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D10.4 Development of adaptation responses and assessment of the limits of adaptations for climate tipping points

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Executive Summary

In this Deliverable we make a first assessment of potential adaptation responses to climate tipping points and the corresponding limits to adaptation. Key points are that:

Framework for considering adaptation responses: passing climate tipping points can affect adaptation responses by changing the magnitude, timing and rate of impacts, the persistence and reversibility of impacts, and in some cases the sign of impacts (i.e. the direction of environmental change). Whilst previous work emphasised the challenge of adapting to tipping points in the direction of environmental change, we explore the adaptation challenges of this broader range of tipping point impacts, highlighting where they force abrupt changes in adaptation strategy (sometimes called 'adaptation tipping points').

Physical impacts of passing different climate tipping points: we assess and summarise the physical effects of passing ten different climate tipping points: Arctic sea-ice loss, Greenland ice sheet meltdown, West and East Antarctic ice sheet instability, Atlantic meridional overturning circulation collapse, ENSO increase in amplitude, Indian summer monsoon weakening, West African monsoon collapse, Amazon rainforest dieback, boreal forest dieback, drying of southwest North America.

Translating physical impacts into economic impacts: we consider how the physical impacts of passing climate tipping points can be translated into economic impacts, making a specific case study of how the heat-stress related impacts on production of abrupt Arctic sea-ice loss would cascade through the global economy (utilising a newly developed model; 'ACCLIMATE'). We find a heterogeneous pattern of first-order effects on production – with some countries suffering and some benefiting – and a quite different pattern of higher-order effects occurring through supply chains. The cascading higher-order effects represent about a third of the overall effects on production.

Adaptation responses (including limits to adaptation): we consider adaptation responses to climate tipping points in more detail by making two further case studies in the focal region of West Africa, involving migration as an adaptation response, either to abrupt drying (West African monsoon collapse) or to accelerated sea-level rise (due to passing ice sheet tipping points). These case studies consider the vulnerability and exposure of relevant populations and their adaptive capacity to respond to the impacts of passing climate tipping points, particularly through temporary or more permanent of migration.

Summary/Conclusion: We conclude that as well as there being tipping points in the climate system, adaptation may have its own tipping points – including abrupt failures of particular adaptation strategies (limits to adaptation) and abrupt uptake of other strategies (e.g. triggering of widespread migration).

1. Introduction

The point of adaptation is to reduce the potentially dangerous impacts of climate change. However, passing climate tipping points may limit the risk-reducing potential of planned adaptation and could cause limits to adaptation to be exceeded. This deliverable explores adaptation responses to the passing of climate tipping points and corresponding limits to adaptation. Section 2 introduces a framework for considering adaptation responses to climate tipping points, which builds on existing literature and established adaptation frameworks. Section 3 then surveys the physical effects of passing different climate tipping points, building on Deliverable D10.2. Section 4 considers how the physical impacts of passing climate tipping points can be translated into economic impacts, and in particular how those economic impacts may cascade through a globalised economy – making a specific case study of the impacts of Arctic sea-ice loss. As well as the physical effects of passing climate tipping points, assessment of adaptation responses must also consider the exposure of populations to these physical impacts, and their capacity to respond in a way that reduces the biological or social impacts – i.e. their adaptive capacity. Hence Section 5 considers adaptation responses to climate tipping points in more detail, with two further case studies in the focal region of West Africa, involving migration as an adaptation response, either to abrupt drying (West African monsoon collapse) or to accelerated sea-level rise (due to passing ice sheet tipping points).

2. Framework for considering adaptation responses

The IPCC has identified several criteria from the literature that may be used to identify key vulnerabilities to climate change (Schneider et al. 2007): magnitude of impacts, timing of impacts, persistence and reversibility of impacts, likelihood (estimates of uncertainty) of impacts and vulnerabilities and confidence in those estimates, potential for adaptation, distributional aspects of impacts and vulnerabilities, importance of the system(s) at risk. Here we are particularly concerned with climate tipping points and the potential for adaptation to reduce their impacts. In that context, passing climate tipping points can change the magnitude of impacts, the timing of impacts (with the magnitude and timing jointly determining the rate at which impacts accumulate), the persistence and reversibility of impacts, and also the sign of impacts (i.e. the direction of environmental change). For example, tipping a collapse of Greenland or Antarctic ice sheets can greatly increase the eventual magnitude of sea-level rise as well as its timing (and therefore the rate of sea-level rise), and it can make sea-level rise even more difficult to reverse than it already is. As another example, a collapse of the Atlantic Meridional Overturning Circulation (AMOC) could change the direction of climate change regionally, from a warming to a cooling over northwest Europe.

Hulme (2003) argued that if abrupt climate change simply implies changes in the occurrence of extreme weather events, or an accelerated unidirectional change in climate, then the design of adaptation responses can proceed within the existing paradigm, with appropriate adjustments. He acknowledged that *limits to adaptation* in some sectors or regions may be reached, and that costs of adaptation may be large, but argued that strategy can be developed on the basis of a predicted long-term unidirectional change in climate. He argued that abrupt climate change would be more challenging if it implied a *directional* change in climate, using the example of the effect of a collapse of the Atlantic Meridional Overturning Circulation (AMOC) on temperatures in northwest Europe (switching a warming trend to a cooling trend). The fundamental problems with such an outcome are that the future changes in climate being prepared for may be reversed with an essentially unknown probability. Persistence and (ir)reversibility of impacts were not considered as a particular adaptation challenge by Hulme (2003). Here we revisit his argument, opening it out to a wider range of climate tipping point scenarios, and considering *limits to adaptation* in the face of climate tipping points.

It is important to be clear at the outset that 'tipping points' may occur in biological systems and human social systems as well as in the physical climate system. Indeed the concept of a 'tipping point' originally came from the social sciences, specifically the study of racially-segregated neighbourhoods in US cities and associated positive feedbacks in migration dynamics (Grodzins 1957). Here our entry point is a focus on adaptation to climate tipping points, but they in turn may conceivably trigger biological or social tipping points. Indeed the concept of limits to adaptation implies some kind of threshold response and non-linearity where a particular adaptation strategy fails and/or a switch to an alternative strategy becomes optimal.

In the adaptation of non-human biological populations there are clear thresholds and potential 'tipping points'. Notably other species show clear geographic range limits with relatively sharp edges even along smooth environmental gradients. Thus even smooth changes in climate are expected to cause threshold changes in species and populations – indeed this is the basis of climate envelope modelling and associated predictions of future species loss. The limits to biological adaptation along environmental gradients can be understood quantitatively in terms of genetic drift from the geographic core of a population to the periphery preventing genetic variance reaching the level needed for successful adaptation to spatially variable conditions (Polechová and Barton 2015). More broadly, the concept of *evolutionary tipping points* has been introduced (Botero et al. 2015). This theory recognises that there are multiple adaptive strategies for coping with environmental change which may be optimal, depending on the timescale of environmental variation and the predictability of environmental change. The timescale and predictability of environmental change form a 'phase space' in which there are sharp boundaries between adaptive strategies (the evolutionary tipping points) forming a 'phase diagram'. Thus if a species or population following one strategy crosses a phase boundary where a different strategy becomes optimal the result is often a dramatic reduction in population viability.

In the realm of human adaptation to climate change, the concept of 'adaptation tipping points' – where one adaptation strategy that is being followed ceases to be effective and a switch to an alternative strategy is needed – has already been introduced (Kwadijk et al. 2010). This is the direct corollary of 'evolutionary tipping points' (Botero et al. 2015), with the important distinction that it should be easier for humans to change adaptation strategy than for populations subject to natural selection to do so. The distinguishing feature of the 'adaptation tipping points' approach is that it starts by asking "how much change can we cope with (with a particular adaptation strategy)?" An example is sea level rise where building up sea defences is only viable up to a certain amount of sea level rise (Kwadijk et al. 2010). This is pertinent because it has long been recognised that passing physical climate tipping points for the disintegration of major ice sheets can greatly increase the magnitude and rate of sea-level rise.

