely	Likely
ENSO	Very unlikely	Very unlikely	Very unlikely	Unlikely	Unlikely	About as likely as not
AMAZ	Unlikely	Unlikely	Unlikely	Likely	About as likely as not	Virtually certain
(any of 5)	About as likely as not	Likely	Likely	Virtually certain	Likely	Virtually certain
	Subjective judgement of likelihoods based on literature review*					
Year	2200		2200		2200	
Boreal forest	Unlikely		Likely		Very likely	
W African Monsoon	Unlikely		About as likely as not		Likely	
Arctic ice summer	About as likely as not		Very likely		Virtually certain	
Arctic ice winter	Exceptionally unlikely		Unlikely		Likely	
EAIS (Wilkes)	Unlikely		Likely		Virtually certain	
Yedoma permafrost	Very unlikely		Unlikely		Likely	

*Here we adopt the IPCC likelihood scale where in probability terms, virtually certain = 0.99-1, very likely = 0.9-1, likely = 0.66-1, about as likely as not = 0.33-0.66, unlikely = 0-0.33, very unlikely = 0-0.1, exceptionally unlikely = 0-0.01.

Figures

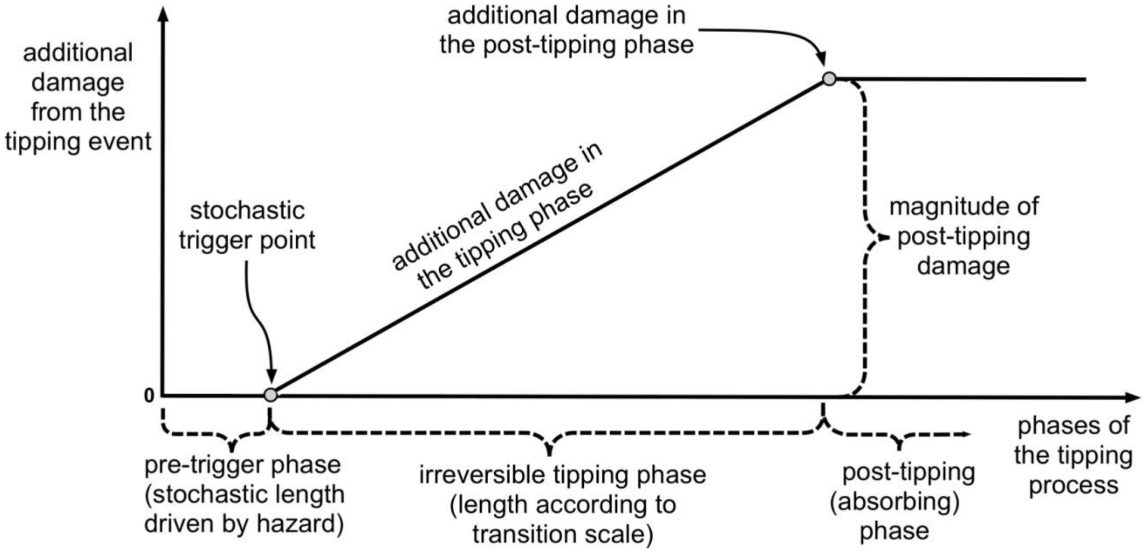

Figure 1 – A schematic of the accumulation of impacts over a transition time, after the passing of a tipping point, showing how the process is represented in the Dynamic-Stochastic Integrated Climate-Economy (DSICE) model (Lontzek et al., 2015).

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