There is a much broader, largely qualitative, discourse about limits to human adaptation to climate change, to what degree they are physical or social in nature, and how they should be assessed. Given that humans are organisms and depend on other living things, most notably for food, then there must be some influence of biological limits to adaptation on human limits to adaptation. Unless we can imagine feeding a projected >9 billion people with food grown in air-conditioned greenhouses then the physiological effects of climate change on cultivated and domesticated organisms as well as their human farmers, can present real physical limits to adaptation. Nevertheless in a social, at least partially globalised, market system, food can be grown in new places and redistributed making the limits to adaptation more economic and technological than physical. A popular social science argument goes further and argues that limits to adaptation are endogenous to society and hence contingent on ethics, knowledge, attitudes to risk, and culture (Adger et al. 2009). Whilst there is clearly a truth to this it is also true that real biological, technological and economic limits to adaptation can play an important role.

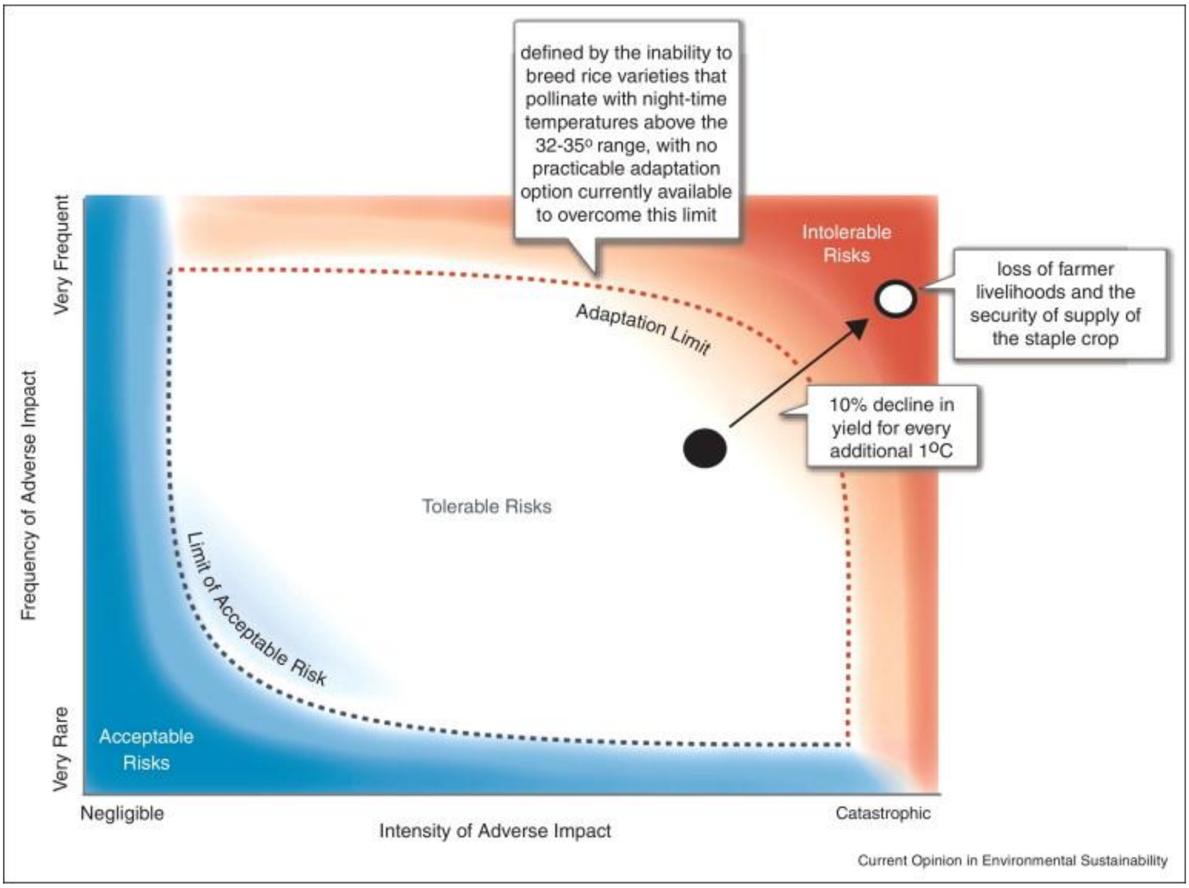


Figure 1: An adaptation limit to rice cultivation (Dow, Berkhout and Preston 2013)

The IPCC Fifth Assessment Report (AR5) adopted an 'actor-centred' risk-based approach to limits to adaptation, which in a qualitative way tries to provide a framework for considering adaptation responses and limits thereof (Dow, Berkhout and Preston 2013; Dow et al. 2013). This recognises real physical limits to adaptation, as well as social limits, as shown in the example of rice cultivation (Figure 1).

Onto such an approach can be overlaid the recognition that adaptation is likely to be imperfect, whereas standard cost-benefit economic analyses usually assume perfect adaptation. An extreme example scenario is that of a 5 metre per century sea level rise (Nicholls, Tol and Vafeidis 2008), due to passing ice sheet tipping points – which stretches the bounds of physical plausibility this century (Lenton and Ciscar 2013), but might be realised in the 22nd century under an RCP8.5 scenario of

Antarctic ice sheet collapse (DeConto and Pollard 2016). A cost-benefit analysis with the FUND 2.8n integrated assessment model (Nicholls, Tol and Vafeidis 2008), assuming perfect (i.e. optimal) adaptation action, predicts high levels of coastal protection around low-lying population centres, which massively reduces the number of people exposed to flooding to around 2-3% of the 400 million that live within 5 metres of sea level. This comes at considerable cost, but one that is less than the cost of abandonment. Meanwhile large (but thinly populated) areas of agricultural land, boreal forest, and tundra are abandoned to rising seas. However, case studies of the Netherlands and the Thames Estuary with the same 5 metre per century driving scenario, suggest that imperfect adaptation, e.g. due to delays in policy implementation, makes abandonment a more likely outcome (Lonsdale et al. 2008; Olsthoorn et al. 2008).

3. Physical impacts of passing different climate tipping points

The physical impacts of passing the nine tipping points originally identified (Lenton et al. 2008) and one additional one (abrupt drying of southwest North America), are summarised in Table 1. Here we provide additional discussion and pointers to the literature on these impacts (Lenton 2012):

Arctic sea-ice loss: 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..." There are two stages to Arctic sea-ice loss; (i) summer sea-ice loss which is non-linear but is thought to be reversible, and (ii) winter (year-round) sea-ice loss which is expected to be more abrupt and more difficult to reverse. Observed impacts of Arctic sea-ice loss already include amplified Arctic warming (Screen and Simmonds 2010), a shift from snowfall to rainfall (Screen and Simmonds 2011) and large-scale changes in atmospheric circulation (Overland and Wang 2010). Warm Atlantic waters are intruding into the Arctic and contributing to ice melt (Spielhagen et al. 2011). Loss of sea ice is accelerating warming of Arctic land surfaces and contributing to permafrost thawing (Lawrence et al. 2008). 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), although other studies argue that Arctic sea-ice loss has decreased temperature variance in mid-latitudes (Screen 2014). Projections of winter Arctic sea-ice loss (Deliverables D10.2, D3.3) show a warming effect that extends to large areas of the mid-latitudes of N America and Eurasia particularly in Winter and Spring, but also to some degree in Summer. In Section 4 we consider how the impacts of this cascade through the global economy.

Greenland ice sheet meltdown: Greenland could ultimately contribute ~7m to global sea-level rise, with a maximum of 50 cm this century (Pfeffer, Harper and O'Neel 2008), although a state-of-the-art estimate is only 4.5 cm this century (Price et al. 2011). The amount by which a Greenland tipping point is passed is expected to affect the rate of melt and hence sea-level rise (Huybrechts and De Wolde 1999). The sea-level rise from melting large ice sheets will not be globally uniform because of gravitational adjustment; it will be smallest nearest the ice sheet that is being lost and greatest on the opposite side of the planet (Mitrovica et al. 2001; Mitrovica, Gomez and Clark 2009). Melt water from Greenland could have a small effect of weakening the Atlantic meridional overturning circulation (AMOC) (Jungclaus et al. 2006; Driesschaert et al. 2007). In the long run, losing the ice sheet would affect patterns of atmospheric circulation in the Northern Hemisphere, and would 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). Flooding of low lying land due to sea-level rise would release carbon to the atmosphere, although this would be partially offset by greening of Greenland itself. During ice-sheet melt, flotillas of icebergs may become an issue in the northernmost Atlantic. Rising sea-level will increase the risk from storm surges (Tebaldi, Strauss and Zervas 2012).

West and East Antarctic ice sheet instability: The parts of West Antarctica grounded below sea-level are vulnerable to marine ice sheet instability and can ultimately contribute ~3 m to global sea-level rise (Bamber et al. 2009). More recently it has been recognised that parts of East Antarctica grounded below sea-level are also vulnerable and could contribute up to ~14 m to global sea-level, with the Wilkes Basin known to be particularly vulnerable with the potential to raise sea-level by ~3-4 m (Mengel and Levermann 2014). Antarctica as a whole could potentially contribute >1 m to sea-level this century (DeConto and Pollard 2016), greater than a previously estimated maximum contribution of ~60 cm this century (Pfeffer, Harper and O'Neel 2008), because outlet glaciers are less constrained by topography than assumed (Levermann et al. 2012). Furthermore, Antarctica could potentially contribute >15 m to global sea-level by 2500 (DeConto and Pollard 2016) with maximum rates of sea-level rise up to 5 m per century (Winkelmann et al. 2015; DeConto and Pollard 2016). Ultimately the entire Antarctic ice sheet containing ~58 m global sea-level rise could be vulnerable to extreme fossil fuel emissions (Winkelmann et al. 2015). As well as the direct threat of sea-level rise to people in low-lying settlements, the resulting flooding would include extensive regions of permafrost in the Arctic, releasing methane and carbon dioxide. During ice sheet collapse armadas of icebergs would head into the Southern Ocean.

Atlantic meridional overturning circulation (AMOC) collapse: Several studies have looked at the impacts of a collapse of the Atlantic meridional overturning circulation (Schwartz and Randall 2003; Link and Tol 2004; Arnell et al. 2005; Kuhlbrodt et al. 2009; Lenton, Footitt and Dlugolecki 2009; Link and Tol 2011; Anthoff, Estrada and Tol 2016), which are typically viewed as catastrophic, potentially causing a 25% reduction in global GDP equivalent to the Great Depression (Nordhaus 1994). One group argues it could have a net economic benefit (Link and Tol 2004; Link and Tol 2011; Anthoff, Estrada and Tol 2016), but this is based only on the effects of AMOC weakening on country-wide mean annual temperature in scenarios where it slows (rather than reverses) temperature rise (Anthoff, Estrada and Tol 2016). However, as Hulme (2003) recognised, a full collapse of the AMOC could reverse a warming trend into a cooling trend in some countries posing a major adaptation challenge. Furthermore, the impacts of AMOC collapse are quite seasonal and extend to many more variables, as explored in Deliverable D10.2 with simulations from the state-of-the-art HadGEM3 model (Jackson et al. 2015), building on earlier work with the HadCM3 model (Vellinga and Wood 2002; Vellinga and Wood 2008). Winters in NW Europe experience the greatest cooling and strengthening of westerly winds. Globally the inter-tropical convergence zone (ITCZ) shifts southward, which in HadGEM3 markedly dries the Amazon and halves the strength of the Indian summer monsoon. Sea-level is also expected to readjust in height increasing by up to ~1m in parts of the North Atlantic region (Levermann et al. 2005). Before a full AMOC collapse, a switch of the sub-polar gyre of 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) (Levermann and Born 2007; Born and Levermann 2010), could increase sea level down the eastern seaboard of the USA by around 25 cm in the regions of Boston, New York and Washington DC (Yin, Schlesinger and Stouffer 2009). AMOC collapse would also remove a major mode of variability in the climate system – the Atlantic Multi-decadal Oscillation (AMO) – and in HadGEM3 it causes a weakening and increase in frequency of ENSO variability (Deliverable D10.2). In terms of extreme events, winter storms would be more violent in NW Europe (Jackson et al. 2015), and a southward shift of warm waters in the equatorial Atlantic would be expected to move hurricanes southward.

ENSO increase in amplitude: An increase in El Niño amplitude with more extreme El Niño and La Nina events has been projected in future (Cai et al. 2014; Cai et al. 2015). This could have severe impacts in many regions, which can be assessed using the known impacts of current ENSO variability on e.g. agriculture (Meza, Hansen and Osgood 2008) and health (Patz et al. 2005). El Niño increases temperature in the tropics and decreases precipitation, reducing tropical cereal yields, cereal production and agricultural value added (Hsiang and Meng 2015). In the temperate regions the opposite effects are observed partly due to global market adjustments (Hsiang and Meng 2015). El Niño has also been associated with increased human conflict (Hsiang, Meng and Cane 2011; Hsiang, Burke and Miguel 2013).

Indian summer monsoon (ISM) weakening: The Indian summer monsoon is prone to directional changes: It has already been weakened by localised aerosol pollution forming 'atmospheric brown clouds' (Ramanathan et al. 2005; Zickfeld et al. 2005; Meehl, Arblaster and Collins 2008; Ramanathan and Carmichael 2008; Lau and Kim 2010), and by land-use changes (Paul et al. 2016), but it is expected to be strengthened by global warming (Zickfeld et al. 2005; Schewe, Levermann and Meinshausen 2011). Palaeo-records also indicate flips on and off of monsoonal rainfall linked to climate changes in the North Atlantic (Burns et al. 2003; Gupta, Anderson and Overpeck 2003; Goswami et al. 2006). Impacts on agriculture are a key future concern and have already been observed (Auffhammer, Ramanathan and Vincent 2006). Monsoon variation has an asymmetric effect on GDP and grain production with rainfall deficits having a larger effect than surpluses, and the impact of droughts remaining at 2-5% of GDP despite a declining contribution of agriculture to GDP (Gadgil and Gadgil 2006). If abrupt monsoon weakening occurs in future, for example linked to weakening of the AMOC, it could cause high damages (Lenton, Footitt and Dlugolecki 2009).

West African monsoon (WAM) collapse: The West African Monsoon is also a system that is prone to changes in the direction of change, with the 1960s-1980s drought, linked to sulphate aerosol pollution cooling the North Atlantic (Rotstatyn and Lohmann 2002), having followed several decades of strengthening rainfall, and weakening of the AMOC having the potential to tip a future southward shift of the West African Monsoon (Hagos and Cook 2007; Chang et al. 2008; Shanahan et al. 2009), causing a large reduction in rainfall in the Sahel and an increase in the Gulf of Guinea and coastal regions. Collapse of the WAM would have severe impacts on agricultural production which involves ~70% of people in the Sahel. Human migration is correlated with past WAM variability, right back to prehistory and the departure of early hominins from Africa (Castañeda et al. 2009). In Section 5 we consider a case study of the potential impacts in Burkina Faso.

Amazon rainforest dieback: The impacts of Amazon dieback would include amplification of regional warming and precipitation decline (Betts et al. 2004), loss of carbon to the atmosphere (Cox et al. 2000), and increased fire frequency (Cochrane and Barber 2009). The 2005 Amazon drought was associated with increased wildfire, interrupted river navigation and trade, decreased hydroelectric power, and decreased agricultural production (Lenton, Footitt and Dlugolecki 2009). An estimate of the economic impacts of future dieback of ~70% of the rainforest (~3.85×10^6 ha) based on the value of its ecosystem services (~$6000/ha) is ~$2.3 trillion (Lenton, Footitt and Dlugolecki 2009).

Boreal forest dieback: In the future, the boreal forest could be replaced over large areas by open woodlands or grasslands, which would in turn amplify summer warming and drying and increase disturbances from fires and insect attacks, producing a potentially strong positive feedback. Forest replacement by steppe grassland would cool the winters and warm the summers.

Drying of Southwest North America: Southwest North America (all land in the region 125–95 °W and 25–40 °N), may be particularly affected by projected global expansion of subtropical dry zones (Held and Soden 2006; Lu, Vecchi and Reichler 2007), with aridity robustly predicted to intensify in future in a transition to something "…unlike any climate state we have seen in the instrumental record" (Seager et al. 2007). Past experience of the dustbowl in the North America prairies indicates very persistent economic impacts of drought linked to out-migration (Hornbeck 2012). Recent drought in California is unprecedented in the last millennium (Griffin and Anchukaitis 2014) and has already had significant economic impacts, for example an estimated $2.7 billion impact on agriculture in 2015 (Howitt et al. 2015). Water resources are being impacted and regional warming and drying is also increasing wildfires (Westerling et al. 2006). Future amplification of these trends suggests high damages (Lenton, Footitt and Dlugolecki 2009).

4. Translating physical impacts into economic impacts

To translate the physical impacts of passing different climate tipping points into economic impacts requires some identification of the economic sectors impacted and some mapping between sectoral impacts and economic variables (Lenton and Ciscar 2012). Ideally, like any assessment of climate change impacts, the impacts of tipping points should look not only at the effects on economic production (GDP) in a certain year, but also at the dynamic effects over time. Fankhauser and Tol (2005) discuss how climate change could affect economic growth, via four categories of economic variables: household welfare (mainly related to non-market impacts), production (mainly related to productive or market activities), capital stock (which might affect economic growth prospects) and labour productivity (also affecting growth as it would affect real wages and, therefore, savings due to the impact on consumption). Table 2 summarises how climate impacts on key sectors would affect these economic variables, following Ciscar et al. (2011). A further important consideration is how the economic impacts of passing a climate tipping point may cascade through a globalised economy. Here we focus on that issue with a specific case study of the impacts of winter (year-round) Arctic sea-ice loss.

4.1 Case study: Arctic sea-ice loss impacts in ACCLIMATE

The idea that climatic conditions influence economic performance dates back to the Ancient Greeks (Dell, Jones and Olken 2014). In light of the significant rise in global mean temperature that can be expected under an unabated increase of future greenhouse-gas emissions (IPCC 2013), a growing body of empirical research has set out to better understand and quantify this relationship – see (Carleton and Hsiang 2016) for a recent review. For example, it has been shown that labour productivity declines quasi-linearly with temperature above a threshold that is estimated to be ≥ 25°C (Pilcher, Nadler and Busch 2002; Dell, Jones and Olken 2009; Hsiang 2010; Burke, Hsiang and

Miguel 2015). Reductions in labour supply associated with temperature shocks are observed mainly but not exclusively (Cachon, Gallino and Olivares 2012; Zivin, Hsiang and Neidell 2015) in industries exposed to outdoor temperature such as forestry, mining and construction where air-conditioning is difficult to put in place (Graff Zivin and Neidell 2014).

Heat stress of workers at hot days can hence lead to an output reduction in certain sectors. These *first-order production losses* may then cause further losses along the supply chain (*higher-order production losses*): In the course of modern rapid globalization a complex web of vertically integrated and globe-spanning supply and value-added chains has emerged (Hummels, Ishii and Yi 2001; Wiedmann et al. 2011; Costinot, Vogel and Wang 2012). As a consequence, local production reductions can evoke supra-regional repercussions through both, the demand- and the supply-side (Christopher and Peck 2004; Veen 2004; Kousky 2014; Okuyama and Santos 2014). Recently, it has been shown that the susceptibility of the global economic network to the propagation of heat stress-related production losses has increased since the beginning of this century and that this increase is mainly due to an enhanced economic connectivity (Wenz and Levermann 2016).

Consequently, future heat stress-related production losses will likely be influenced by the severity of global climate change and its regional realisation, the structural evolution of the global economic network and the adaptation possibilities of workers and firms.

As detailed in Section 3, winter (year-round) sea-ice loss in the Arctic has been projected to have a warming effect that extends to large areas of the mid-latitudes of North America and Eurasia - particularly in winter and spring, but also to some degree in summer (Deliverables D10.2, D3.3). This may entail an altered regional heat stress exposure pattern.

In this case study, we investigate the exposure of countries to heat stress in a 4°C warmer world with Arctic sea-ice loss in winter (scenario #1) in comparison to a 4°C warmer world with a lot of sea-ice left (scenario #2). We analyse the respective effects on the propagation of production losses in the global economic network and on the distribution of higher-order losses across space. We thereby assume the current socio-economic structures and adaptation levels.

Data & Methodology

We build on output of the EC earth system model for runs at 4°C global warming with and without rapid Arctic sea ice loss (Deliverable D3.3). More precisely, we use daily mean temperature data for the year 2080 on a horizontal grid of 0.5°x0.5° resolution and combine it with a socio-economic scenario defined by population and economic data for the year 2011. That is, we construct a counterfactual world where we impose a 4°C warming scenario with and without Arctic sea ice loss in winter on the present-day socio-economic system.

For 186 countries, we compute a population-weighted time-series of daily mean temperature using gridded population data from the ISI-MIP dataset (Frieler et al. 2015) and a country mask provided by the Global Administrative Areas initiative (http://www.gadm.org/country) that assigns grid cells to countries.

The global economic network is constructed from data of the Eora26 World multi-regional Input-Output dataset (Lenzen et al. 2012) that covers annually averaged monetary transactions between

26 industry sectors and final demand in the 186 countries (in USD). These input and output flows at day-level are interpreted as directed links in a network of regional sectors and final demand (Maluck and Donner 2015). The sum of all output flows of a regional sector yields its daily production level.

Following a recent econometric study (Hsiang 2010), the first-order production losses due to heat stress are computed proportional to the daily temperature above 27°C. As suggested by the data, the daily production of the sectors construction, agriculture & fishing and mining & quarrying is reduced by a factor of 0.6%, 0.8% and 4.2%, respectively, for each degree above this threshold.

In order to estimate higher-order production losses that might arise from these direct effects, we use the numerical model *Acclimate* (Bierkandt et al. 2014; Wenz et al. 2014). The model attributes several basic economic features to all regional sectors in the global economic network and describes their dynamic interaction at a daily timescale. It propagates production losses from one regional sector to another via forward (supply shortages) and backward (demand reductions) linkages in the network. In case of supply shortages, the production of a regional sector is limited by the minimal relative availability of one input good across all input goods (assumption of perfect complementarity). That is, if, for example, 10% of one input good and less of all other inputs is missing, production is reduced by this factor. The loss propagation is buffered by the existence of stored goods, by transportation times and by the possibility to redirect demand to other suppliers. The reader is referred to (Wenz et al. 2014) for a detailed model description, (Wenz and Levermann 2016) for the precise model set-up and (Otto et al. 2016) for a comparison to other modelling approaches such as Computable General Equilibrium or Input-Output models.

Results

For both scenarios and each country we compute daily first- and higher-order production losses due to heat stress as described above. We find that globally aggregated daily losses, i.e. the sum of all national losses per day, show a typical seasonal cycle with highest first- and higher-order losses in summer and lowest losses in winter. Higher-order losses lag behind first-order losses because of storage capacities and transport times. They constitute about one third of *total production losses* which are defined as the sum of first- and higher-order losses.

We compare production losses per country in 2080 under a scenario of Arctic sea ice loss in winter (scenario #1) to a scenario where a lot of Arctic sea ice is left (scenario #2) by computing the percentage change in annually aggregated losses in 2080 (Figure 2). We thereby differentiate between first-order, higher-order and total production losses.

Regarding the direct exposure of countries to heat stress, we find that first-order production losses increase in some countries under a scenario of Arctic sea ice loss in winter whereas they decrease in others (Figure 2(a)). Most notably, they are much higher in many European countries as well as in South Africa, Chile and Argentina. In some of these countries (e.g. in Sweden) there are only heat stress days and thus first-order production losses under a scenario (#1) of Arctic sea ice loss in winter but not under a scenario (#2) where a lot of Arctic sea ice is left. In other countries, this observation is reversed in that first-order production losses are reduced if we assume Arctic sea ice loss in winter. The reduction is most pronounced in some Eastern European countries such as the Ukraine or the Baltic region and in Canada.

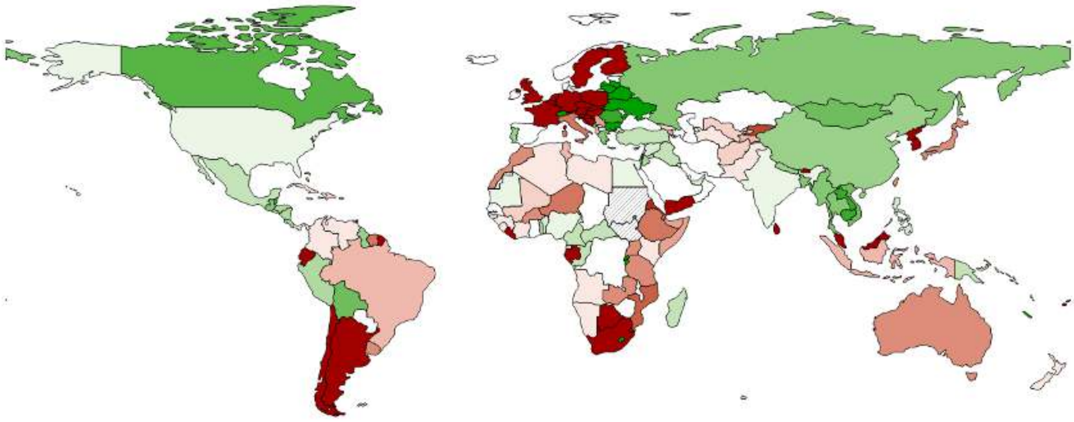
Because of the complex structure of the global economic network and the numerous trade links between countries, a country's percentage change in higher-order production losses can be completely different to that in first-order losses. In fact, we observe that many countries (e.g. the USA or Russia) that experience less heat stress and hence less first-order production losses if we assume Arctic sea ice loss in winter face an increase in higher-order losses under the same scenario (Figure 2(b)). While, directly, they suffer less from heat stress, they are indirectly more affected because their trading partners (or the trading partners of their trading partners) are subject to heat stress-induced production reductions and pass the resulting losses on via supply and demand-change cascades. Similarly, other countries such as Germany or Brazil that suffer from an increase in first-order production losses under scenario #1 encounter less higher-order effects because their trading partners are less affected.

Comparing total production losses per country in 2080 under scenario #1 and scenario #2 (Figure 2 (c)), we find a regional pattern of percentage change in total losses that is similar to that of first-order production losses. This is in line with our finding that first-order losses represent the larger part of total production losses.

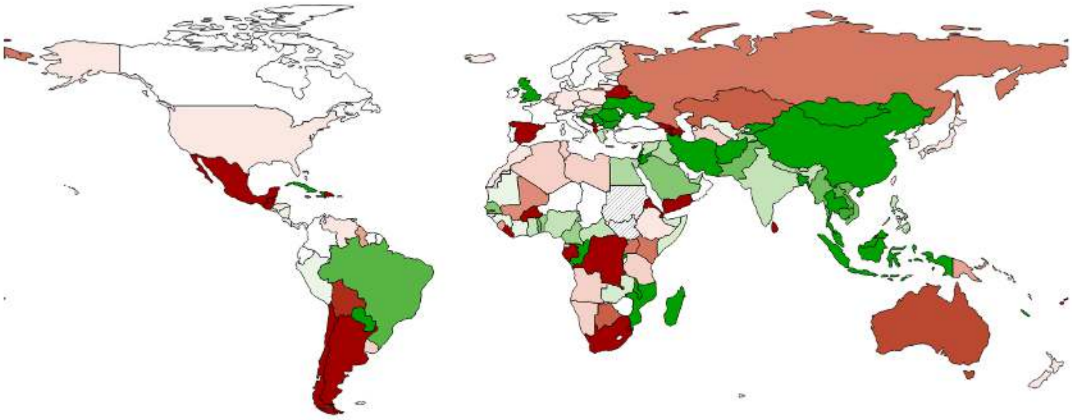
Conclusion

Information about the distribution of climate impacts across countries is of great importance for international climate negotiations and transfers, for mitigation schemes as well as for adaptation measures (Edenhofer, Pichs-Madruga and Sokona 2014; Burke, Hsiang and Miguel 2015). Our findings suggests that a country's exposure to heat stress-related production losses can be quite different dependent on whether there is a lot of Arctic sea ice left or not. While some countries benefit from a rapid sea ice loss in the Arctic, others experience higher production losses. This holds for both, first-order and higher-order production losses, and the change can be of opposite sign for the two types of vulnerability. These two types require different adaptation measures: a higher exposure to first-order production losses necessitates e.g. investments in cooling strategies or a shift of working hours whereas a higher exposure to the indirect effects of heat stress requires adaptation strategies that render trade relations climate-smart (e.g. a diversification of trading partners or an increase in storage capacities (Levermann 2014)).

a) First-order production losses



b) Higher-order production losses



c) Total production losses

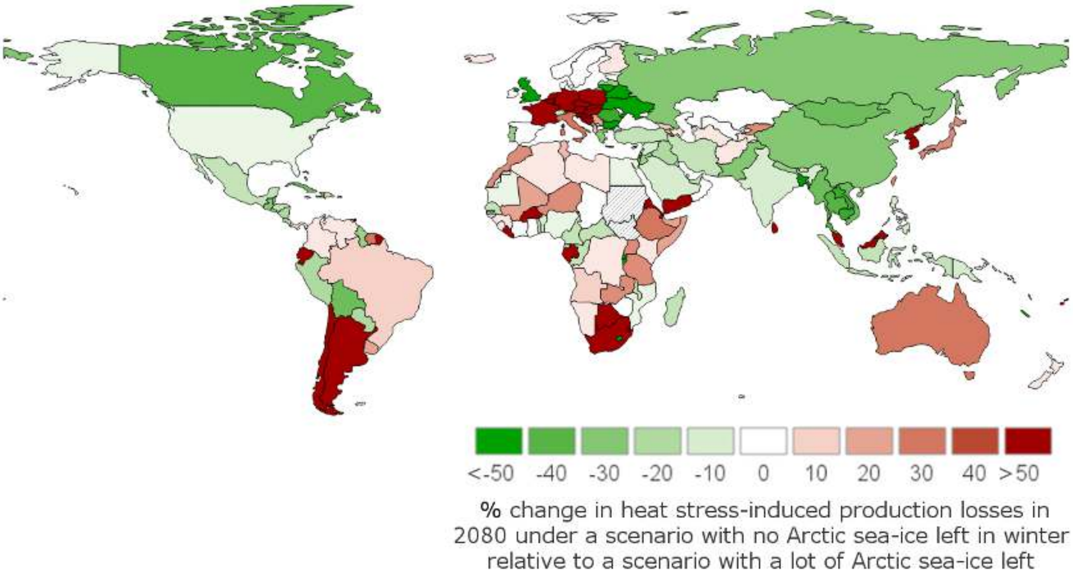


Figure 2: Change in heat stress-induced production losses due to winter Arctic sea ice loss. Countries are coloured according to the percentage change in heat stress-related production losses

that they experience in 2080 under a scenario with Arctic sea ice loss in winter relative to a scenario with winter Arctic sea ice remaining. Panels (a), (b) and (c) show the percentage change in first-order, higher-order and total production losses, respectively. While some countries experience less heat stress and thus less first-order production losses under a scenario of Arctic sea ice loss in winter (green colour), others encounter an increase in first-order losses (red colour; Panel (a)). For some countries, this relation is reversed if higher-order losses are regarded (Panel (b)). First-order production losses represent the larger part of total production losses (Panel (c)). Grey hatched areas denote that a country was excluded from the analysis because reliable economic data were scarce.

5. Adaptation responses (including limits to adaptation)

We now consider adaptation responses to climate tipping points in more detail, with two different case studies involving migration as an adaptation response, either to abrupt drying or to accelerated sea-level rise, in the focal region of West Africa. Before launching into the case studies we expand on the concept of social tipping points and how they might be triggered by climate tipping points.

5.1 Social tipping points

From a social science perspective, the tipping point concept can illuminate the limits to a society's adaptive responses to climate change. Contrary to what is often assumed, the relationship between climate change and its social impacts is not linear. The limits of a societies' resilience might be surpassed well before a climate tipping point is reached. Generally speaking, tipping points are reached when a self-reinforcing process drives further change. This positive feedback can be countered by self-regulating negative feedback, which restores the system back to a stable state. The perception of climate change can affect the social feedback dynamics. The ways through which climate impacts are perceived and mitigated in a society is thus crucial to the understanding of social tipping points.

The concept of social tipping points is distinct from climate tipping points as it indicates the limit of a society's resilience to climate change. It refers to the effects of both slow onset and abrupt changes on a social structure, which do not evolve in parallel with climatic tipping points. The risk of reaching social tipping points long before potential climate tipping points unfold is especially relevant in the developing world where adaptive capacity and resilience are often lower.

With regards to migration dynamics, no direct relationship between the scale of climate impacts and migration impacts can be expected. Small changes in climate can sometimes have vast effects on migration patterns, whilst large changes in climatic can sometimes only have small effects on migration. Climate hotspots are therefore not necessarily migration hotspots. Furthermore, climate change can create a situation of immobility. A preliminary conclusion is that climate change will change migration dynamics in a non-linear way. Therefore, climate tipping points do not necessarily cause migration tipping points.

In terms of feedback mechanisms mentioned above, a reduction of economic productivity can encourage significant amounts of people to leave, in search of better economic opportunities, which exemplifies a positive feedback mechanism. Negative feedback can result from financial and social remittances, which gives those who stayed behind the means to remain. Remittances could also act as a positive feedback as the additional money may give other family members the means to leave, which they did not have before.

In the following sections we will elaborate on two case studies conducted in the West African Sahel, Senegal and Burkina Faso. Intra-regional mobility, due to environmental as well as other reasons, is common in West Africa and more significant than intercontinental migration (Zickgraf 2015). Both studies look at the impact of climate change on migration. With these patterns in mind we attempt to project potential impacts of the collapse of the West African monsoon, as well as high rates of future sea-level rise on migration, and aim to assess the limits of migration as an adaptation strategy to climate change.

5.2 Case study: Migration in response to Sahel drying

In Burkina Faso, a semi-arid country in the West African Sahel, 90 % of the workforce is employed in the agricultural sector which is highly dependent upon rainfall (FAO 2014). During the 1970s until the mid-1980 the country was struck by severe droughts (Hampshire and Randall 1999; Nicholson 2001; Roncoli, Ingram and Kirshen 2001). Since the 1990s, rainfall increased again (Lodoun et al. 2013). Currently, rainfall quantities in Burkina Faso are stable but still lower than before the 1970-80 droughts (De Longueville et al. 2016). In general, the Burkinian rainfall regime is irregular due to its position in the Sahel. Apart from droughts the country is also is confronted with floods (Sally, Lévite and Cour 2011). While there is little empirical evidence supporting this, as rain-fed agriculture is Burkina Faso's main source of income, this easily leads to the assumption that environmental factors will influence socio-economic conditions and are therefore tied to migratory responses (Henry, Schoumaker and Beauchemin 2004).

Migration as a climate adaptation strategy

In West Africa, including Burkina Faso, people generally respond to seasonal variability and droughts, which render crop production highly uncertain, by engaging in cyclical intraregional migration (Cordell, Gregory and Piche 1996; Rain 1999). Migration of a few household members, mostly young men, is a strategy to diversify the household income in economically uncertain times (Roncoli, Ingram and Kirshen 2001; Henry, Schoumaker and Beauchemin 2004). In relation to environmental change, such as more frequent droughts or floods, that has an impact on crop production, migration can be considered an adaptation strategy.

Henry (2004) found that rainfall variability can have an influence on the migration destination as international migration is costlier and thus less viable in drier periods. This holds for urban destinations as well. Both permanent and temporary rural-rural migration occurs more in drier areas, especially if the area was even drier in the three preceding years. The relationship between rainfall and migration to urban areas is not significant. Repeated droughts can lead to permanent migration to other rural areas, while it decreases the occurrence of short-term migration over long distances. However, the ability to engage in long-distance migration generally decreases after unfavourable harvests. Overall, the relation between irregular rainfall conditions and migration is weak, which was also found by (Henry, Schoumaker and Beauchemin 2004). A survey conducted in 1974 and 1975, following the great Sahelian droughts, revealed that only 4% of migrants pointed to drought as a significant migration driver, which could be explained by the extensive food distribution. Still, throughout the entire region, the great Sahelian droughts of 1968-1973 displaced one million people (Afolayan and Adelekan 1999).

As demonstrated by Peyraut (2012), populations resettled in the aftermath of the 2009-2010 floods were more concerned with the effects of repetitive droughts on their livelihoods than with one-time events such as floods. This finding is supported by Henry (2004), who observed that droughts tend to increase the risk of long-term migration to rural areas and decrease the risk of short-term moves to distant destinations.

Under climate change, temperature is projected to rise approximately +0.8°C by 2025, and approximately +1.7°C by 2050 in Burkina Faso, with drought risk increasing and rainfall levels decreasing up to 30% in July, August and September and increasing up to 80% in November (Faso 2007). The tipping point that will affect Burkina Faso the most is the collapse or southward shift of the West African Monsoon, which would lead to reduced rainfall in the Sahel (Chang et al. 2008). It is clear that linear climate change as well changes to the West African Monsoon, will have severe impacts on crop productivity and the overall Burkinese economy, which is highly dependent on agriculture.

Climate adaptation measures, such as management of soil fertility and irrigation are often not adopted as farmers lack the financial means. As highlighted by Barbier et al. (2009), soil and water conservation practices are frequently implemented in the West African Sahel but mainly because of growing land scarcity and new market opportunities rather than climate variability. Technical adaptation measures that are available to farmers are use of several crop varieties or mix-cropping and postponing seeding dates (Fosu-Mensah, Vlek and MacCarthy 2012). In southern Burkina Faso, farmers involved in cotton production tend to specialize. In the North, farmers do not use crop diversification but rather diversify their income through off farm activities (Reardon, Delgado and Matlon 1992).

Case study in the framework of the HELIX project

Due to the unpredictability of climate change as well as the human responses to its consequences, the particular consequences for migration are hard to foresee. Crucial to the understanding of populations' responses to climate change are their perceptions of these changes. The case study conducted by de Longueville, Gemenne and Ozer (2015) in the context of the HELIX project illustrates the importance of perceptions of environmental change with regards to migration drivers. The study is based on perception data collected in the framework of the African Monsoon Multidisciplinary Analysis (AMMA) project, which was carried out in five West African countries between November 2007 and June 2008. A socioeconomic survey was conducted between November 2007 and June 2008, in four regions and climatic zones in Burkina Faso. While most respondents indicated a decrease in rainfall between 1988 and 2008, rainfall stations registered relative stable rainfall levels for that same period. Perceptions of temperature increases were consistent with observations.

The survey also gauged at the respondents' migration intentions in response to climate change. At the time of the survey, more than 45% of households had members who migrated temporarily, while 14% had permanent migrants. 78.1% of the respondents identified poverty as the main cause of migration, while only 1.6% pointed to rainfall deficits. Temporary migration was only seen as a first adaptation strategy in response to a drought by 12.7%, while 17.5% mentioned migration among other strategies. In case of droughts, households mentioned a combination of strategies, starting with the sale of livestock and the decrease of food intake. In response to a generally drier climate, temporary and permanent migration was cited as first adaptation strategy by 7.8% and 6.9% of the surveyed population respectively. In response to worsening rainfall conditions over 25% mentioned permanent migration among potential adaptation strategies. For both permanent and temporary migration this is over 40%.

Implications of a collapse of the West African Monsoon for migration as an adaptation strategy

These findings lead to the expectation of increased future migration flows from this region. Considering the overly pessimistic perception of rainfall conditions this could even happen before rainfall levels significantly decrease. Furthermore, people will most probably anticipate decreasing rainfall levels (De Longueville, Gemenne and Ozer 2015). Given that a significant proportion of Burkinian households considers to migrate in case of worsening rainfall conditions, a southward shift of the West African Monsoon and the associated permanent reduction in rainfall levels is expected to increase migration within and potentially from Burkina Faso considerably. In order to confirm this finding, further research has to be undertaken to investigate other variables that may influence the social tipping point leading to increased migration. The evolution of socioeconomic conditions in the country, as well as climate adaptation measures have an impact on migration intentions that would need to be factored in.

While repeated droughts can lead to more long-term migration, in the longer run, the impact of a series of failed harvests on household income can be expected to temper and even nullify this effect. Furthermore, frequent droughts decrease the occurrence of short-term migration over long distances. Better use of adaptation measures such as soil fertility management, irrigation, soil and water conservation practices, could prevent agricultural productivity losses to a certain extent. However, the magnitude of the impacts of a collapse of the West African Monsoon can most probably not be mitigated by these adaptation measures. Declining crop productivity and thus household income is a likely consequence of these climatic changes. Taking into account the observation that both long-term and short-term migration ceases to be a viable adaptation strategy if the financial means are not available, it can be assumed that migration as an adaptation response to climate change is no longer effective in the face of severe droughts associated with a collapse of the West African Monsoon. If the effects of such collapse render crop production infeasible, in a country as dependant on agriculture as Burkina Faso, distress migration could be the only option left. In this case, migration is no longer an adaptation strategy but rather a last-resort response to extreme environmental change.

5.3 Case study: Migration in response to sea-level rise

The Senegalese coast suffers from sea-level rise and related coastal erosion, flooding, soil salinization, and increased storm surges related to climate change (Cormier Salem 2013). The consequences include stronger waves, decreases in maritime biodiversity, and depletion of fish stocks. These are exacerbated by human-induced environmental degradation such as overfishing by industrial vessels. Senegalese fishing industry suffers from these environmental changes. The United

Nations Food and Agricultural Organization (FAO) calculated that around 600,000 livelihoods directly or indirectly related to the industry are under threat (FAO 2008). This precarious situation has important transformative and intensifying effects on Senegalese fishermen's mobility.

Since the end of the 19th century, Senegalese fishermen migrated to areas across the whole sub-region (Binet, Failler and Thorpe 2012). Nowadays, many experienced fishermen engage in temporary, seasonal migration along the West African coast, including Mauritania. However, the artisanal fishing licences granted to Senegalese fishermen by Mauritania have not been extended in 2017 (UndercurrentNews 2017). The decreasing fish stocks in Senegalese waters drives fishermen without licences further northward towards Mauritanian waters, where they are often stopped by the Mauritian coast guard (Al Mouahidi 2017). Others move permanently, for instance to work in fishing factories in Mauritania, which is traditionally not a fishing country (Zickgraf 2015).

In the framework of the HELIX project, Caroline Zickgraf (2015) conducted a case study in Saint-Louis, a Northern coastal city, close to the border of Mauritania. The case study is based on qualitative interviews and focus groups with migrant and non-migrant fishermen in Guet Ndar. This fishing quarter in Saint-Louis, is one of the most densely populated urban districts in West Africa. Nearly all inhabitants of Guet Ndar rely, directly or indirectly, on the fishing industry for their livelihoods. Through network-sampling, different occupations, ages, gender, and geographical locations were included in the study. This way, differences in perceived environmental change were captured.

Vulnerability and migratory responses

The people living in Guet Ndar are vulnerable due to the quarter's overpopulation, the endangerment of their livelihoods due to decreasing fish stocks and the impacts of coastal erosion and storm surges on infrastructure. The depletion of fish stocks has significantly extended the duration of the fishermen's mobility. While they used to migrate seasonally to fish locally part of the year, currently, many move for up to 10 or 11 months to Mauretania. However, most still considering their migration to be temporary.

Coastal erosion and storms resulting from sea-level rise have already destroyed a considerable amount of houses leading to the displacement of people living close to the ocean. These people perceived coastal erosion as the most important threat. While most wished to stay due to cultural attachment to the sea and their fishing career, they either had the intention to move away, or were already building a second home further inland. Most people did not give up their homes at the sea side and built their second house relatively close to the ocean so that they could continue to work in the fishing industry. People living further away from the water were more troubled by the economic consequences of the decreasing fish stocks. Perceptions of vulnerability influence migration intentions as these differentiated vulnerabilities feed into the type of migration. International labour migration is a way to diversify household income in the face of the decreasing fish stocks, while internal relocation is a response to coastal erosion. Both types of migration are interlinked as international labour migration generally provides the funds for internal relocation. However, as the poorest and most vulnerable inhabitants of Guet Ndar benefit less from remittances, they are less protected from the impacts of sea-level rise. For them migration could only improve resilience as an immediate coping strategy, without providing long-term protection. Overall, international mobility mainly serves as a long-term adaptation strategy for the wealthiest, while future sea-level rise will exacerbate the vulnerability of those that are unable to organise their relocation. This can ultimately result in more distress migration (Afifi, Liwenga and Kwezi 2014).

The limits of migration as an adaptation strategy in the face of ice sheet tipping points

It is clear that coastal erosion as a consequence of sea-level rise, inevitably leads to relocation in Saint-Louis. The impacts of climate change, combined with overpopulation and economic hardship due to maritime resource degradation will increase migratory pressure in the future. In case of a collapse of the Greenland or Antarctic ice sheets, accelerated sea-level rise will severely impact this process. As long as fishermen are located close enough to the ocean, they can continue to foresee in their livelihood in Senegalese and international waters, as well as by sending several household members abroad. It is exactly the possibility to migrate to Mauretania that allows the least vulnerable inhabitants of Guet Ndar to relocate to areas less exposed to sea-level rise, while maintaining their traditional livelihoods. In these circumstances, migration serves as an adaptation strategy to climate change. However, currently, this only holds for the most affluent. In order to enable the entire population to benefit from this strategy, governance assistance is needed for those who do not have the means or the networks to migrate. In this regard, Zickgraf stresses the importance of accounting for local livelihood strategies, which allow the community to continue to rely on the fishing industry, for instance by facilitating the commute to the seaside. When conducting vulnerability and resilience assessments or designing adaptation plans, these livelihood strategies as well as the socioeconomic differences within a community need to be taken into account.

In coastal areas where it is not possible to migrate to nearby areas where fishing expertise is needed, the adaptive capacity of migration is lower. Coastal erosion in Cotonou in Benin, for instance, leads to a process where the more affluent coastal residents permanently move out of the risk zone, whereas poorer fishermen and people who moved closer to the sea as they are unable to pay rent elsewhere in the city, end up in vicious circle of aggravating vulnerability. As their houses are destroyed they build makeshift houses in the same risk area that are damaged time and time again (de Longueville et al. 2015). Here it seems that migration as an adaptation strategy has already reached its limits as the remaining residents do not have the means to migrate, either to move away from the encroaching sea or to provide for remittances that can improve their resilience. These populations become ‘trapped’ as they are “unable to move away from danger because of a lack of assets, and it is this very feature which will make them even more vulnerable to environmental change” (Foresight 2011) (p. 28).

These cases demonstrate that alternative livelihoods need to be available in order to sustain a community’s ability to adapt to rising sea-levels. Adaptation strategies are context-specific and often face difficulties related to existing laws or political considerations such as the shifting Mauritanian policy on fishing licences. If Mauritania does not resume the granting of licences to Senegalese fishermen, migration as an adaptation strategy in Guet Ndar will be less effective.

6. Summary/Conclusion

Our review and case studies highlight that as well as there being tipping points in the climate system, adaptation may have its own tipping points – including abrupt failures of particular adaptation strategies (limits to adaptation) and abrupt uptake of other strategies (e.g. conceivably triggering of widespread migration). Not all climate tipping points translate into tipping points in impacts or in adaptation strategies. Passing climate tipping points often translates into an acceleration of impacts that were occurring anyway, but not necessarily an abrupt discontinuity in impacts. Notably, passing ice-sheet tipping points will accelerate sea-level rise but the abruptness here is only in the first derivative of the impact (an abrupt increase in rate). This may in turn bring forward the time when a particular limit to adaptation is reached (e.g. raising sea defences fails as a strategy). Furthermore, the irreversible commitment to larger impacts that can arise from passing tipping points, e.g. a greater sea-level rise commitment due to passing ice sheet tipping points, will ultimately mean that more limits to adaptation will be breached. It may thus be useful to think in terms of passing some climate tipping points as making irreversible commitments to passing limits to adaptation (at some point in the future). Other tipping points are more reversible in principle, e.g. Arctic sea-ice loss, but can unfold much more rapidly. Our case study of abrupt winter Arctic sea-ice loss shows that the resulting impacts from heat stress are geographically variable in both sign and magnitude, are overall deleterious, and that they propagate through a globalised economy, such that indirect impacts represent around a third of total impacts. The globalised economy is often framed as an aid to adaptation, through its ability to redistribute resources, for example if there is a food security crisis in one region this can be buffered by purchasing food in a globalised market. However, our Arctic sea-ice case study demonstrates that a globalised economy can also increase the damages and the adaptation challenge from passing a regional climate tipping point. Some climate tipping points can change the sign of environmental change and these may pose a particular adaptation challenge (Hulme 2003). However, regions such as the Sahel which already experience marked increases and decreases in rainfall provide examples of adaptation strategies – notably non-permanent migration – that buffer against such uncertainty. In such cases a more permanent, abrupt, directional change in conditions, for example a persistent drying due to collapse of the West African monsoon would represent a greater adaptation challenge and could tip a change in adaptation strategies to more permanent migration.

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Table 1: Potential physical impacts of passing different climate tipping points

Tipping event	**Temperature**	**Sea level**	**Precipitation**	**Atmospheric circulation**	**Ocean circulation**	**Biogeochemical cycles**	**Modes of variability**	**Extreme events**
Arctic sea-ice loss	↑Arctic & N. Hem.	(minimal effect)	Local shift from snowfall to rainfall	↓polar vortex, shift in storm track	Intrusion of warm Atlantic waters	↑Permafrost thawing, ↑CO_2, CH_4	Shift in NAO centre of action	Cold winters in Europe
Greenland ice sheet meltdown	Local ↑	≤7 m global ≤0.5 m/century uneven	Local shift to rainfall	Less jet stream deflection?	↓AMOC, loss of Irminger Sea convection	Flooding of permafrost, ↑CO_2, CH_4	(via effects on AMOC)	Storm surges, icebergs
West and East Antarctic ice sheet instability	Local ↑	~17 m global >1 m by 2100 >3 m/century	Local shift	Uneven polar vortex?	↓or↑ AMOC, ACC affected	Flooding of permafrost, ↑CO_2, CH_4	(via effects on AMOC)	Iceberg armadas storm surges
Atlantic circulation (AMOC) collapse	↓N. Atlantic ↑S. Hem.	Regional shifts ↑0.5m in parts of N. Atlantic	Collapse WAM, weaker ISM, ↓(↑) Amazonia	S shift of ITCZ, Atlantic storm track shift	Fundamental reorganisation	↑CO_2, biome changes	AMO ceases, ↓(↑) ENSO	Cold winters in Europe, hurricanes S?
Increase in ENSO amplitude	↑S Asia, S Australia... ↓in NZ	Regional effects	↓SE Asia, E Australia, Amazon...	Walker circulation change	↑AMOC, warming Ross, Amundsen seas	↑CO_2, reduced land C storage	Coupled changes to PDO, AMO	Droughts, floods
Indian summer monsoon (ISM) weakening	Local ↑summer	-	↓ in India	Regional reorganisation	?	?	Coupling to SO?	Drought in India, heatwaves
West African monsoon (WAM) collapse	↑in Sahel ↓coastal W Africa	-	↓Sahel, ↑coastal W Africa	Regional reorganisation	?	Possible greening of Sahel/Sahara	Coupling to AMOC?	Source region for Atlantic hurricanes
Amazon rainforest dieback	↑regional	-	↓regional	Walker circulation?	-	↑CO_2	Feedback to ENSO?	Droughts, fires
Boreal forest dieback	↓winter ↑summer	-	↓regional?	Regional effects?	-	↑CO_2	-	Fires, insect pests
Drying of SW North America	↑regional	-	↓regional	Regional effects?	-	↑CO_2	-	Droughts, fires

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

Table 2. Mapping between sectoral impacts and economic variables

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